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Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering



Research Report

**C.L. Huxley, T.S. Gill, L.S. Carroll, and
A. Thompson**



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By:

C.L. Huxley, T.S. Gill, L.S. Carroll, and A. Thompson

March 2004

Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU

Bibliographic reference:

Huxley, C.L., Gill, T.S., Carroll, L.S., & Thompson, A. (2004): *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering – Research Report*. Report to the Minerals Industry Research Organisation and The Department of the Environment, Food and Rural Affairs. Symonds Group Ltd, East Grinstead.

Publication:

Copies of this report, together with associated case study leaflets, may be found on the Minerals Industry Research Organisation's website (www.miro.org.uk).

Alternatively hard copies of this report, together with supporting documents on each of the experiments undertaken as part of this research project, may be obtained from:

Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU

Telephone: 01342 327161
Fax: 01342 315927

Acknowledgements:

This report was produced from research carried out by Symonds Group Ltd, for the Minerals Industry Research Organisation (through the Minerals Industry Sustainable Technology funding programme), under research contracts MA/1/2/008 and MA/3/2/005.

Additional funding, and guidance, was provided by the Environment Agency, Hanson Aggregates, Lafarge Aggregates, RMC Aggregates, and Tarmac Southern.

The authors are grateful to all members of the Steering Group (see below), and to various personnel from mineral operators, Local Planning Authorities, and the Environment Agency who assisted in this study.

Simon Neale (Hydrogeology Policy & Process Team Technical Advisor)	Environment Agency
Laurence Crump (Head of Geological Services)	Hanson Aggregates
Duncan Wardrop (Minerals Resources Manager)	Lafarge Aggregates
David Roberts (Head of Geological Services)	RMC Aggregates
Chris Pointer (Senior Hydrogeologist)	RMC Aggregates
Susan Willard (Senior Hydrogeologist)	RMC Aggregates
Eddie Bailey (Senior Geologist)	Tarmac Southern
Gavin Chaplin (Senior Hydrogeologist)	BCL Consultant
	Hydrogeologists Ltd

Disclaimer:

Whilst due consideration has been given to comments received from those listed above, this report sets out the views of the authors alone. This publication and references within it to any methodology, process, service, manufacturer, or company do not constitute its endorsement or recommendation by the Minerals Industry Research Organisation or The Department for Environment, Food and Rural Affairs.

EXECUTIVE SUMMARY

Introduction

It has long been recognised that quarry 'dewatering' (lowering groundwater levels, usually by pumping, to allow working below the normal water table) can have potential adverse impacts on groundwater and surface water resources, and on associated sensitive receptors such as nearby watercourses, wetland habitats and public water supply boreholes.

It is equally well established, however, that most of these adverse effects can be avoided, or at least controlled within acceptable limits, by the use of appropriate mitigation measures. Both the potential effects and the available mitigation techniques were reviewed in the 1998 Guide to Good Practice on *'Reducing the Effects of Surface Mineral Workings on the Water Environment'*, produced by Symonds Group for the former DETR (now DEFRA / ODPM).

One of the many mitigation techniques highlighted in that report was the use of artificial '**recharge features**' to limit the adverse effects of dewatering by returning abstracted water back to the ground. Whilst the concept of artificial recharge is well established on theoretical grounds, and is used in other circumstances (such as aquifer storage recovery and infiltration drainage systems), very little published information has hitherto been available on the effectiveness of the technique for limiting the effects of quarry dewatering, or on the practicalities involved.

Such information is needed in order to allow mineral operators to understand the factors that need to be considered in the design of appropriate systems, and to give both Mineral Planning Authorities and the Environment Agency confidence in the likely effectiveness of those designs in mitigating potential impacts.

From 2005, the implementation of the Water Act 2003 will give the Environment Agency greater direct control of both abstraction (including quarry dewatering) and discharge, through the use of 'water transfer licenses'. These will take account of the way in which the abstracted water is used and, in particular, whether or not it is returned to the same or a different 'source' after being abstracted. Recharge features, which are specifically designed to return the water to the source from which it is abstracted, offer clear advantages in this regard.

The Principles of Artificial Recharge

Where dewatering could potentially lead to the drawdown of groundwater levels within a zone of dewatering influence in the surrounding aquifer, recharge features aim to infiltrate some of the abstracted water back into the ground so as to minimise the drawdown of original groundwater levels within the vicinity of sensitive receptors.

In effect, a 'recharge mound' is created beneath the recharge feature. When this is superimposed on the expected drawdown profile within the zone of dewatering influence, it reduces the head gradient between the recharge feature and the sensitive receptor and may even reverse it, in some situations. This effectively 'shields' the area beyond the recharge feature from the influence of the dewatering operation and allows groundwater levels in those areas to recover.

Artificial recharge may be achieved by a variety of surface or sub-surface methods, including injection wells (direct to groundwater); open recharge trenches / gravel filled trenches or buried drains (recharge via the unsaturated zone); and indirect recharge through natural surface water features.

The main concerns expressed in published literature, and in reference design guides, about the use of artificial recharge features, relate to the potential reduction in infiltration capacity with time, as a result of clogging with fines, micro-organisms, or precipitates (the latter may result from the exposure of groundwater to oxidation processes at the surface and/or to the mixing waters of different chemistries. There are certain differences however between the different techniques:

Injection wells (or recharge wells) have the advantage of returning water directly back to groundwater and thereby avoid some of the problems of chemical precipitation that can sometimes occur with other methods. However, construction, installation and running costs are likely to be significantly greater than for simpler recharge trenches. Theoretically, a properly designed recharge well will have a recharge rate the same as its pumping capacity, but potential problems (such as suspended solids, water quality and air entrainment) may be found to reduce the recharge rate over time.

Recharge trenches and buried drains are similar in principle to the soakaways and infiltration trenches that are increasingly used for drainage within the engineering industry. However, whereas soakaway design is primarily concerned with optimising the volume of water which can be drained, with recharge features the main emphasis has to be on the maintenance of specific groundwater levels.

Experimental Results

Despite new case study information, there is still little clear evidence on the extent to which recharge features have actually succeeded in their objective. Two short term preliminary experiments carried out as part of this research have therefore been invaluable in highlighting some of the practical issues involved.

The first of the new experiments was undertaken at Chamberhouse Farm, a greenfield site located approximately 5 km east of Newbury. The aim of this experiment was to create a temporary zone of dewatering influence, and then to discharge abstracted water to two nearby recharge trenches in order to monitor how water levels responded.

The second, contrasting experiment, at an operational site, was undertaken at Methley Quarry, near Castleford. This experiment aimed to investigate how rapidly an existing zone of dewatering influence reacted to the commencement of recharging through a trench and how well this response could be predicted by groundwater modelling.

The short term results from the experimental sites showed that the groundwater levels responded swiftly at the commencement of recharging, but that the response achieved was only a localised effect, decreasing with distance from the trenches. The results highlighted the importance of the internal surface area of the recharge features and their position in relation to the sensitive features being protected.

Implications of the Research Findings

There is still some way to go before all of the necessary issues relating to the use of artificial recharge features have been explored, but a number of useful implications are now beginning to emerge, as a direct result of this research. These relate both to the technical aspects of groundwater behaviour and to the practical design and planning considerations involved in implementing these techniques.

The essential point is that recharge features and/or any other mitigation works need to be 'fit for purpose' and designed to counter specific identified risks. They will not be suitable for all situations, and will not always be necessary. An essential first step in deciding what needs to be done is therefore to assess the potential risks through an understanding of the local groundwater and surface water system. If dewatering is considered to be necessary and vulnerable features might be affected, the next stage is to develop a conceptual model of the groundwater / surface water system, calculating a theoretical zone of dewatering influence from the excavation and then calculating the theoretical maximum drawdown of groundwater levels beneath the feature(s) that need to be protected.

Considerable effort may need to be devoted to the fundamental task of getting this understanding right, but it must also be remembered that natural systems are often complex and that uncertainties will always exist. If recharge features are likely to be suitable, consideration must then be given to the best ways of optimising their effectiveness within the constraints imposed by site layout, quarrying operations and land ownership.

In most cases, this is likely to involve placing the recharge features as close as possible to the areas that need protecting against drawdown, maximising the internal surface area of the trenches and, if necessary, raising the sides of the trenches above ground level through the use of bunds in order to raise water levels. In some cases, recharge features may need to be used in combination with other mitigation measures, such as low permeability barriers, in order to improve their efficiency. This is especially likely where the features have to be sited close to the area of active dewatering.

Numerical groundwater modelling may be a useful tool to aid the decision making process, and to inform the design of whatever method of mitigation is chosen, but this should be undertaken only if necessary, and if an adequate conceptual understanding has been gained from empirical monitoring data. Groundwater levels, both within and outside of the expected radius of dewatering influence, should also be regularly monitored and compared to agreed acceptable levels and model predictions (where available) so that modifications can be made, if required.

The Environment Agency should always be consulted at the earliest possible stage in order to ascertain whether they are satisfied with the proposed approach, and to confirm which consents need to be applied for. For their part, the Agency should recognise the considerable benefits that can be derived from recharge features, in terms of minimising the overall impact on individual aquifers, and should take this into account in the terms of the licenses required.

Conclusions

The detailed findings of this research provide a unique source of reference for both mineral operators and the Environment Agency, and should help to promote the greater use of recharge features to mitigate the impacts of quarry dewatering. The research has not only consolidated existing knowledge on the subject; it has made substantial new advances based on empirical observations and controlled experiments. Further research is needed, however, in order to build on the progress that has been made, so that important design criteria can be developed for different situations, and so that a more comprehensive guide to best practice can eventually be

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Appendix A Case Studies

Appendix B Recharge Trench Experiments

1. INTRODUCTION

1.1. Terms of Reference

- 1.1.1 It has long been recognised that quarrying operations can potentially have adverse impacts on the quality, levels and flow characteristics of both groundwater and surface waters, and on associated sensitive receptors such as wetland habitats and public water supply boreholes.
- 1.1.2 It is equally well established, however, that most of these potential adverse effects can be avoided, or at least controlled within acceptable limits, by the use of appropriate mitigation measures.
- 1.1.3 Both the potential effects and the available mitigation techniques were reviewed in the publication '*Reducing the Effects of Surface Mineral Workings on the Water Environment: A Guide to Good Practice*' (Thompson *et al*, 1998), produced by Symonds Group Limited for the former DETR (now the Department of the Environment, Food and Rural Affairs (DEFRA) and the Office of the Deputy Prime Minister).
- 1.1.4 One of the many mitigation techniques highlighted in that report was the use of artificial '**recharge features**' to limit the adverse effects of 'dewatering' (lowering groundwater levels, usually by pumping, so that quarries can be worked below the normal water table).
- 1.1.5 Whilst the concept of artificial recharge – feeding the 'dewatered' water back into the ground so as to maintain natural groundwater levels beyond the limits of the quarry – is well established on theoretical grounds, very little published information has hitherto been available on the effectiveness of recharge features in achieving this aim and the practicalities of optimising their efficiency in doing so.
- 1.1.6 This report sets out the findings of new research carried out by Symonds Group in partnership with Lafarge Aggregates; Tarmac (Southern); RMC Aggregates; Hanson Aggregates; and the Environment Agency, to address these deficiencies.
- 1.1.7 The research has been funded partly through the **Minerals Industry Sustainable Technology** (MIST) programme of the Aggregates Levy Sustainability Fund (ALSF), administered by the Minerals Industry Research Organisation (MIRO), and partly by financial and in-kind contributions from all of the research partners listed above. The research was undertaken between January 2003 and March 2004.

1.2. Aims and Objectives

- 1.2.1 The overall aims of this research were to collate existing information from literature and industrial experience, and to investigate the role of recharge features as a mechanism for mitigating the effects of quarry dewatering, including an assessment of factors associated with optimising their efficiency.
- 1.2.2 The more specific objectives of this research have been to:
- (i) Identify situations where recharge features are currently being used / have been used to mitigate the impacts of dewatering of mineral excavations;
 - (ii) Identify situations where there is potential for the use of recharge features;
 - (iii) Identify the appropriate specification, construction and location of recharge features;
 - (iv) Identify appropriate management of recharge features for optimal efficiency; and
 - (v) Identify the limitations of recharge features.

1.2.3 This research has focused on the use of recharge features in sand and gravel deposits within England, particularly within floodplain settings. Some of the lessons learnt, however, are more widely applicable to other forms of surface mineral workings in these and other deposits that are characterised by inter-granular (rather than fissure or karstic) flow conditions.

1.3. Research Methodology

1.3.1 The methodology for this research has involved:

- (i) A review of available literature on the use of recharge features, and associated information (e.g. aquifer storage recovery, soakaways);
- (ii) Gathering examples of the use of recharge features from the minerals industry, and assessment of what lessons may be learnt from their experiences;
- (iii) Running two experimental sites, in different settings, to try and gain an understanding of some of the potential key factors in the design of any recharge feature;
- (iv) Production of a transient groundwater model, for one of the experimental sites, in order to ascertain whether prediction of groundwater responses to the commencement of recharging is possible; and
- (v) Production of this report, which includes the findings from the previous four tasks and highlights considerations when planning or designing a mitigation measure for quarry dewatering.

1.4. The Scope and Purpose of this Report

1.4.1 This report represents the main output from the 'MIST' research project. It provides information on the use of recharge features and their design, together with commentary on their use in combination with other mitigation measures.

1.4.2 It is anticipated that this information may enable planners, Environment Agency personnel and mineral operators to hold more informed discussions on proposals for the use of recharge features as potential mitigation measures, either on their own or (more commonly) as part of a multi level mitigation strategy.

1.4.3 The report has been subdivided into the following sections:

- (i) Background information on quarrying dewatering and potential mitigation measures (Chapter 2);
- (ii) An overview of recharge features (Chapter 3);
- (iii) Discussion of the two experiments (and groundwater modelling) undertaken as part of this research (Chapters 4 and 5);
- (iv) Relevant legislation and discussion of licensing issues (Chapter 6);
- (v) A review of the implications of the research findings for the use of recharge features, including technical considerations (Chapter 7) and other planning and design issues (Chapter 8); and
- (vi) Recommendations for further work (Chapter 9).

1.4.4 Case studies from our industrial project partners may be found in Appendix A, and are referred to throughout the guidance document. Separate, more detailed reports on each of the experimental sites have been produced and are available from Symonds Group.

2. DEWATERING: BACKGROUND & MITIGATION

2.1. Principles of Dewatering

- 2.1.1 Sand and gravel extraction commonly takes place in river floodplains and adjoining river terrace features, where the deposits extend beneath the water table. Working such deposits below the water table can be done 'wet', by dredging from floating pontoons or from a dragline at the side of the excavation. Alternatively it can be undertaken 'dry', through dewatering of the excavation, allowing a more efficient and safe operation, and is preferred by most aggregate companies.
- 2.1.2 The dewatering process involves the artificial lowering of groundwater levels below the excavation (Figure 2.1). It is most commonly carried out by pumping from a sump located in the deepest part of the quarry, to keep pace with the inflow of groundwater. Alternatively dewatering methods may involve the use of drains, abstraction of groundwater from boreholes ('wellpoints') located around the perimeter of the site, from trenches or from shafts. Detailed discussion of dewatering methods may be found in CIRIA Report 113 (1998).

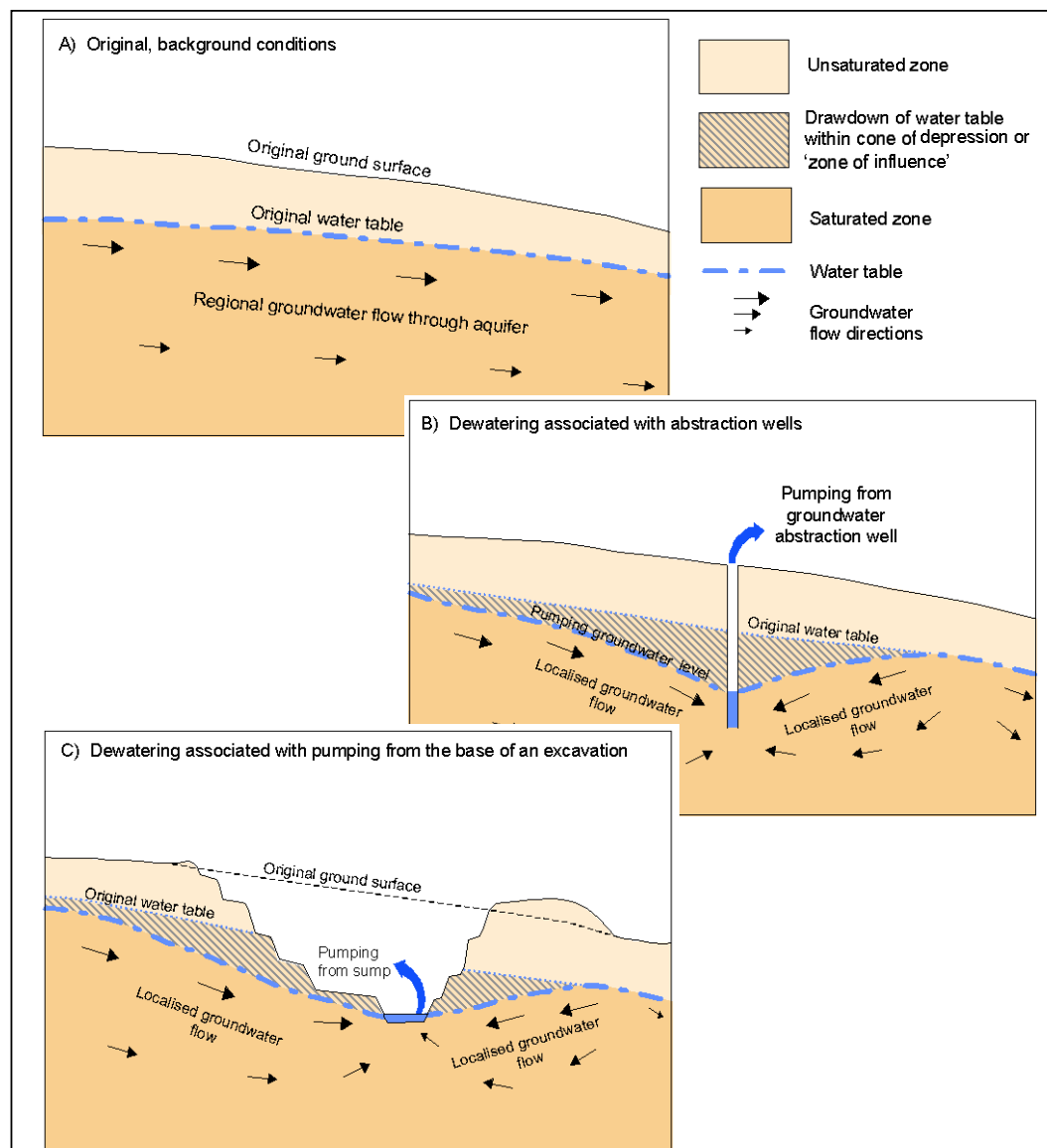


Figure 2.1: Schematic diagram illustrating the principles of dewatering in a simple, unconfined aquifer

- 2.1.3 Whichever method of dewatering is used, the effect is broadly the same, with groundwater levels being lowered and a cone of depression being imposed on the water table centred on the excavation (Figure 2.1). In reality, the majority of natural geological systems are not homogeneous and values of permeability will vary in different directions. In such cases, the extent of drawdown will show a corresponding variation, leading to the development of an irregular 'zone of dewatering influence' rather than a circular and symmetrical cone of depression.
- 2.1.4 The extent of the zone of dewatering influence on the surrounding groundwater levels is dependent upon a number of factors including:
- (i) The depth of dewatering in the excavation (i.e. the amount by which the water table has been lowered);
 - (ii) The permeability of the sediments (which determines the zone of dewatering influence);
 - (iii) The extent of the area of dewatering, particularly the size of a particular quarry or pit; and
 - (iv) The rate and distribution of rainfall and other forms of recharge (e.g. stream leakage) that ameliorate drawdown.
- 2.1.5 Approximate estimates of the radius of dewatering influence may be potentially made using Equation 1 (CIRIA Report 113, 1998). Estimates of permeability may be taken either from literature references (e.g. Domenico and Schwartz, 1997), or calculated from particle size distribution analysis (using the Hazen formula¹) of an aquifer sample.

Equation 1: $R_0 = Ch \sqrt{K}$

Where:

- R_0 = approximate radius of influence (m)
- C = factor (1500 for line flow to a trench or 2000 for line flow to a series of wellpoints)
- h = drawdown at excavation (m)
- K = permeability (m/s)

- 2.1.6 Details of the assumptions underlying Equation 1 were not found in any known publications, and therefore the equation should be used with caution.
- 2.1.7 For a known dewatering, or abstraction rate, it may be possible to calculate the steady state radius of influence for an abstraction well through re-arrangement of the Thiem equation (Kruseman & de Ridder, 1994, Equation 3.2) in the case of confined aquifers (**Equation 2**), or through re-arrangement of the Thiem Dupuit equation (Kruseman & de Ridder, 1994, Equation 5.7) in the case of unconfined aquifers (**Equation 3**).
- 2.1.8 Equation parameters are illustrated in Figures 2.2 and 2.3 respectively.

¹ $K = C(d_{10})^2$. Where K is hydraulic conductivity (cm/s), d_{10} is the effective grain size (cm) - otherwise defined as the sieve size (cm) at which 10% of a sample can pass, and C is a coefficient based upon the type of material (Fetter, 1994)

Equation 2: $\log(R_0) = \frac{2\pi KD(s_{mw})}{2.3Q} + \log(r_{mw})$

Where:

- R_0 = radius of influence (m)
- K = Hydraulic conductivity of the aquifer (m/d)
- D = Thickness of the aquifer (m)
- s_w = drawdown in sump or abstraction well (m)
- r_w = radius of sump or abstraction well (m)
- Q = abstraction well discharge (m^3/d)

Assumptions:

- The aquifer is confined;
- The aquifer has a seemingly infinite areal extent;
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping;
- Prior to pumping, the piezometric surface is horizontal (or nearly so) over the area that may be influenced by pumping;
- The aquifer is pumped at a constant discharge rate;
- The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow; and
- Flow to the well is in steady state.

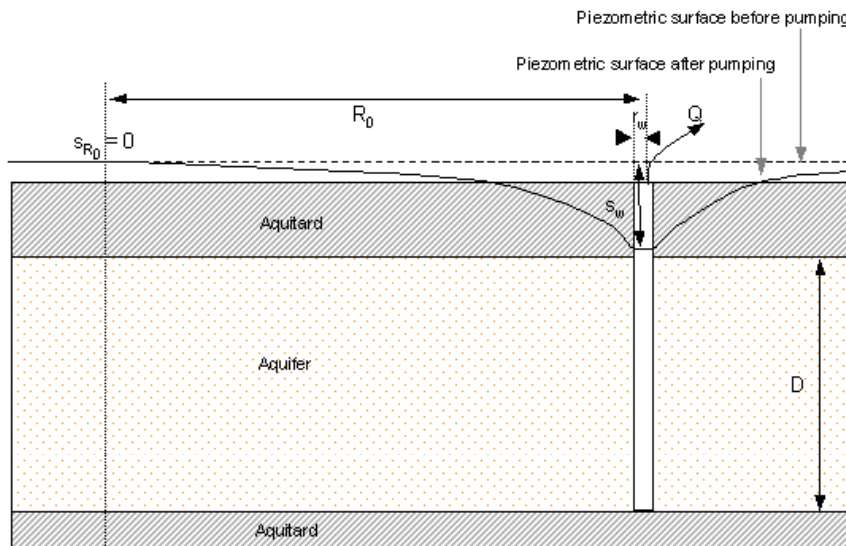


Figure 2.2: Schematic cross section diagram of a pumped confined aquifer in steady state conditions.

Equation 3: $\ln(R_0) = \frac{\pi K}{Q} (h_B^2 - (h_B - s_w)^2) + \ln(r_w)$

Where:

- R_0 = radius of influence (m)
- K = Hydraulic Conductivity of the aquifer (m/d)
- h_B = background (pre-dewatering) water table above datum (m)
- s_w = drawdown in sump or abstraction well (m)
- r_w = radius of sump or abstraction well (m)
- Q = abstraction well discharge (m^3/d)

Assumptions:

- The aquifer is unconfined;
- The aquifer has a seemingly infinite areal extent;
- The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by pumping;

- Prior to pumping, the water table is horizontal over the area that may be influenced by pumping;
- The aquifer is pumped at a constant discharge rate;
- The well penetrates the entire aquifer and thus receives water from the entire saturated thickness of the aquifer;
- Flow to the well is in steady state; and
- The Dupuit assumptions² are satisfied.

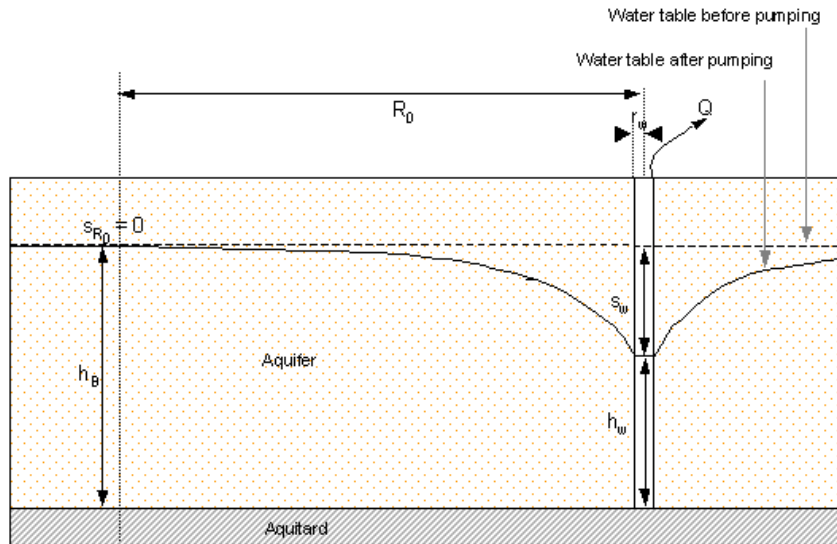


Figure 2.3: Schematic cross section diagram of a pumped unconfined aquifer in steady state conditions.

- 2.1.9 Theoretical predictions of the radius of dewatering influence may be calculated from the above equations, using either literature or field values of permeability. This may be useful, for example, in assessing the amount of drawdown required at a certain distance from the point of dewatering to enable dry working of the mineral throughout the excavation.
- 2.1.10 Numerical groundwater modelling for a site may be needed where more complex systems (involving, for example, spatially varying aquifer properties) make the use of analytical methods inappropriate.

2.2. Potential Effects of Dewatering

- 2.2.1 In some situations environmental impact assessment of dewatering may indicate that lowering the groundwater table will not adversely affect the surrounding area, and may in some situations bring benefits such as enhanced slope stability and reduced flood frequencies (Thompson et al, 1998).
- 2.2.2 More commonly, however, there are likely to be potential adverse effects which will need to be carefully assessed and monitored, and which may need to be mitigated during and/or after the lifetime of the dewatering operations. These effects include direct impacts on groundwater and surface water characteristics and indirect effects on other dependent receptors, such as abstraction wells and sensitive habitats (see below).

² The velocity of flow is proportional to the tangent of the hydraulic gradient instead of the sine. Flow is horizontal and uniform everywhere in a vertical section through the axis of the well.

- 2.2.3 Where such potential exists, the nature of the risk and the type of mitigation required will need to be assessed through the use of appropriate baseline monitoring, site investigation and prediction. The latter should relate not only to the potential effect but also to the likely efficacy of the mitigation measures proposed, and may include conceptual, analytical or numerical modelling – as appropriate to the significance of the risk in each case.

Reduction in volume of groundwater stored within the saturated zone

- 2.2.4 A direct implication of dewatering is that it can lead to the temporary loss of a valuable resource through a transient reduction in the volume of groundwater stored in that area of aquifer (NRA, 1992). Groundwater for public supply is almost fully committed in many areas, particularly in Southern England where the majority of sand and gravel workings may be found. Pumping large quantities from an aquifer over many years, to maintain low groundwater levels for mineral extraction, does not usually represent the best use of this natural resource.
- 2.2.5 Although some of the abstracted water may be returned to the ground, much of it is normally 'lost' (from the local groundwater system) either by discharging to surface water or through evaporation from settlement ponds. Such losses have been found to be most significant in shallow Quaternary gravel deposits, where the depth of dewatering represents a high proportion of the total thickness of the original saturated zone.
- 2.2.6 The majority of sand and gravel deposits are classified as Minor Aquifers under the Environment Agency's groundwater vulnerability scheme, which means that they may be important for local water supply and in supporting base flow to rivers and streams. With the implementation of the Water Framework Directive (see Chapter 6 for further information) and the move towards sustainable integrated management of the whole groundwater and surface water catchment, this issue may potentially become of increasing significance when considering the effects of dewatering.

Derogation of existing or planned groundwater abstraction wells

- 2.2.7 Apart from the temporary reduction in the volume of stored water, dewatering can sometimes cause derogation of individual abstraction wells, resulting in the need for these to be deepened or replaced. The effect may be temporary or permanent, depending upon the restoration plan for the site. Again, this is commonly a problem in highly permeable deposits (such as Quaternary gravels and karstic limestone aquifers) where the zone of dewatering influence can extend some considerable distance beyond the margins of the excavation.
- 2.2.8 In some cases, dewatering within one aquifer may affect water levels in an adjacent aquifer, where they are in hydraulic continuity. This is a particular risk where river gravel deposits cut across outcrops of Major Aquifers such as the Chalk (notably in the Thames Valley) and the Sherwood Sandstone (in parts of the Trent Valley). In these areas the gravels and underlying rocks are considered by the Environment Agency as a single Major Aquifer unit.

Impacts on surface water features / flora / fauna

- 2.2.9 Many surface water features (rivers, lakes, pools and wetlands) interact closely with, and may be permanently or seasonally dependent upon, groundwater. These features may be of national or international importance, such as Sites of Special Scientific Interest (SSSI) and candidate Special Areas of Conservation (cSAC). A lowering of the water table by dewatering may therefore have an indirect impact on these features and on the habitats and wildlife that they sustain.
- 2.2.10 Even small scale lowering of groundwater levels may potentially influence the viability of fragile ecosystems, such as wetlands, mires and wet heathland, where these occur in close proximity to a quarry. As well as the direct effects of reduced soil moisture, lowering of water levels and reduced inflow of surface water may cause a change to the chemistry of the habitat, leading to potential damage to environmentally sensitive flora and associated fauna.
- 2.2.11 It is most commonly in relation to the protection of such habitats that recharge features have, in fact, been used (or at least proposed).

Contamination from external sources, caused or exacerbated by changes in groundwater flow paths

- 2.2.12 One of the potential secondary effects of dewatering is that groundwater flow paths can be modified by groundwater being drawn towards the excavation within the zone of dewatering influence. This, in itself, does not necessarily lead to problems, but it can do so under certain circumstances. Whether problems are likely to occur is dependent upon where water is being drawn in from, what lies within its path, and the rates of flow induced.
- 2.2.13 Problems may occur when contamination from external sources is drawn towards the quarry, necessitating the treatment and disposal of large quantities of polluted groundwater. Sources of contamination may include landfill sites, old industrial sites, oil refineries, petrol stations, gas works and a variety of agricultural sources. The problems are compounded when sensitive receptors are located along the modified groundwater path, in between the source and the quarry.

Saline intrusion caused or exacerbated by changes in groundwater flow paths

- 2.2.14 Similar effects can arise where large scale pumping causes the ingress of saline groundwater, usually in coastal locations, but also in situations where saline water is present in aquifers adjacent to, or below the pumped aquifer.
- 2.2.15 Saline intrusion is the landward movement of the saline interface that exists where coastal aquifers discharge into the sea or tidal estuaries. This interface is the natural division between saline groundwater beneath the sea and the fresh groundwater on land. The interface has a natural equilibrium position defined, in part, by the rate of flow of fresh groundwater towards the coast. If this flow rate is reduced, for example by high rates of groundwater abstraction or quarry dewatering inland, the equilibrium position will change and there will be a landward movement of the saline interface.
- 2.2.16 Neither the lowering of groundwater levels to below sea level, nor a complete reversal of groundwater flow directions are therefore essential for saline intrusion to occur. Again the problems are compounded if sensitive receptors such as freshwater lakes, wetlands or groundwater supply sources are located between the quarry and the coast.

Subsidence and settlement caused by falling groundwater levels and induced flows

- 2.2.17 Subsidence and settlement, mainly affecting confined aquifers, may be potentially induced by the process of dewatering in a number of different ways:
- (i) Through the shrinkage of clay soils which are susceptible to changes in moisture content; and
 - (ii) Through the removal of hydraulic support of sediment particles.
- 2.2.18 Careful monitoring of settlement, combined with the use of mitigation measures (such as recharge features) to limit the groundwater drawdown in the vicinity of sensitive structures may be needed to avoid such problems.

Degradation of archaeological sites

- 2.2.19 The change from saturated to unsaturated conditions induced by dewatering may cause the oxidation, rotting and deterioration of previously waterlogged archaeological features and artefacts. Specialist advice on this risk would need to be sought, in each case, from appropriate experts.

2.3. Mitigation Measures

- 2.3.1 A wide range of measures may be employed to avoid, minimise or compensate for the various potential adverse effects outlined above. These may include:
- (i) Limiting the depth and / or surface extent of the excavation / dewatering so that the zone of dewatering influence does not affect sensitive features;
 - (ii) Dewatering in small cells, one at a time, so as to reduce the pumping rates required and the surface area of dewatering;
 - (iii) Use of 'closed circuit' dewatering schemes which involve recharging the abstracted water to ground within the site or close to the site rather than pumping off-site;
 - (iv) In the case of floodplain sites, recharging abstracted water back into the aquifer in order to reduce the impact on surface water flows;
 - (v) Recharging the dewatered water directly into surface watercourses, lakes or other features that could potentially be affected;
 - (vi) Installation of a low permeability cut-off barrier around all of the site, or between the excavation and sensitive features; and
 - (vii) Continuous monitoring of water levels in nearby abstraction wells and watercourse and provision of additional mitigation and compensation measures as required.
- 2.3.2 The choice of method(s) to be used at a given site will depend on a range of factors including the significance of the risk, the likely effectiveness of the various techniques in dealing with the problem, their suitability (for other reasons) for the location involved, and cost. The first and second of these, in particular, can only be properly assessed by gaining a good understanding of the local geological and hydrogeological conditions, preferably based on site investigations and sound baseline monitoring data.
- 2.3.3 Reality may often differ from theoretical predictions, however, and a flexible strategy that can react to the actual consequences observed once dewatering begins, will usually be the best solution.
- 2.3.4 Appendix A provides a series of documented case studies in which many of options listed above have been used, either singly or in combination. These are summarised in Table 2.1, below.
- 2.3.5 Case studies 1 to 3 are examples of where low permeability barriers have been shown to be an effective measure for reducing the extent of a zone of dewatering influence. In the case of the Efford Quarry / Landfill site, for example, recharge trenches have been used successfully in combination with low permeability barriers in order to manage the surface water input into nearby protected salt marshes.
- 2.3.6 Stanwick Quarry (Case Study no. 4) and Eversley Quarry (Case Study no. 7) are examples of where recharge features have been used or proposed as methods to mitigate the potential risk of settlement beneath a road viaduct or nearby housing, respectively. Case studies 5, 6, 8 and 9 outline different schemes where recharge features have been used or proposed for the purpose of minimising the impact of dewatering on habitats perceived to be sensitive to changes in groundwater levels

	Name, Location (Operator)	Protected Feature	Mitigation Method	Overview
1.	Efford Quarry & Landfill, Hamps. (Hamps County Council / Onyx)	Pennington & Keyhaven Saltmarshes (SSSI)	Low permeability barrier & recharge trench.	Successful example of the use of a low permeability barrier (installed to prevent contaminant migration) which mitigated the lateral extent of zone of dewatering influence, and use of a recharge trench to carefully manage water regime of delicate saltmarshes.
2.	Condover Quarry, Shrops. (Hanson Aggregates)	Bomere Pool (SSSI)	Proposed recharge trench	Quaternary clay lens acted as a natural low permeability barrier, thus negating need for recharge trench.
3.	Colne Fen Quarry, Earith, Cambs. (Hanson Aggregates)	Private fishery lakes	Clay cut off trench	Hydrogeological studies suggested that a recharge feature sufficient to mitigate dewatering impacts would be impractical, thus a clay cut off trench was proposed.
4.	Stanwick Quarry, Nothants. (Hanson Aggregates)	A6 Viaduct	Recharge trenches	Example of mitigating dewatering effects in order to prevent settlement of man made structure.
5.	Stonecastle Farm Quarry, Kent. (Lafarge Aggregates)	Hartlake public water supply wells	Proposed recharge trenches	Steady state groundwater modeling was undertaken in order to predict potential impacts of quarry dewatering, and to ascertain the most appropriate mitigation method.
6.	Ellingham Hall, Norfolk. (RMC Aggregates)	Wild fowl farm ponds	Recharge lagoon	Use of a recharge lagoon system in order to manage site discharge within consented limits, which also helped mitigation of quarry dewatering.
7.	Eversley Quarry, Berkshire. (RMC Aggregates)	Private housing and water supply.	Recharge trench and well point injection system	Low pH, and high iron content, groundwater led to rapid clogging of recharge trench with iron oxide during it's trial. An alternative injection system is proposed & will be trialed.
8.	Norton Disney, Notts. (RMC Aggregates)	Ancient woodland & wetland	Buried French drain	Example of an alternative form of recharge feature which had to be buried for health and safety reasons.
9.	Tattershall Thorper, Lincs. (RMC Aggregates)	Myers Plantation SSSI	Recharge trench and clay bund	Combined mitigation measure which was successful in maintaining water levels within the SSSI.

Table 2.1: Case Studies

3. RECHARGE FEATURES: AN OVERVIEW

3.1. Introduction

- 3.1.1 When considering the most appropriate mitigation approach to deal with quarry dewatering impacts, it is necessary to first consider the requirements of the feature needing protection (whether ecological, man-made, or a groundwater resource). It is important to recognise the fact that the water environment, and associated ecosystems, are dynamic and will change naturally, both seasonally and in the longer term (Wardrop et al, 2001). As such, any mitigation scheme should aim to minimise changes to the dynamics of the system (or should try to mimic these natural variations).
- 3.1.2 In the case of an ecological habitat it will be important to understand how the ecosystem depends on or interacts with the local groundwater regime. For example, the habitat may be reliant on maximum (or minimum) absolute groundwater levels, or it may be dependent upon the range of groundwater levels over time, or on the rate of release of water from the seepage zone. In this respect it should be noted that artificial recharge schemes have the potential to infiltrate large amounts of water, increasing groundwater levels above the natural variation for extended periods. This could be just as detrimental to an ecosystem as prolonged lowering of water levels (English Nature, 1994).
- 3.1.3 In addition, it will be important to establish the degree of tolerance that the ecosystem may have to changes in these factors, since it may be possible for the habitat or species concerned to withstand an increase or decrease in groundwater levels for a limited period without there being a significant permanent impact.
- 3.1.4 The same basic principles (of understanding how the system works) apply in the case of man-made features, where lowering of groundwater levels may lead to settlement or subsidence as a result of clay shrinkage or removal of hydraulic support, mainly in the case of confined aquifers. It may be important to ascertain how much settlement below a structure may be considered to be tolerable in the short and long term. In addition, consideration should be given to the way in which re-wetting of the clays or mineral deposits could lead to uneven settlement.
- 3.1.5 With respect to impacts on public and private groundwater supplies, the demands placed upon the local groundwater resource should be borne in mind when considering plans for the dewatering of an excavation and the transfer of abstracted water. In this regard, the use of recharge features has the advantage of minimising the net removal of water from the local aquifer. This may be especially important in catchments that have high abstraction demands placed upon them.

3.2. Principles of Recharge Features

- 3.2.1 The underlying principle of all hydrogeology is that groundwater will flow from areas of high groundwater levels (or 'head') to areas of low groundwater head (i.e. it will flow down the hydraulic gradient). The volume of water flowing through an aquifer (or 'groundwater discharge') may be calculated through the use of Darcy's Law (**Equation 4**):

Equation 4: $Q = KiA$

Where: Q = discharge (m^3/day)
 K = hydraulic conductivity (m/day)
 i = hydraulic gradient (dimensionless)
 A = saturated cross sectional area of flow (m^2)

- 3.2.2 The *specific discharge rate* (' q ', m/day) may be calculated by dividing Q by the saturated cross sectional area perpendicular to the flow direction (A). Groundwater velocity may be calculated by dividing specific discharge by porosity (the Darcy velocity).

- 3.2.3 Where quarry dewatering has led (or could potentially lead) to the development of a zone of dewatering influence in the surrounding water table, and a subsequent lowering of groundwater levels at distance from the excavation, recharge features aim to infiltrate some of the abstracted water back into the ground between the quarry and any sensitive receptor(s) in order to restore (or maintain) groundwater levels, hydraulic gradients and groundwater flows in those areas.
- 3.2.4 In effect, a 'recharge mound' is created beneath the recharge feature. When this is superimposed on the expected drawdown profile within the zone of dewatering influence, it steepens the head gradient between the recharge feature and the excavation whilst reducing, or even reversing the gradient on the side away from the excavation. This effectively 'shields' the area beyond the recharge feature from the influence of the dewatering operation and allows groundwater levels in those areas to recover. In the short term, the recovery results directly from the flow of groundwater out from the recharge feature, but in the longer term this effect is supplemented by 'natural' recharge from other sources (i.e. rainfall and groundwater from adjoining parts of the aquifer).
- 3.2.5 Artificial recharge may be achieved in a variety of surface or sub-surface methods, including:
- (i) Injection wells (direct to groundwater);
 - (ii) Buried drains or gravel filled trenches (recharge via the unsaturated zone); or
 - (iii) Indirect recharge through natural surface water features, lagoons or ditches.
- 3.2.6 A detailed literature review, updating that undertaken by Symonds for the DETR Guide to Good Practice (Thompson et al, 1998), identified very few papers or references which contained useful information on the implementation of recharge features as a mitigation measure for quarry dewatering. It did, however, reveal some useful information regarding other types of artificial recharge, mainly in relation to aquifer storage recovery (ASR) and infiltration drainage systems. Many of the issues raised in these examples were found to be applicable to quarry recharge features.

3.3. Injection Wells

Principles

- 3.3.1 The use of injection wells (or recharge wells) as part of ASR schemes is well documented both in the UK and the United States, and the principles involved and lessons learned are relevant here.
- 3.3.2 Such wells have the advantage of injecting water directly back to groundwater (Figure 3.1 below) and thereby avoid some of the problems of chemical precipitation that can sometimes occur with other methods (see below). These benefits come at a price, however, since the construction, installation and running costs are likely to be significantly greater than for a simpler recharge trench.

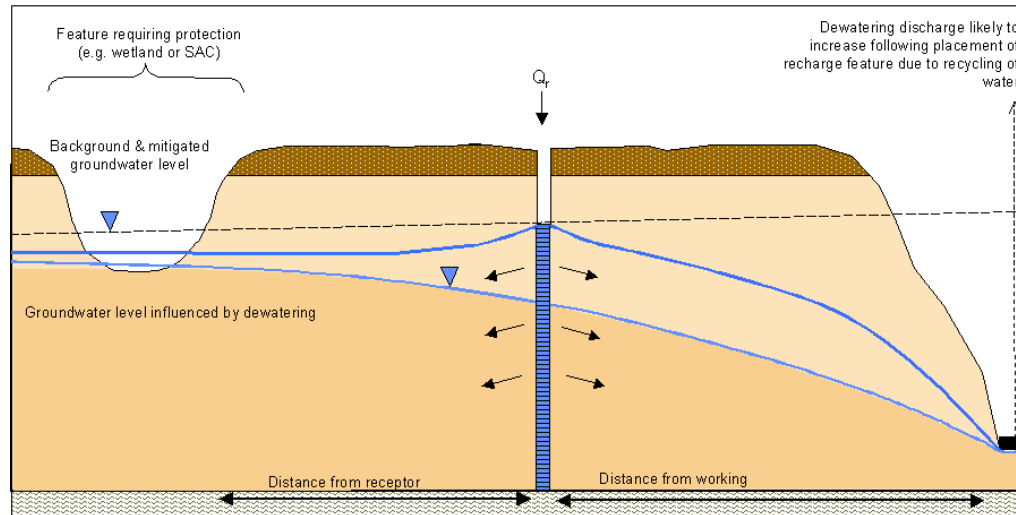


Figure 3.1: Recharge injection well

Case Studies

- 3.3.3 No examples of the use of recharge wells as a mitigation measure for quarry dewatering were found within published literature. The use of such measures is, however, currently being considered at RMC's Eversley quarry (see Appendix A).

Potential Issues and Design Considerations for Injection Wells

- 3.3.4 Well design considerations are much the same as for abstraction wells (such as screening appropriate sections of the aquifer), guidance on which may be found in '*Groundwater and Wells*' (Driscoll, 1986). However injection wells are considered more likely to fail as a result of:
- (i) Water chemistry;
 - (ii) Air entrainment;
 - (iii) Thermal interference; and
 - (iv) Suspended solids.
- 3.3.5 It has been observed that pumping recharge water with suspended solids at concentrations as low as 1 mg/l can clog injection wells within a short period of time. For example, a 6 inch test well in California, pumping at 174 m³/day and injecting water with 3.3 mg/l suspended solids, showed a 30% increase in the injection water level within 9 days (Driscoll, 1986). A successful recharge well in Nebraska was continuously injected at 4,090 m³/day for 6 months. During this period, the additional head build up was 1.8 m, even though the recharge water contained only 0.004 mg/l of sediment. It was considered that air entrainment or water quality changes may have contributed to this decrease in entry permeability (Driscoll, 1986).
- 3.3.6 Clogging of screens is considered to be the most serious problem in injection well operation, hence screen properties (including open area and length) should be optimised. Driscoll (1986) advises that the average entrance velocity for injection wells should be 0.015 m/sec, with screens being twice as long as for an abstraction well pumping the same volume of water.
- 3.3.7 Driscoll (1986) further advises that the end of the injection tubing should terminate below the static water level in an unscreened section of the well, and should be so designed that positive pressure exists along its entire length. Careful control of the positive injection pressure will need to be considered in unconsolidated sediments (Driscoll, 1986).

- 3.3.8 Calculation of the recharge rate required for an injection well penetrating an unconfined aquifer (one which is not overlain by an aquitard) is given by the following equation (Driscoll, 1986). Figure 3.2 illustrates the different parameters:

Equation 5:

$$Q_r = \frac{K (h_w^2 - H_0^2)}{0.733 \log (r_0/r_w)}$$

Where:

- Q_r = rate of injection (m^3/day)
- K = hydraulic conductivity (m/day)
- h_w = head (within the injection well) above the bottom of the aquifer while recharging (m)
- H_0 = pre-recharging head above the bottom of the aquifer taking place (m)
- r_0 = radius of recharge influence (m)
- r_w = radius of injection well (m)

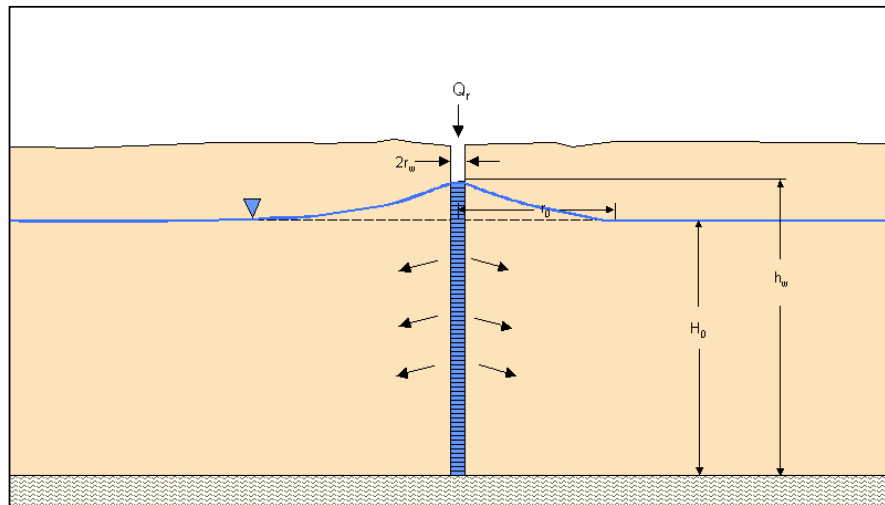


Figure 3.2: Radial flow from an injection well

- 3.3.9 Theoretically, a properly designed recharge well will have a recharge rate similar to its pumping capacity, but problems associated with generating a sufficient head differential, water quality and turbidity may be found to reduce the recharge rate over relatively short periods of time.
- 3.3.10 In an ordinary abstraction well, for example, some fine sediment will be removed continually from the formation, whereas in an injection well these fines are not removed. In fact the fine material contained in the injection water may continuously collect in the filter pack, outside the screen, or in the formation. Over time the formation may slowly become clogged, reducing the capacity of the aquifer to receive water. Because this phenomenon is inevitable, most injection well designers specify that the screen length be much longer than for a water supply well of equal capacity, to reduce the requirement for maintenance (Driscoll, 1986).
- 3.3.11 Clogging of the formation around the screen can be caused not only by sediment, but also by air bubbles entrained in the injected water. When air is entrained within injection water, a potentially significant loss of hydraulic conductivity may be possible, because air bubbles can effectively block the outward passage of water by plugging pore spaces within the aquifer.

- 3.3.12 Clogging by chemical precipitation is another common problem of injection wells. Precipitates can be formed by mixing waters of different quality (including differing oxygen content, temperatures or pH) leading to encrustation on the screen. Untreated injection water that has a high mineral content can be expected to create encrustation problems. Similarly, injecting an oxidised solution into an in-situ reducing environment can cause oxidation of iron and manganese hydroxides on entry into groundwater. Further discussion of chemical processes is given below.
- 3.3.13 Clogging by bacterial action may occasionally occur in recharge wells. Bacterial growth can be promoted by the change in temperature caused by injection, especially when warmer water is added to a cool aquifer.
- 3.3.14 Operation and maintenance procedures should aim to minimise the potential impact of some of the issues highlighted above. To minimise clogging of the screen by sediment, consideration should be given to passing pumped water through a settlement lagoon first, and pumping the injection well on a regular basis (re-developing the well) to remove any silt build up.
- 3.3.15 In addition, consideration may be given to passing recharge water through a de-aeration system prior to injection in order to remove air bubbles and oxygen.
- 3.3.16 Alternatively oxides may be removed from solution prior to injection. For example, in the case of Eversley Quarry the natural groundwater was found to have a very low pH (2.5) and high levels of iron (such that on exposure to the atmosphere in a recharge trench oxidation to iron oxide led to rapid clogging of the trial recharge trench). As an alternative, an injection well system has been proposed whereby recharge water will be taken from an artificial storage lake fed by water derived from surface run-off from the hills to the north of Eversley Quarry in order to dilute the background acidity of both surface water and groundwater to a pH of around 6 from which iron will precipitate out of solution and settle out in the storage lake.
- 3.3.17 Alternative methods to encourage the precipitation of iron oxides may include passing low pH, high iron waters over chalk gravel. Precipitation is likely to be rapid, although the effectiveness of the chalk gravel will diminish with time and will need to be regularly replaced.
- 3.3.18 Either way, the chemistry of the injection water will be such as to minimise the risk of iron oxide accumulation within the jetting wells, and iron oxide precipitate deposits will be retained in the settlement lagoon rather than being injected leading to potential clogging. Trials of the injection system are due to take place during 2004.

3.4. Recharge Trenches and Lagoons

- 3.4.1 In terms of drainage design, soakaways, filter drains and infiltration trenches are often used within the engineering industry to assist in the percolation of surface run off to the ground. Some CIRIA publications (for example CIRIA Report 156) are of particular relevance with respect to recharge trenches which may be considered as a type of soakaway.

Principles

- 3.4.2 The principle of recharging through the infiltration of water into the ground, through the unsaturated zone (vadose zone) to the underlying water table remains the same irrespective of whether a recharge trench is open or filled with gravel.
- 3.4.3 In order for water to move vertically downward, soil moisture content in the underlying soils must reach field capacity. This represents the maximum volume of water which can be stored in soil against gravity. Once the moisture content of the soil exceeds field capacity, water will percolate to the underlying water table.

- 3.4.4 As in the saturated zone, flow in the unsaturated zone is driven by the hydraulic head gradient. Calculations of fluxes may be approximated using Darcy's Law (**Equation 4**, p11), however the presence of air within the unsaturated zone (which makes it harder for water to flow) means that values of hydraulic conductivity vary with moisture content, decreasing as moisture content decreases. The lower the moisture content, the greater the proportion of air and the greater the surface tension (negative pressure), and hence the lower the effective hydraulic conductivity (Domenico and Schwartz, 1997).
- 3.4.5 Where there is a constant source of surface water infiltrating the ground, as in the case of recharge trenches, the movement of water through the unsaturated zone can be described as a plug with the saturated front moving vertically down under gravity until such time as it reaches the capillary fringe immediately above the water table (Fetter 1994). Once the recharge front reaches the water table, a recharge mound beneath the trench has effectively been formed and the vadose zone below the trench is effectively saturated.
- 3.4.6 The reduced hydraulic conductivity within the vadose zone means that the movement of water through this zone is slower than if the zone were fully saturated. Therefore the development of a recharge mound fully connected to the base of the recharge trench may take time, dependent upon background soil moisture content, hydraulic conductivity and the thickness of the unsaturated zone.
- 3.4.7 The level to which a recharge mound will rise, as illustrated in Figure 3.3 is considered to be dependent upon the permeability of the bed deposits, the elevation of the base of the trench, the head level maintained in the feature, and the distance from the point of dewatering. Further consideration of these factors was undertaken during the two experiments, which are discussed further in Chapters 4 and 5.

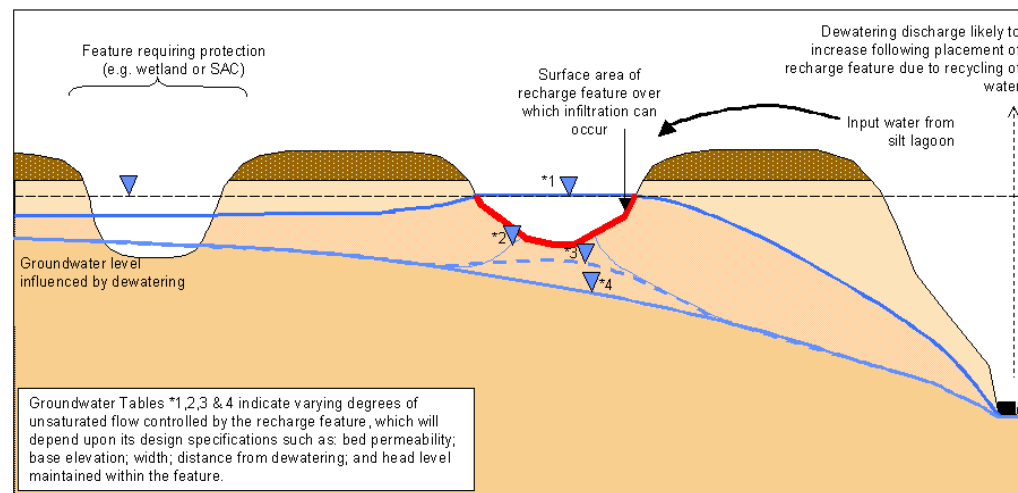


Figure 3.3: Principles of recharging to groundwater via a recharge trench

Case Studies

- 3.4.8 As noted earlier, very few case study examples of the use of recharge trenches are available in published literature. The review by Cliff & Smart (1996) is one recent exception, although this dealt only with shallow water table sites (the authors being unaware of any deep water table sites where recharge trenches have been used).
- 3.4.9 Some of the new case studies (see Table 2.1, above and Appendix A) relate to the use of recharge trenches, either in isolation or in combination with other measures such as clay bunds.

Potential Issues and Design Considerations for Recharge Trenches

- 3.4.10 A number of potential issues (in terms of both quantities of water which may be potentially recharged and infiltration capacity of such features) and design considerations are raised within published literature, and outlined below. Further exploration of some of the key points raised were undertaken within the experimental sites (Chapters 4 and 5, below).
- 3.4.11 Not all of the water which is discharged to a recharge trench may find its way to the water table. In addition to water retained in unsaturated storage, a certain proportion may be lost as interflow within the vadose zone (the zone above the water table) to contribute to overland flow. Other water may be lost as overland flow directly, or as evaporation.
- 3.4.12 As well as flowing towards the feature to be protected, water from the recharge mound created beneath the trench will also be drawn back in towards the excavation (Figure 3.3). As a result, the rate of pumping needed to maintain the required drawdown within the excavation is likely to increase due to the re-circulation of water. The effect will be most noticeable when the recharge trench is located very close to the excavation.
- 3.4.13 A review of the limited literature available indicates a varied approach to recharge trench design. Recharge features may be constructed as open water bodies, or filled with gravel or stone (with or without a distributor pipe). Guidance on trench design is scarce. The main guidance identified relates to soakaway design (BRE Digest 365), with design considerations driven by the storage volume required to deal with site drainage rather than the amount of percolation required to maintain groundwater levels.
- 3.4.14 In the case of surface recharge features, the permeability of soils and sub-layers, the area of recharge, the head gradient, and the length of time water is in contact with the soil are all considered to be important.
- 3.4.15 English Nature (1994) recommends that trench side slopes should be between a gradient of 1:1.5 and 1:2. Additionally, in order to make temporary slopes safe, consideration of the angle of the slope and geotechnical stability when saturated should be made. Guidance on safe temporary slope angles is given in CIRIA Report 113.
- 3.4.16 In addition English Nature (1994) recommends that a 150 mm to 200 mm thick layer of coarse well sorted material be placed in the base of the trench. This advice is based on lagoon recharge experiments undertaken by Southern Water at Church Farm, Hardham, Sussex during the 1970's, which indicated that the presence of such a layer led to increased infiltration capacities and aided maintenance when required.
- 3.4.17 However, percolation is not necessarily always through the base of a recharge trench. For example at a Lafarge sand and gravel quarry, overlying the Lias Clay and lying 30 m from the Wollaston Meadows SSSI near Northampton, infiltration was predominantly through the sides of the trench (Cliff and Smart, 1998). At the site practical difficulties were encountered when it was observed that the rate of infiltration was lower than the pumping rate to the trench. This was resolved through construction of a high level overflow. An alternative approach may have been to pump less water to the recharge trench.
- 3.4.18 Trenches do not necessarily need to extend to the saturated zone since continued operation leads to the formation of a groundwater mound (Figure 3.3), however the reference does make comment that if they do extend to the saturated zone it may hinder long term maintenance (English Nature, 1994).
- 3.4.19 Traditional infiltration design for drainage tends to take the form of soakaways or gravel filled trenches. In a review of published work on the performance of commonly used drainage infiltration features, Pratt (2001) observed that in soils of poorer infiltration capacity the majority of water discharged to the feature was lost to either evaporation or plant transpiration rather than groundwater recharge.

- 3.4.20 Without intervention, the infiltration capacity of the recharge trench itself may potentially decrease with time as a result of a number of factors:
- (i) Sedimentation;
 - (ii) Vegetation overgrowth;
 - (iii) Microbial growth; and
 - (iv) Chemical incompatibility between recharging water and receiving groundwater.

Sedimentation and Microbial Growth

- 3.4.21 Wu and Hang (2000), quoting from work undertaken by Schalchi (1995), stated that factors governing siltation of a river bed include:
- (i) Grain sizes of sediment and gravel;
 - (ii) Sediment concentration; and
 - (iii) Seepage flow velocity.
- 3.4.22 Although potential deterioration of the infiltration capacity of soakaways over time is highlighted by relevant BRE and CIRIA design guides (BRE 365, CIRIA Report 156), Pratt (2001) observes that few instances of such deterioration have been reported in either the academic or technical press.
- 3.4.23 Extensive use has been made of U-shaped collecting channels and silt traps (Pratt, 2001) and wet sumps or T piece inlets (BRE digest 365) in order to filter out as much sediment as possible before the waters reach the infiltration feature.
- 3.4.24 Wu and Huang's (2000) experiments showed that the quantity of sediment infiltrating the gravel matrix increases with the seepage flow rate, due to the stronger seepage forces. However it was also observed that with time the seepage flow strengthens the bridging between the sand particles and hence leads to an increase in the quantity of captured sediment.
- 3.4.25 During the early 1990s, six recharge trenches, filled with gravel in a laboratory simulated sand aquifer at the Rocky Mountain Arsenal in the United States, were used to look at the reduction in infiltration capacity which may be associated with clogging due to sedimentation and microbial growth (Warner et al, 1994).
- 3.4.26 It was observed that the formation of a bacterial mat at the inlet boundary of the sand column reduced the saturated hydraulic conductivity by four orders of magnitude. Plugging may be expected to occur primarily close to the inlet pipe where microorganisms are supplied with fresh nutrients. This encourages biofilm development and in turn traps sediment.
- 3.4.27 Recharge rates were observed to be reduced after 100 days as a result of sediment and microbial fouling of the gravel trench when water containing sediment and bacteria was injected. However it was noted that such a reduction was not observed where water containing sediment only was injected.
- 3.4.28 In all experiments, biofouling and sedimentation were observed to be restricted to the gravel filled trench, with no effect on the surrounding sand aquifer. It was also observed that the presence or absence of geotextile wrap had no influence on lessening the reduction in the recharge capacity of the trench over time.

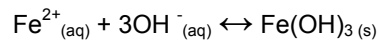
Chemical Compatibility

3.4.29 In addition to microbially mediated reactions, the main geochemical reactions which may occur when recharge waters are introduced into groundwater include:

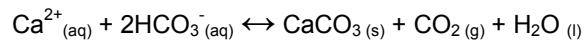
- (i) Adsorption / desorption;
- (ii) Ion exchange;
- (iii) Oxidation / reduction; and
- (iv) Dissolution / precipitation.

3.4.30 Adsorption, oxidation / reduction and precipitation, in particular, have the potential to lead to clogging of pores within the aquifer. Major chemical changes may be expected where there is a large difference between the chemical quality of injected water and in situ water, and where the natural groundwater system does not possess a sufficient pH buffering capacity (BGS, 2002).

3.4.31 In some areas of the country sand and gravel groundwaters may have high concentrations of iron or manganese in solution, such as in the case of Eversley Quarry. When oxygenated water is injected into the aquifer's reducing environment, precipitation of iron and manganese oxides and hydroxides may lead to plugging of aquifer pores and reduction in infiltration capacity.



3.4.32 In addition, the mixing of carbonate or bicarbonate rich waters may lead to disturbance of the carbonate system (which is a pH controlled equilibrium) (see below), leading potentially to precipitation of calcite and to clogging of the aquifer pores.



3.4.33 Significant temperature differences between the injected water and receiving water, which could be as much as 10 °C, may result in increased chemical rates of reaction which in turn may potentially lead to precipitation of minerals from the injected water and hence decrease in permeability.

3.5. Summary

3.5.1 The review of published literature and industry case studies has revealed situations where recharge features have been considered to be successful in mitigating impacts of quarry dewatering, and also indicated instances where their use has posed problems.

3.5.2 However the lack of published quantitative information regarding recharge features and their optimal operation means that firm conclusions / recommendations cannot be made based upon existing information. In order to address this, it was decided to run two contrasting experiments:

- (i) Chamberhouse Farm, Newbury, Berkshire (Tarmac Southern); and
- (ii) Methley Quarry, Mickletown, Yorkshire (Lafarge Aggregates).

3.5.3 A brief overview of each experiment and its findings is given in Chapters 4 and 5, below. Separate reports for each experiment have been prepared and are available from Symonds Group.

4. EXPERIMENT 1: CHAMBERHOUSE FARM

4.1. Aims and Objectives

- 4.1.1 The aim of the Chamberhouse Farm experiment was to create a temporary zone of dewatering influence, and then to discharge abstracted water to nearby recharge trenches in order to monitor how water levels responded.
- 4.1.2 The experiment was undertaken in order to explore some the practical factors that may contribute to the effectiveness of a recharge trench, especially with respect to the maintenance or reversal of lowering of groundwater levels below a nearby sensitive feature. The factors considered included the:
- (i) Optimal depth of the recharge feature in comparison to aquifer depth;
 - (ii) Distance of the recharge feature from the dewatered excavation;
 - (iii) Optimum width / dimensions of the feature; and
 - (iv) Distance from the base of the trench to lowered groundwater table.

4.2. Background

- 4.2.1 Chamberhouse Farm, proposed by Tarmac Southern, is a greenfield site located approximately 5 km east of Newbury, Berkshire at national grid reference 451600 165900.
- 4.2.2 The site is situated within the 1 in 5 year modelled floodplain of the River Kennet and within an area of ecological importance. The Thatcham Reedbeds, constituting a Site of Special Scientific Interest (SSSI) and candidate Special Area of Conservation (cSAC) site, are located approximately 270 m north of the experimental area.
- 4.2.3 Abutting the Chamberhouse Farm site, and located approximately 85 m north of the experimental area, lie the Bowdown and Chamberhouse Woods SSSI. In addition, the River Kennet, located approximately 285 m south is also classified as a SSSI.
- 4.2.4 Within the experimental area the River Terrace and Valley sand and gravel mineral deposit were overlain by overburden of 0.9 m and 1.8 m thickness. This comprised topsoil, alluvium (described as a light grey brown silty clays, with occasional fine sand and gravel) and occasional peat.
- 4.2.5 The sand and gravel deposits were observed to be poorly sorted grey flint gravel with 10% - 20% white to light grey coarse grained clean sand, with little silt evident. Thicknesses of 2.8 m to 5.1 m were recorded in the vicinity of the experimental area. Underlying the sands and gravels, drilling within the experimental area revealed a blue grey stiff to firm silty clay, interpreted to be the London Clay.
- 4.2.6 Principal surface drainage is afforded by the River Kennet, flowing from west to east along the southern boundary of the Chamberhouse Farm site. Priors Moor Ditch (Figure 4.1), which generally flows from west to east through the centre of the Chamberhouse Farm site, is entirely man-made being constructed for the purposes of land drainage and has significant local influence on groundwater levels.
- 4.2.7 Running along the southern boundary of the western end of the Chamberhouse Farm site, within 50 m of the experimental area, lies Widemead Ditch. The ditch appears to be entirely man made and does not appear to have an influence on local groundwater levels. Local land drainage ditches are located on the south eastern and south western boundaries of the experimental area.

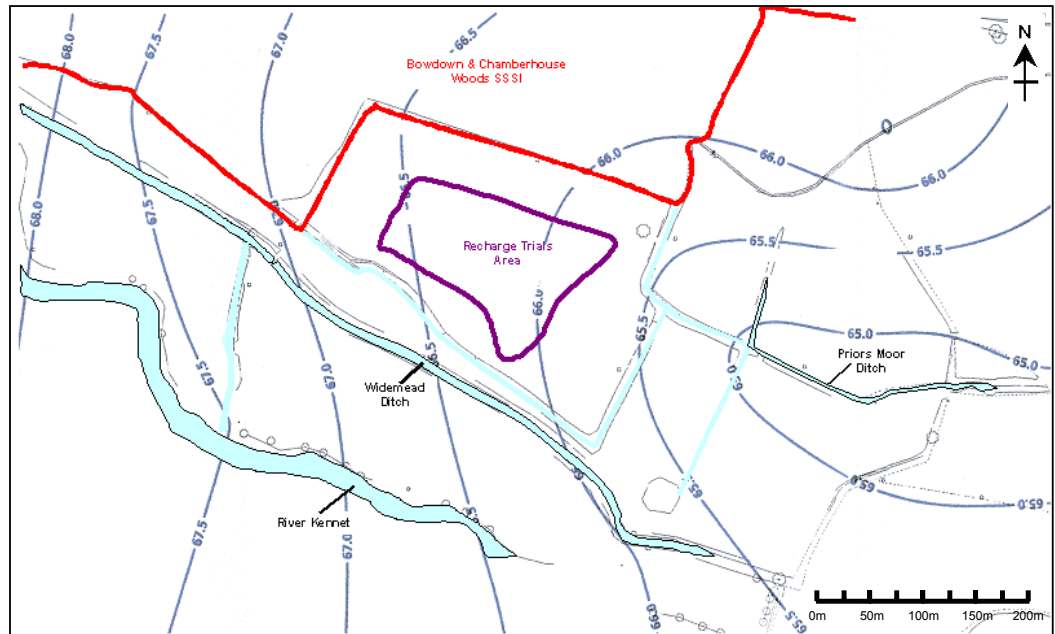


Figure 4.1: Chamberhouse Farm modelled background groundwater levels (Tarmac Quarry Products, 1998)

- 4.2.8 Historic groundwater levels within the experimental area range from 66.78 m AOD to 65.87 m AOD (approximately 0.63 m to 1.54 m below ground level). Within the installed monitoring wells, water levels were observed to generally coincide with the boundary of the overburden and the sand and gravel. Background groundwater levels recorded were found to be approximately 1.1 m below ground level (bgl), varying from 66.37 m AOD to 65.96 m AOD across the site.
- 4.2.9 Groundwater levels recorded within the Bowdown and Chamberhouse Woods SSSI between 1990 and 1993 varied from 65.57 m AOD (recorded in Dec 1990) to 66.92 m AOD (recorded in Jan 1993) with an average of 66.6 m AOD.
- 4.2.10 Generally groundwater flow across the Chamberhouse Farm site is from west to east, however the influence of the Priors Moor Ditch manifests in north easterly and south easterly components of groundwater flow locally.

4.3. Methodology

- 4.3.1 The overall purpose of the experiment was to generate a zone of dewatering influence in groundwater levels below the experimental area of Chamberhouse Farm. At the point where one metre of drawdown could be predicted it was proposed to install two recharge trenches (on opposite sides of the zone of dewatering influence and of differing dimensions) and discharge the abstracted water to each of them (in roughly equal volumes) for an extended period, whilst continually monitoring to observe changes which might be attributable to recharging.
- 4.3.2 Originally, it was proposed to run the experiment for a six month period in order to ascertain some of the potential maintenance issues which may influence recharge trench efficiency in the long term. However, licensing and planning consent requirements to undertake such work (see Chapter 6) meant that it was not possible to undertake the experiment for six months within the one year duration of the research project.
- 4.3.3 In order to meet the concerns of West Berkshire Council, English Nature and the Environment Agency, within the time scale of the research project, it was decided to limit the duration of the experiment to one month, and to pump groundwater from an 8" abstraction well instead the originally proposed excavation, in order to generate a similar zone of dewatering influence.

- 4.3.4 Groundwater was abstracted at 35 l/s and discharged in equal amounts to two recharge trenches (one located to the north of the excavation, and one located to the south of the excavation, Figure 4.2).
- 4.3.5 Trench 1 (north of the abstraction well) was designed to be approximately 10 m long, 1 m wide and 1 m deep (a maximum internal surface area of 32 m²), such that its base would be placed in the top of the sand and gravel deposits and the thickness of unsaturated zone below the trench would be approximately 1 m when groundwater levels were depressed during pumping.
- 4.3.6 With a thinner unsaturated zone of 0.5 m, Trench 2 (south of the abstraction well) was designed to be approximately 1.5 m deep, by 5 m long and 2 m wide (maintaining the same basal area as Trench 1, with a maximum internal surface area of 31 m²).
- 4.3.7 In order to ascertain the influence of siltation upon recharge efficiency, abstracted water was discharged directly to each trench without passing through a settlement lagoon system first. Any excess abstracted water that could not be accommodated within either of the recharge trenches was discharged, via overflow ditches (lined with polyethylene sheeting to prevent recharge), to nearby ditches (Figure 4.2).

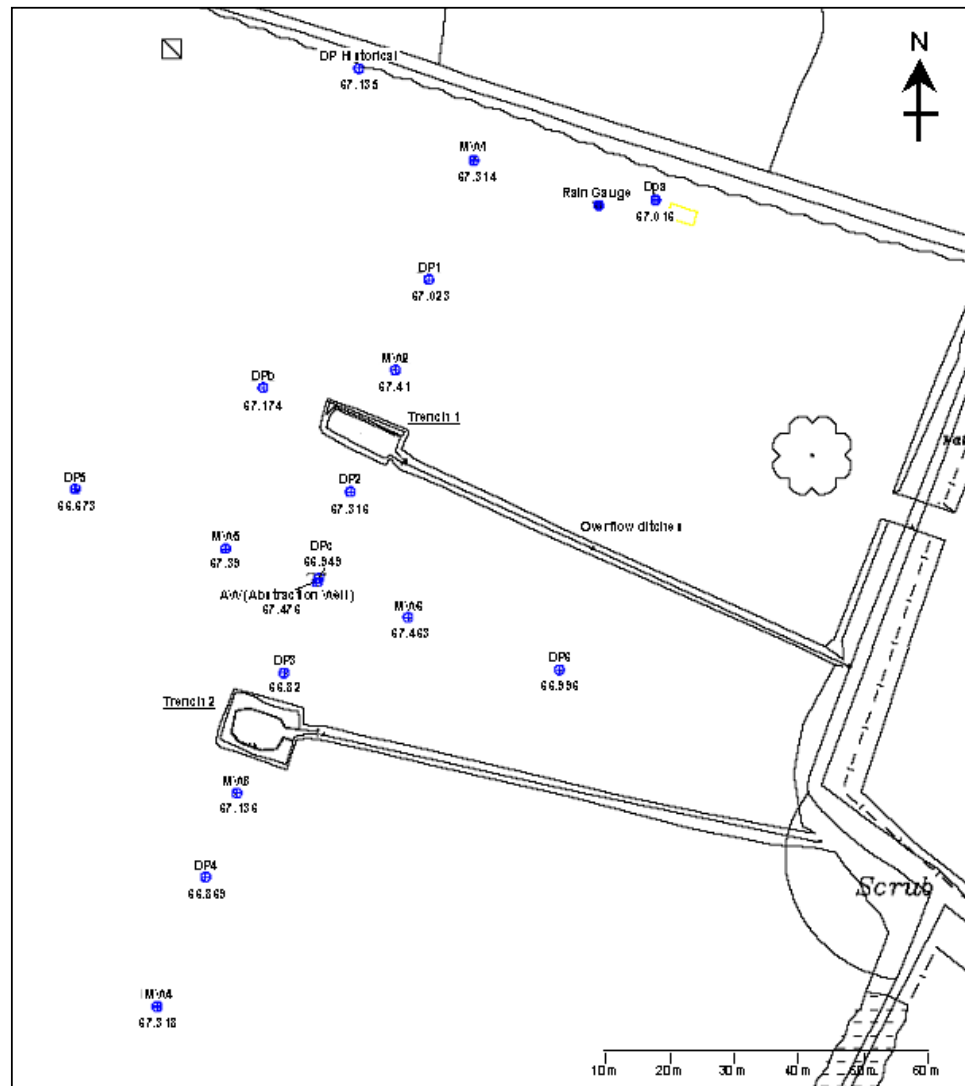


Figure 4.2: Chamberhouse Farm experimental layout

4.4. The Experiment

- 4.4.1 Figure 4.2 shows the overall layout of the experiment, with 50 mm monitoring wells with slotted screen over the sand and gravel aquifer (and fitted with continuous data loggers) and 19 mm drive in piezometers (which were manually dipped). Monitoring wells are labelled 'MW', and drive in piezometers 'DP' respectively.
- 4.4.2 Figure 4.3 shows the overall results of the groundwater level and rainfall monitoring for the duration of the experiment. It may be noted that significant rainfall events occurred on 22 November, 26 November, 1 December and 11 – 13 December which had a direct flashy impact on groundwater levels within a short period of time.
- 4.4.3 Following an initial phase of background monitoring and pump testing (to gather further information on the hydraulic properties of the aquifer), water levels within the abstraction well had been drawn down by approximately 3 m, with depressed groundwater levels below the bases Trench 1 and 2 at 0.75 m and 0.25 m respectively.
- 4.4.4 Discharge of abstracted water to each of the recharge trenches (21 l/s to Trench 1 and 15 l/s to Trench 2) was undertaken from Saturday 29 November 2003 until Monday 8 December 2003. During this period of recharging, it was observed that a potentially significant proportion of water discharged entered the overflow ditches. In order to ascertain the rate at which all water discharged entered the aquifer, discharge rates were varied between 14:00 Monday 8 December 2003 and 00:00 Thursday 11 December 2003 (i.e. overflow was reduced to 0 l/s).

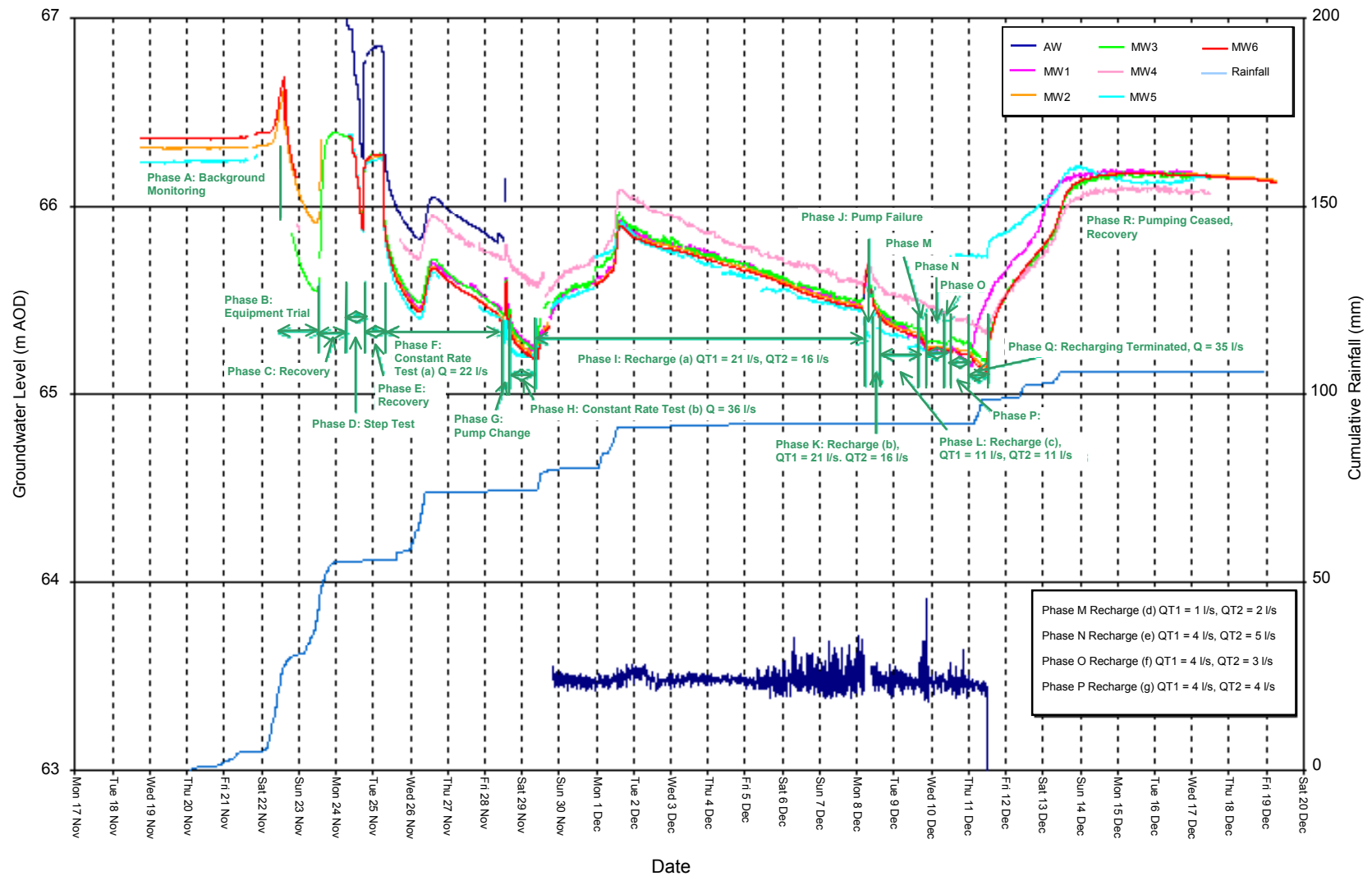


Figure 4.3: Chamberhouse Farm experiment – groundwater level data (m AOD) and cumulative rainfall (mm)

4.5. Results

- 4.5.1 Figure 4.3 shows the variation in all groundwater levels throughout the duration of the experiment. Figures 4.4 to 4.6 (see below) show different monitoring wells in more detail.

Initial Pumping

- 4.5.2 Within 24 hours of pumping at a constant rate of 22 l/s, from an electro-submersible pump groundwater levels in MW2 and MW3 (approximately 33.5 m from the abstraction well) had decreased by approximately 0.75 m. It was observed between these wells and each of the other monitoring wells at increasing distance (MW1 and MW4), drawdown was only 0.1 m less than in MW2 or MW3. This suggested that the zone of dewatering influence was likely to be a flat, relatively symmetrical, far reaching zone of dewatering influence indicative of high permeability sediments.
- 4.5.3 Analysis of results from the initial stage of the constant discharge test, prior to the rainfall event of 26 November were used to ascertain the behaviour of the aquifer and to estimate some of its hydraulic parameters. This indicated that the sand and gravel aquifer was behaving in a manner closely resembling that of an unconfined aquifer.
- 4.5.4 Potential transmissivity values (calculated using Neumann's analytical method for unconfined unsteady state data, Kruseman & De Ridder, 1994) ranged from 741 m²/d to 867 m²/d for early time data; and 795 m²/d to 1042 m²/d for late time data. Assuming an average sand and gravel aquifer thickness of approximately 4 m, this generated a permeability range of approximately 185 m/d to 217 m/d for early time data, and 199 m/d to 261 m/d for late time data.
- 4.5.5 During this initial stage of Phase F it became apparent that drawdown within the surrounding area was not in the region of the 1 m required for the excavation of the recharge trenches. Therefore it was decided (with the consent of the Environment Agency) to change the submersible pump for a surface mounted pump (Phase G), and to abstract groundwater at a rate of up to 50 l/s to generate a greater drawdown (Phase H).
- 4.5.6 Pumping at a rate of 35 l/s generated a total drawdown within the abstraction well of 3 m, and in the vicinity of MW2 and MW3 (both located approximately 33.5 m from the abstraction well) of just over 1 m. Drawdown in DPc, located next to the abstraction well (AW), was however found to be approximately 1 m prior to recharging. This suggests that the difference in pumped groundwater levels in DPc and AW of approximately 2 m represents significant head losses, which is likely to be attributable to turbulent flow in and immediately adjacent to the well.
- 4.5.7 In order to judge the degree of success of the recharge features, comparison was made between actual drawdown before and after recharging. Prior to recharging, the maximum drawdown in groundwater levels for each monitoring wells were as follows: MW1 approximately 1 m; MW2 1.07 m; MW3 1.11m; MW4 0.82 m; MW5 1.02; and MW6 1.16 m.
- 4.5.8 This suggested that the zone of dewatering influence associated with the Chamberhouse Farm experiment was a relatively flat, horizontal zone of dewatering influence.

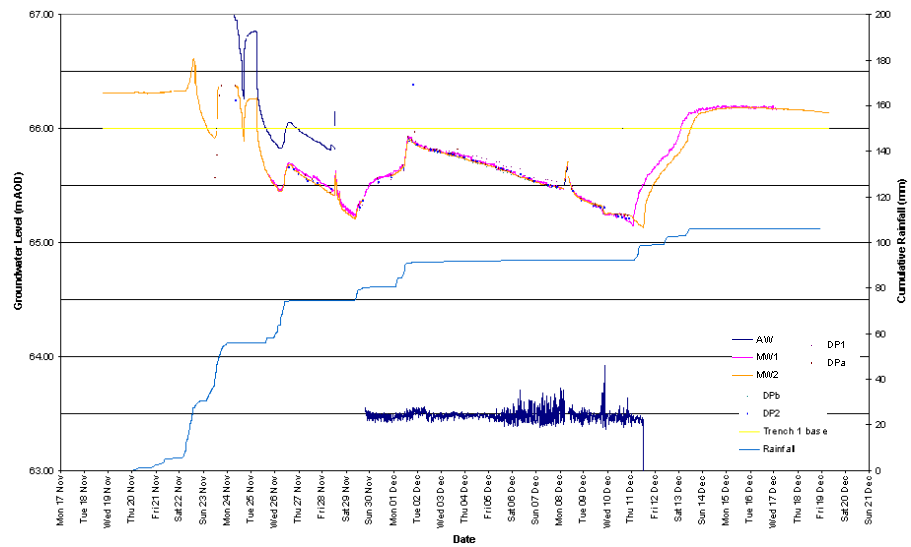


Figure 4.4: Groundwater levels (m AOD) near to Trench 1

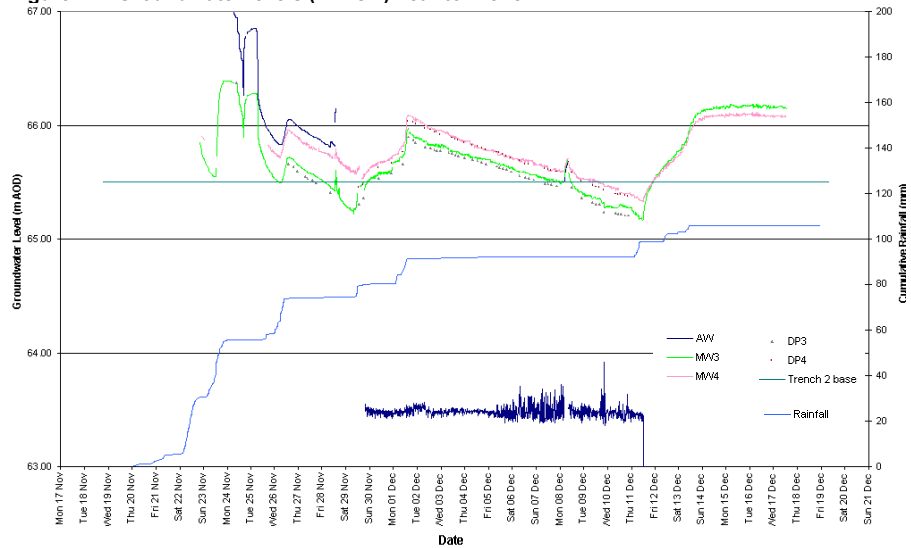


Figure 4.5: Groundwater levels (m AOD) near to Trench 2

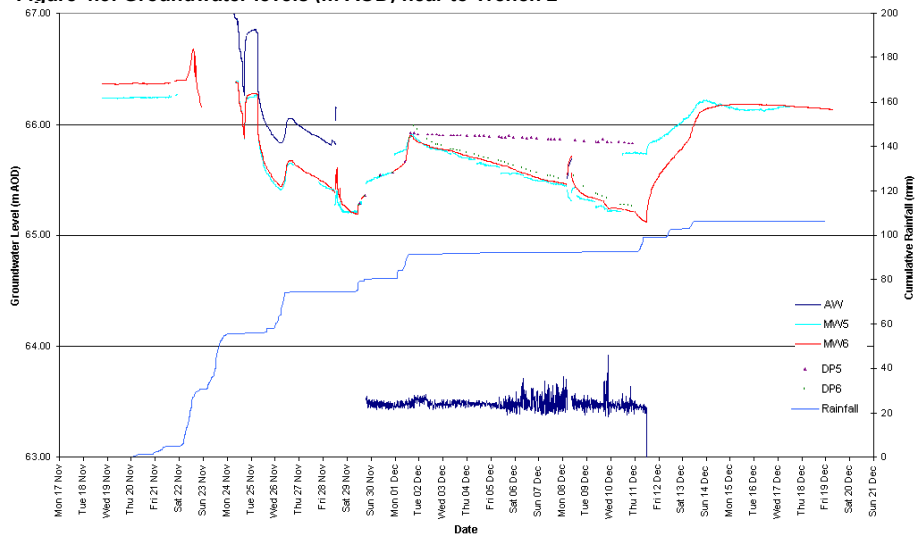


Figure 4.6: Groundwater levels (m AOD) between trenches

Recharge Period

- 4.5.9 Figures 4.4 to 4.6 illustrate groundwater levels in monitoring wells and drive in piezometers in the proximity of Trench 1, Trench 2 and those located in between the trenches (for example MW5 and MW6).
- 4.5.10 An initial period of groundwater level recovery immediately after recharging may be observed. Although some of this may be attributable to the rainfall event of 29 November, as previous rainfall events were reflected as spikes in groundwater levels. This was not the case during the 29 – 30 November period, and hence it may be assumed that the rise in groundwater levels during this time may be attributable to the commencement of recharging.
- 4.5.11 Groundwater levels rose by approximately 0.53 m to 0.59 m prior to the rainfall event of 1 December when groundwater levels were observed to jump by a further 0.2 m. Following this rainfall event, which brought groundwater levels to an artificial high, levels were generally observed to decline until by 8 December they had reached approximately the same levels as just before the rainfall event of 1 December (with the exception of DP5).
- 4.5.12 Water levels within Trench 1 (1 m deep) remained essentially constant during the first phase of recharging fluctuating between 0.93 m and 0.98 m. Within Trench 2 (1.5 m deep) levels remained relatively constant at approximately 0.88 m to 0.90 m.
- 4.5.13 During this recharge period, measurements of input rates to the recharge trenches, and output rates to the overflow ditches were regularly collected. Figure 4.7 plots infiltration rates from the trenches as a percentage of the total discharge input rate. In the case of Trench 1 (receiving a constant discharge of approximately 22 l/s), losses to overflow ditches were initially high with only 40% infiltrating to ground, but within 24 hours had increased to around 70% and then after a further five days increased to around 72% to 80% infiltration.

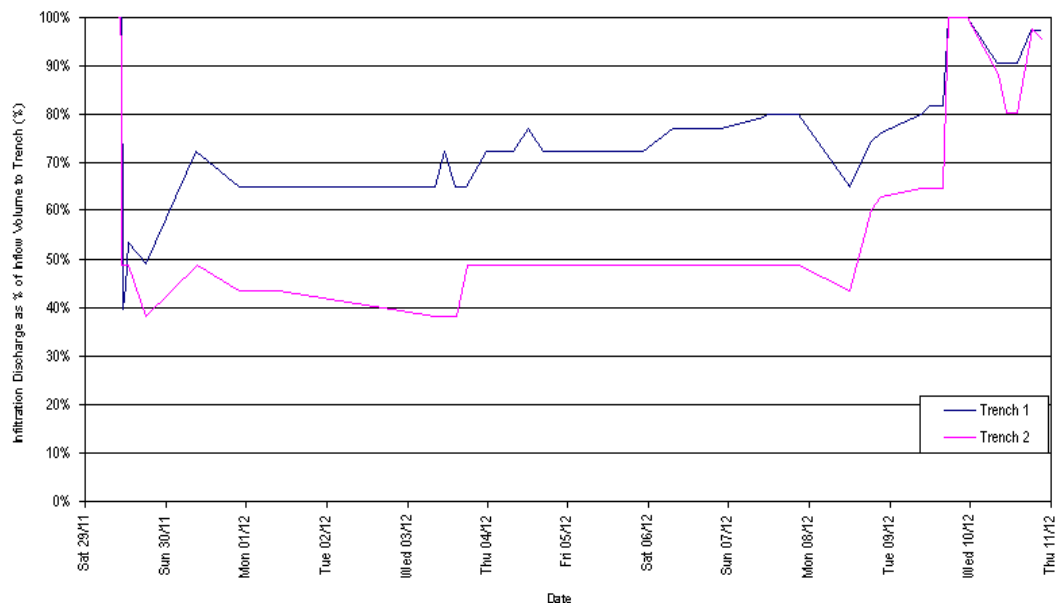


Figure 4.7: Trench infiltration rates as a % of inflow rates

- 4.5.14 In contrast, it was observed that output rates to the overflow ditches were proportionally higher for Trench 2, which was in receipt of a lower groundwater discharge (15 l/s). From commencement of recharging, the infiltration to ground was approximately 40% to 50% of the total volume inputted, and remained relatively consistent during the following six days.

- 4.5.15 During the final phases of the experiment (from 8 December 2003), it was decided to vary input rates to the trenches, while maintaining a constant abstraction rate, in order to see at what rate all the discharge would enter the groundwater system (i.e. an equilibrium may be reached such that no water was 'lost' to the system) and hence what impact this might have on groundwater levels.
- 4.5.16 Losses to overflow ditches from Trench 2 were found to be approximately twice the proportion of losses from Trench 1. Discharge rates had to be reduced to less than 4 l/s before overflow ceased and 100% of the water discharged to the trenches reached the groundwater.
- 4.5.17 By the end of Phase P, groundwater levels had returned to similar levels to those recorded prior to recharging. Recharging was ceased on 11 December 2003, recharge trenches backfilled, and then pumping ceased.
- 4.5.18 Recovery of groundwater levels (with the influence of rainfall events) from 12-19 December 2003 showed quicker recovery in MW1 and MW4, which is as would be expected given their distance from the point of abstraction and the fact that they showed the least amount of total drawdown of all the monitoring wells.

Trench 1

- 4.5.19 Analysis of the potential influence of Trench 1 on underlying groundwater levels was undertaken by focusing on monitoring results from MW1 (43.5 m from Trench 1), MW2 (at a distance of 10 m), DP1 (25 m from Trench 1), DP2 (10 m distance), Dpa and DPb (Figure 4.4).
- 4.5.20 Background groundwater levels in MW2 prior to pumping were approximately 66.31 mAOD. The base of Trench 1, being 1 m deep, was approximately at 66 mAOD.
- 4.5.21 During the initial pumping trial, groundwater levels in MW1 and MW2 were approximately the same (with a difference of only a few centimetres) despite a distance of 33.5 m between the monitoring wells. The maximum drawdown observed prior to recharging was 1.07 m for MW2 and approximately 1 m for MW1. Similar drawdown were also observed in the drive in piezometers.
- 4.5.22 The rate of drawdown from 26 November (65.486 mAOD, MW2) to 29 November (65.239 mAOD, MW2) was observed to be approximately 0.003 m (0.3 cm) per hour (a total drawdown of 0.247 m).
- 4.5.23 Figure 4.8 shows in more detail the initial period following commencement of recharging. During 30 November when there were no rainfall events, groundwater levels were observed to rise at a rate, potentially as a result of recharging from Trench 1, of approximately 0.005 m/hr (0.5 cm/hr).
- 4.5.24 Groundwater levels in MW1 and MW2, together with the drive in piezometers, were observed to exhibit the same behaviour, with increases in levels occurring at the same time.

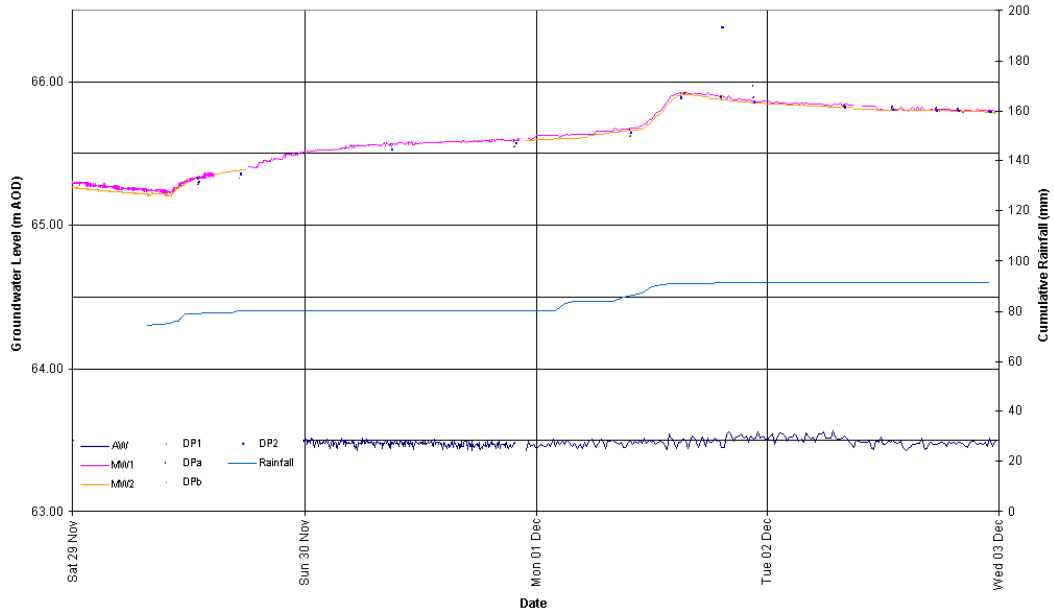


Figure 4.8: Initial recharge period – Trench 1

- 4.5.25 Following the artificial high of the rainfall event of 1-2 December, groundwater levels were observed to fall. During a period without rainfall, levels could still be seen to be in decline with levels in MW2 dropping from 65.578 m AOD to 65.137 m AOD (a total drawdown of 0.441 m) in the space of ten days (a rate of 0.0006 m/hr).
- 4.5.26 During the final phases of the experiment when input rates to Trench 1 were reduced, the rate of drawdown, was observed to increase to between 0.004 m/hr and 0.006 m/hr as outlined in Table 4.1.

Trench 1 Input rate (l/s)	Groundwater Level (m AOD) Start	Groundwater Level (m AOD) Finish	Recharge Period Duration (hrs)	Drawdown rate (m/hr)
22	65.578	65.473	176	0.0006 (MW2)
11	65.470	65.314	26.5	0.006 (MW2)
3.9	65.233	65.137	22	0.004 (MW2)
3.9	65.218	65.151	11	0.006 (MW1)

Table 4.1: Drawdown rates during recharging to Trench 1

- 4.5.27 Groundwater levels in both MW1 and MW2 had recovered to around 66.143 m AOD within 7 days of cessation of pumping, approximately 0.17 m below the original background level recorded at the start of the experiment.

Trench 2

- 4.5.28 Analysis of the potential influence of Trench 2 on underlying groundwater levels was undertaken by focusing on monitoring results from MW3 and DP3 (both 10 m from Trench 2), DP4 (25 m distance), and MW4 (located approximately 43.5 m from Trench 2) (Figure 4.5).
- 4.5.29 Background groundwater levels in the vicinity, prior to pumping, were approximately 66.37 m AOD. The base of Trench 2, being 1.5 m deep, was approximately at 65.5 m AOD.

- 4.5.30 Groundwater levels in MW3 were found to be consistently lower than MW4 by approximately 0.2 m, as would be expected given the closer proximity of MW3 to the abstraction well. The maximum drawdown observed in MW3 was 1.11m, whilst in MW4 it was 0.82 m. The rate of drawdown from 26 November to 29 November was observed to be approximately 0.003 m/hr in MW3 and 0.002 m/hr in MW4 similar to rates observed to the north of the abstraction well.
- 4.5.31 Figure 4.9 shows in more detail the initial period following commencement of recharging. During 30 November groundwater levels were observed to rise at a rate of approximately 0.006 m/hr in MW3, and 0.005 m/hr in MW4, and may be potentially attributed to recharging from Trench 2.
- 4.5.32 One observation during this period of recharging was that the difference in water levels between MW3 and MW4 was reduced to 10 cm, potentially indicative of the influence of recharging from Trench 2.
- 4.5.33 Groundwater levels in DP3 and DP4 were observed to be marginally less than the levels observed within MW3 and MW4. This would be expected since DP3 lies closer to the point of abstraction than MW3, likewise in the case of DP4, which lies closer than MW4.
- 4.5.34 Prior to the rainfall event of 1 – 2 December groundwater levels had risen by approximately 0.5 m to around 65.58 m AOD in MW3 and DP3. This was approximately the same elevation as the base of Trench 2 (65.5m AOD).

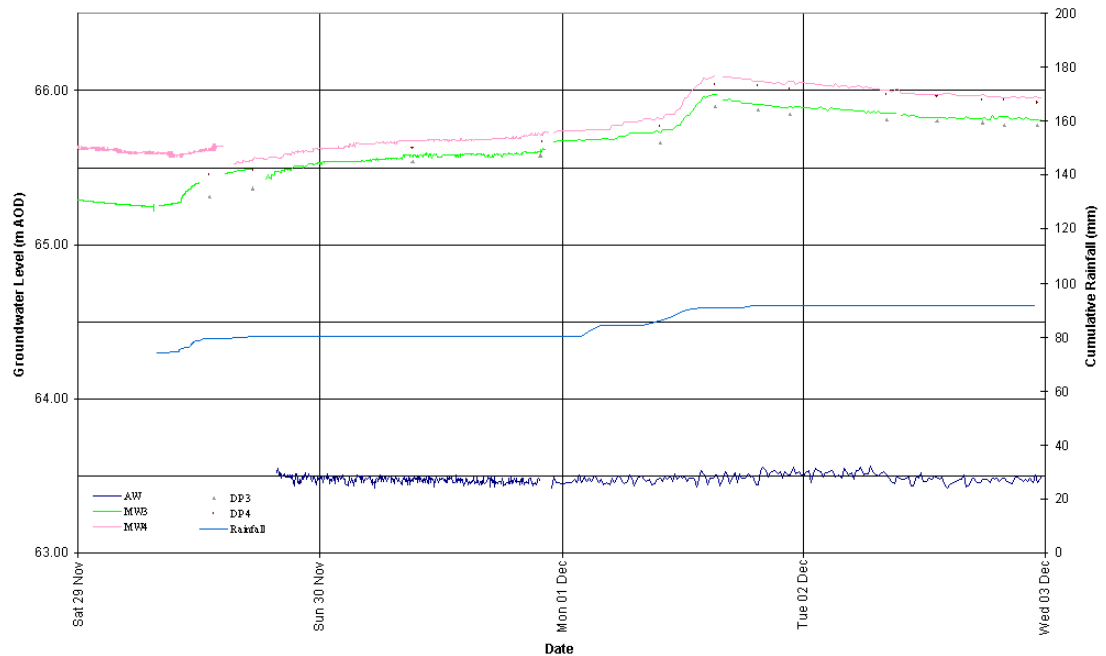


Figure 4.9: Initial recharge period – Trench 2

- 4.5.35 Following the artificial high of the rainfall event of 1-2 December, groundwater levels were again observed to fall. During a period without rainfall, levels were seen to decline at similar rates to those observed in monitoring wells in the vicinity of Trench 1. Differences in groundwater levels in MW3 and MW4 remained approximately 10 cm. As before, the rate of drawdown was found to vary slightly with the input rate to the trench:

Trench 2 Input rate (l/s)	Groundwater Level (m AOD) Start	Groundwater Level (m AOD) Finish	Recharge Period Duration (hrs)	Drawdown rate (m/hr)
<u>MW3</u>				
15 l/s	65.580	65.462	184	0.0006
11 l/s	65.462	65.358	26	0.0040
2 l/s	65.358	65.318	4 (but then levels constant)	0.0100 dropping to 0 m/hr
5 l/s	65.303	65.270	8	0.0040
<u>MW4</u>				
15 l/s	65.691	65.593	184	0.0005
11 l/s	65.593	65.500	26	0.0040
2 l/s	65.500	65.468	5	0.0060
5 l/s	65.389	65.385	8	0.0005

Table 4.2: Drawdown rates during recharging to Trench 2

- 4.5.36 During the later stages of the experiment when lower volumes of water were being discharged to Trench 2, differences in groundwater levels in MW3 and MW4 had returned to 20 cm. When recharging ceased, but pumping still continued drawdown rates were observed to increase from 0.004 m/hr to 0.009 m/hr in MW3.
- 4.5.37 After the cessation of pumping, groundwater levels within MW3 and MW4 showed an immediate rise, with levels in MW3 recovering more quickly and ending up approximately 20 cm higher than MW4. Final groundwater levels were observed to be approximately 0.19 m below background levels prior to pumping.

In Between Trenches

- 4.5.38 Analysis of the potential influence of both trenches on underlying groundwater levels to the west and east of the point of abstraction was undertaken by focusing on monitoring results from MW5, MW6, DP5, and DP6 (Figure 4.6).
- 4.5.39 Background groundwater levels in the vicinity, prior to pumping, were approximately 66.235 m AOD in MW5 and 66.363 m AOD in MW6. Groundwater levels within MW5 and MW6 were observed to be approximately the same during the constant discharge test. The maximum drawdown observed in MW5 was 1.02m, whilst in MW6 it was 1.16 m. The rate of drawdown from 26 November to 29 November was observed to be approximately 0.003 m/hr on average in both monitoring wells.
- 4.5.40 Figure 4.10 shows in more detail the initial period following commencement of recharging. Groundwater levels in MW5 and MW6 (together with DP5 and DP6) were approximately the same and tended to increase by the same amounts. Levels were calculated to rise at approximately 0.004 m/hr.

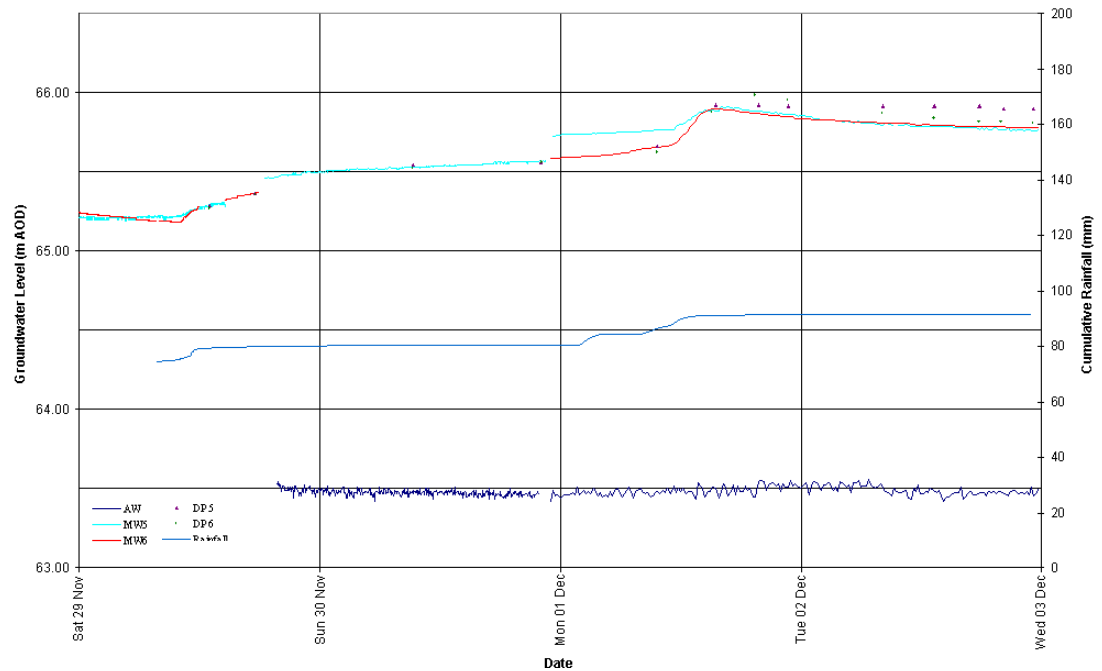


Figure 4.10: Initial recharge period – in between trenches

- 4.5.41 Groundwater levels in DP5 were observed to increase at the same rate as MW6 during the initial stages of recharging (up to 65.913 m AOD). In contrast to MW5, MW6 and DP6, however, water levels in DP5 then remained essentially constant (or only a very small drawdown of around 8 cm) for the remainder of the experiment duration.
- 4.5.42 Following the artificial high of the rainfall event of 1-2 December, groundwater levels in MW5, MW6 and DP6 were observed to fall at similar rates to those observed in other monitoring wells within the experimental area. After the cessation of pumping, groundwater levels were observed to rise quickly, reaching levels within 0.1 m of the original background levels within four days.

4.6. Discussion

- 4.6.1 During the course of the initial pumping stages of the experiment, groundwater level responses indicated that the aquifer was likely to be behaving in an unsteady state unconfined manner. Drawdown was observed to range from 0.82 m to 1.16 m in the surrounding monitoring wells, prior to recharging. This suggested that the zone of dewatering influence associated with the Chamberhouse Farm experiment was relatively flat and horizontal.
- 4.6.2 Observed drawdown rates, prior to recharging, were found to be approximately equal in all monitoring wells at approximately 0.3 cm/hr. On recharging, groundwater levels were observed to respond almost immediately in MW1, MW2 and MW3. A slight delay of approximately 30 minutes was observed before levels in MW4 were seen to start to rise. This may potentially reflect a slight propagation of the recharge front between MW3 and MW4.
- 4.6.3 Prior to the rainfall event of 1-2 December, which further increased groundwater levels, the levels in all monitoring wells (regardless of location) were observed to have risen by approximately 0.5 m (at a rate of between 0.4 cm/hr to 0.6 cm/hr). In the case of Trench 2, with a smaller unsaturated zone to begin with, groundwater levels may have risen above the base of the trench.

- 4.6.4 Following the rainfall event, groundwater levels were observed to decline again, however it was found that drawdown rates (using levels prior to the rainfall event and at the end of an extensive period of no rainfall) had decreased from 0.3 cm/hr to 0.06 cm/hr which may be attributed to the impact of discharging abstracted water to the recharge trenches. Alternatively this may reflect the intermediate stage when pumping of an unconfined aquifer in unsteady state when drawdown rates are found to be significantly lower than those observed at either early or late pumping time.
- 4.6.5 However, given that the rate of recovery in the groundwater level, after recharging through the trenches had commenced, was estimated to be between 0.4 cm/hr and 0.6 cm/hr, and the original drawdown rate was found to be approximately 0.3 cm/hr, it may be expected that a net gain to groundwater levels of around 0.1-0.3 cm/hr may be observed, yet levels still continued to decline during recharging.
- 4.6.6 It was estimated that approximately 51% to 62% of the groundwater discharged to Trench 2 was lost as output to the overflow ditches (and hence to the underlying groundwater system). Whereas for Trench 1 (discharge rate 21 l/s), proportions were observed to be lower (20% to 35% of the input volume) after initially high losses.

4.7. Theory

- 4.7.1 In order to begin to understand the response of groundwater levels during recharging, it is useful to consider the water balance of the experiment. Figure 4.11 (below) schematically demonstrates this during the initial phase of recharging.

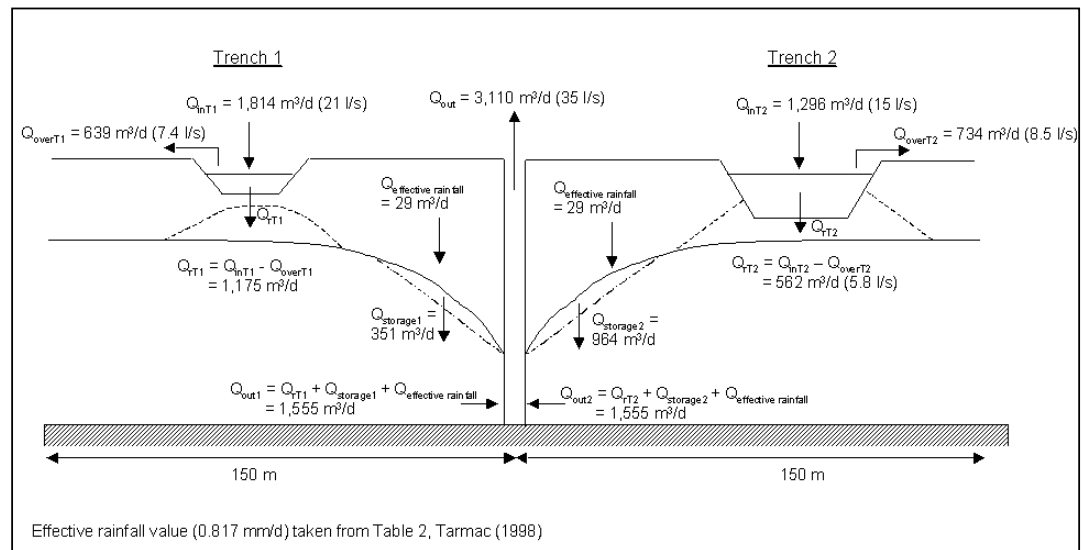


Figure 4.11: Chamberhouse Farm experiment water balance

- 4.7.2 When a groundwater system is in steady state, flow is independent of time and water levels will no longer change. Prior to reaching a steady state situation, groundwater flow is said to be in unsteady state. Groundwater flow is based upon the conservation of fluid mass which balances inputs, outputs and changes in water mass within a porous media according to the equation:

Equation 6: $Q_{input} = Q_{output} - \Delta M_s$

Where:

Q_{input} = mass inflow

Q_{output} = mass outflow

ΔM_s = change in mass storage with time

- 4.7.3 In a steady state situation Q_{input} is equal to Q_{output} , and therefore there is no further change in the volume of water either released or taken into storage. In an unsteady state situation, where inputs and outputs are not equal, the groundwater system will seek to re-establish equilibrium by either releasing or taking water into storage. Alternatively the system may re-dress the balance through increasing or decreasing the inputs / outputs as appropriate (e.g. increased leakage from a surface watercourse to balance groundwater abstraction.)
- 4.7.4 In the case of the experimental site (Figure 4.11), it may be seen that the volume of water pumped from the well was 3,110 m³/day. 1,814 m³/d of this was pumped into Trench 1, whilst Trench 2 received approximately 1,296 m³/d. From the records of discharge into the overflow ditches, it may be calculated that essentially 639 m³/d and 734 m³/d were lost, via lined overflows, from Trench 1 and Trench 2 respectively. This therefore leaves a maximum of 1,175 m³/d (Trench 1) and 562 m³/d (Trench 2) to be recharged back into groundwater.
- 4.7.5 This total input of 1,795 m³/d is likely to have been insufficient to meet the 3,110 m³/d demand of the abstraction well (even when including for the additional contribution of rainfall recharge). Therefore the groundwater system would need to release water from storage in order to maintain conservation of the fluid mass.
- 4.7.6 In an unconfined aquifer, additional groundwater will mainly be released from storage through the draining of groundwater from the aquifer's pores, thus lowering groundwater levels. The volume of water released may be calculated by:

Equation 7: $V_w = \Delta WT \times 1m^2 \times S$

Where:

- V_w = Volume of water released (m³)
- ΔWT = change in water table (m)
- S = Storage coefficient (combination of specific yield and specific storage values)

- 4.7.7 Darcy's law (shown below) governing groundwater flow, also relies on the principle of conservation of fluid mass:

Equation 8: $Q = KiA$

Where:

- Q = Discharge rate (m³/d)
- K = Hydraulic conductivity (m/d)
- I = Hydraulic gradient (-)
- A = Cross sectional area perpendicular to flow (m²)

- 4.7.8 As water levels drop in order to release water from storage, the cross sectional area term of Darcy's law may be reduced. Since K remains constant, this may lead to an increase in the hydraulic gradient term in order to maintain Q .
- 4.7.9 In time the inputs and outputs to the groundwater system will balance (i.e. have reached steady state), and no further changes to groundwater levels will be observed.
- 4.7.10 The situation may also be reversed in that if inputs to the aquifer exceed outputs, water may be taken into storage in order to balance the equilibrium. In accordance with Equation 7, this may be seen as an increase in water table levels in order to conserve the fluid mass balance.
- 4.7.11 In the case of the Chamberhouse Farm experiment, groundwater levels initially rose for a 24 hour period after recharging commenced. However, after this first initial period of recovery, groundwater levels were observed to decline.
- 4.7.12 Figure 4.12 uses the principles of superposition to illustrate the potential response of groundwater levels to recharging which may have occurred during the Chamberhouse Farm experiment. This may suggest that at the start of recharging inputs to the groundwater system exceed outputs and hence water is taken into storage (with an associated rise in groundwater levels).

4.7.13 Over time water levels which may be associated with recharging alone are likely to reach a steady state. However in the case of the pumping curve continued drawdown may indicate that the aquifer is still in unsteady state leading to an overall decline in groundwater levels. However, one observation which may be made from Figure 4.12 is that overall groundwater levels are not as low as they would be if no recharging was to take place.

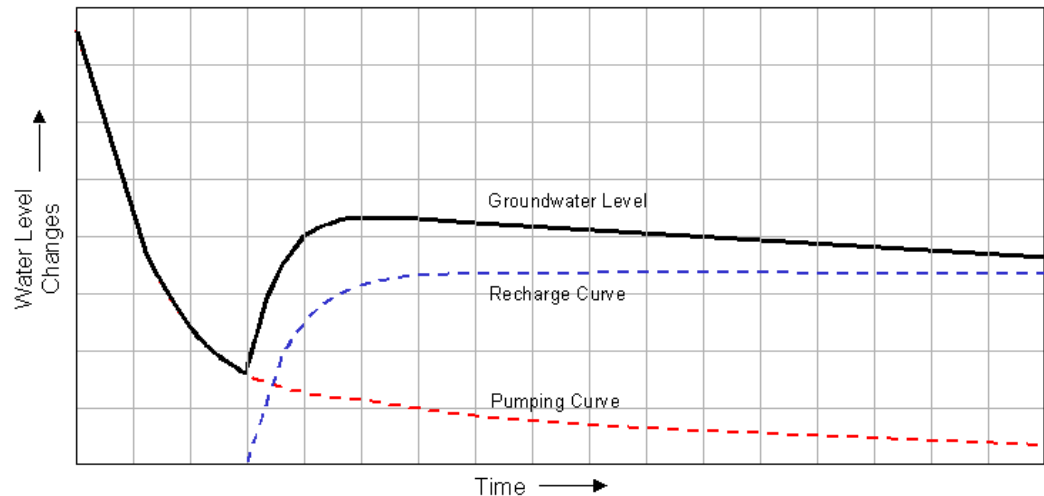


Figure 4.12: Schematic diagram showing the theoretical response of groundwater levels to recharging at Chamberhouse Farm.

4.7.14 Consideration of Darcy's law allows us to explore how recharge volumes from the two recharge trenches may be affected by underlying groundwater levels. Since both trenches had the same basal area (A) and may be assumed to have similar values of hydraulic conductivity (K), one of the key factors which may potentially influence the volume of water entering the underlying aquifer may be the hydraulic gradient (i). The hydraulic gradient represents the difference between water levels within the trench and groundwater levels within the underlying aquifer over a short distance (Figure 4.11).

4.7.15 Theoretically, during the unsteady state development of a zone of dewatering influence it may be possible to bring the zone of dewatering influence to an early pseudo steady state by balancing inputs (recharge volumes and effective rainfall) with outputs (abstraction and overflows) from the start of dewatering thus potentially minimising the extent of the zone of dewatering influence or it's rate of expansion. In reality, we cannot say whether or not this is the case from the data collected during this experiment.

4.7.16 Following the principles of fluid mass conservation, reversal of lowered groundwater levels would have required input of recharge volumes into the underlying aquifer which were greater than the output volumes. As shown in Equation 6, when input volumes (including that generated from effective rainfall) are greater than output volumes, water will be taken into storage to restore equilibrium. This would be reflected as an increase in groundwater levels (according to Equation 7).

4.7.17 In the case of Chamberhouse Farm experiment, a proportion of the input volume to each of the recharge trenches was lost to the overflow ditches, and hence potentially lost to the underlying groundwater system.

4.7.18 Introduction of greater volumes of water to the aquifer, in the case of this experiment, may require increasing the internal surface area of the trench (thus increasing the recharge volume in accordance with Darcy's Law), or alternatively increasing the hydraulic gradient by raising water levels within the trenches to above ground level, perhaps through the use of bunds. In addition to potential issues associated with geotechnical stability, the development of such structures within the floodplain may be an issue.

4.8. Experiment 1 Summary

- 4.8.1 Experimental results showed that the permeability of the sand and gravel aquifer was higher than originally predicted, leading to a greater potential radius of influence and hence greater predicted drawdown at MW1 (the monitoring well closest to the Bowdown and Chamberhouse Woods SSSI).
- 4.8.2 Even though some rise in groundwater levels was apparent as a result of recharging, the total rise in groundwater levels of 0.5 m was not enough to lead to groundwater levels recovering to background in the vicinity of the SSSI. If the recharge trench had been located in closer proximity to the SSSI, or had been a larger size, this may have made a difference.
- 4.8.3 What can be seen from the Chamberhouse Farm experiment is that during recharging drawdown rates were significantly lower than prior to recharging. Where ecosystems (or man-made structures) are sensitive to even small changes in groundwater levels, this may be important.
- 4.8.4 Groundwater level responses to recharging from Trench 1 and 2 appear to occur at the same time and have the same magnitude of impact. This may suggest that the difference in basal trench dimensions did not make a significant difference. This may be due to the fact that the overall internal surface area for each trench was approximately the same.
- 4.8.5 What is not known, and cannot be judged from the data collected during this experiment, is whether if recharging to the aquifer had been started at the same time as groundwater abstraction, whether the extent of the zone of dewatering influence could have been minimised or it's rate of expansion slowed down.
- 4.8.6 Further detailed information on the Chamberhouse Farm experiment may be found in Symonds Group's report (2004a).

5. EXPERIMENT 2: METHLEY QUARRY

5.1. Aims and Objectives

- 5.1.1 In contrast to the Chamberhouse Farm site, Methley quarry was an operational site with an existing zone of dewatering influence generated as a result of quarry dewatering. Experiment 2 aimed to investigate how rapidly such an existing zone of dewatering influence, associated with an actual working excavation, reacted to the commencement of recharging and how well this response could be predicted.
- 5.1.2 In order to achieve this, a short-term experiment was undertaken on site to gather real quantitative data (both in space and time) to allow assessment of the response to recharge. A groundwater model was used to investigate the predicted response to recharging and the model results were compared to observations from the site experiment.
- 5.1.3 The groundwater model was also used to investigate the relative importance of the following factors:
- (i) The trench depth required to prevent perching of the water within the recharge feature;
 - (ii) Volumes of water that may be required for the recharge feature in comparison to dewatering volumes, and any additional water losses through evaporation, including development of a water balance of the process;
 - (iii) Effect of any clogging of the base or the sides of the recharge feature on the performance of the feature (i.e. decrease in the permeability of the base and sides of the recharge feature); and
 - (iv) The effects of the variable internal surface area of the recharge feature (base and sides) on its efficiency.

5.2. Background

- 5.2.1 The Methley Quarry site (owned by Methley Estates, but operated by Lafarge Aggregates) is located approximately 2 km north-west of Castleford, West Yorkshire, near to the town of Mickletown (national grid reference 4150 2700).
- 5.2.2 The site is situated on Second Terrace Sands and Gravels and Alluvium, bound to the north and east by the River Aire and to the south by the River Calder. The Mickletown Ings Site of Special Scientific Interest (SSSI) is situated approximately 500 m to the north-west of the quarry site (Figure 5.1).
- 5.2.3 The site is an operational quarry that has been actively dewatering the gravels for over 10 years. Historic and current groundwater records demonstrate that a zone of dewatering influence has developed around the site.
- 5.2.4 Extraction of mineral is currently confined to Phase 9 (Figure 5.1). Phases 1 to 4, in the eastern part of the site, have been restored, backfilled with the overburden, sub-soil and topsoil, mostly comprising sand, silt and clay. Former extraction Phases 5 to 8 are now used as part of the water circulation system for the abstracted water.
- 5.2.5 The region around Wakefield has a history of surface mineral workings; mostly exploiting the Carboniferous Coal Measures that underlie the Terraced Sands and Gravels. In the area surrounding Methley Quarry, RJB Mining have undertaken opencast coal extraction approximately 1 kilometre to the northwest of Mickletown Ings, north of the River Aire, for many years.

- 5.2.6 Concerns that dewatering of Methley Quarry may have an adverse impact on the Mickletown Ings SSSI led to the inclusion within the original planning application for the site for provision of a recharge trench to help to mitigate any impact which might be observed.

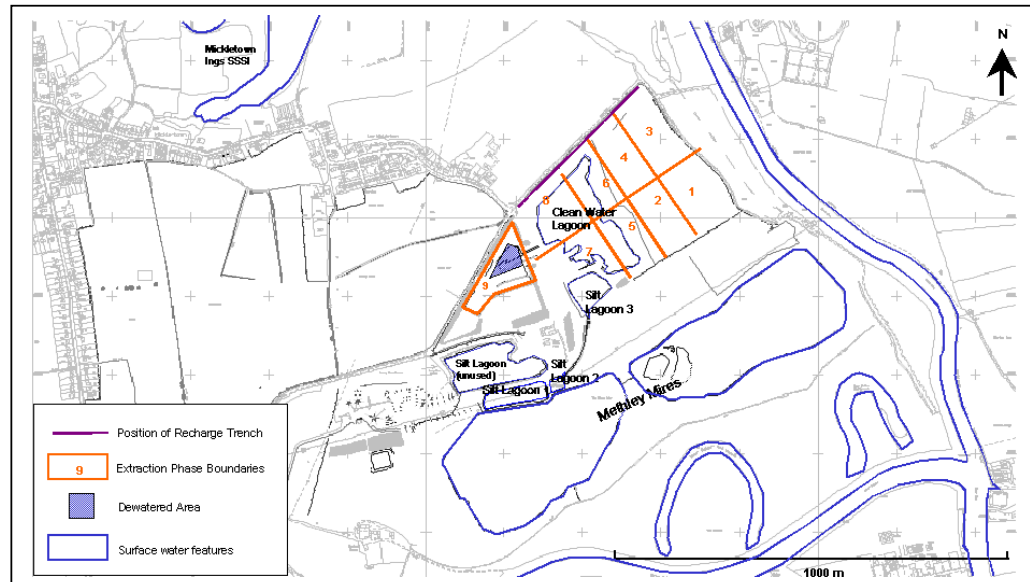


Figure 5.1: Methley Quarry

- 5.2.7 The recharge feature is located along the north-western boundary of the quarry site, (Figure 5.1). The recharge trench was to be put into use if the water levels in the Mickletown Ings SSSI and the monitoring well BH8 were to fall below specified trigger levels of 9.8 m AOD and 12.59 m AOD, respectively. Prior to the experiment the recharge feature had not been used.
- 5.2.8 In the design for the recharge feature the trench was to be excavated to a depth of approximately 2 m, through the full thickness of the topsoil and overburden and into the gravel deposits. The base of the trench would still lie above the level of the water table, and was designed to be 1 m wide with side-slopes of 1 in 1.5. The western section of the trench had been constructed to these specifications, but further east along the trench was found to be narrower and not as deep. Since its construction the trench had not been used and, prior to undertaking the experiment, the trench was overgrown with vegetation.

Geology

- 5.2.9 The Terraced Sand and Gravel deposits are a reasonably clean sand and gravel with very little silt and clay. Any clay that is present occurs as 0.2 m to 1 m thick lenses, which are not laterally continuous. Alluvial deposits comprise sandy clays and gravelly clays, and are found to overlie the sands and gravels across the whole area, varying in thickness between 1 and 7 m. The thickness of the sand and gravel deposits at the Methley quarry site were found to range between 6 m and 12 m, with greater thicknesses to the south west. To the north of the quarry site, towards the Mickletown Ings the deposits appear to become thinner, ranging between 1 m and 6 m, with the base of the material being closer to the surface and containing a greater amount of clay.
- 5.2.10 The underlying solid geology comprises the Carboniferous Middle Coal Measures. These consist of a complex cyclic sequence of mudstones, siltstones, sandstones, seat earths and coal, dipping in a north easterly direction. As a result of folding and extensive faulting, individual beds are commonly discontinuous and restricted to the area in which they are found. Borehole logs show the Terraced Sands and Gravels to sit directly above a mudstone horizon of the Coal Measures, which is thought to be 10 m thick in the vicinity of Willow Grove Farm, within the boundaries of Methley Quarry.

Hydrology

- 5.2.11 The area surrounding Methley Quarry is bounded by the Rivers Aire and Calder. The River Aire flows in a south-easterly direction, and at its closest point lies within 100 m of the eastern boundary of the quarry site. The River Calder is situated approximately 500 m south of Methley Quarry, and flows eastward.
- 5.2.12 Other surface water features in the vicinity of Methley quarry include the Mickletown Ings SSSI; the Methley Mires lagoons and oxbow lakes to the south of the quarry; silt and clean water lagoons at the quarry site; and a series of drainage ditches that surround the quarry.
- 5.2.13 The Mickletown Ings SSSI is a wetland comprising shallow areas of open water fringed by marshland. The Ings are considered to have formed as a result of mining subsidence that has progressively inundated the low-lying fields in the floodplain of the River Aire. The Ings now support a diverse habitat for aquatic flora and associated invertebrate fauna.
- 5.2.14 The Methley Mires comprise two lagoons (former mineral extraction areas), joined by a pipe, located approximately 100 m south of the quarry site, and are considered to be an expression of groundwater. Water is abstracted from these lagoons for mineral washing, then water is returned to the lagoons having passed through the silt lagoons of the water circulation system at the site.
- 5.2.15 The water level in the final silt lagoon is maintained by overflow pipes at 8.24 m AOD. The beds of the lagoons would be expected to be silted up and therefore connectivity with groundwater is likely to be restricted. The bed of the clean water lagoon, however, was observed to comprise gravel with a small amount of silt and it is likely that the lagoon would maintain some continuity with the groundwater. Water levels for the clean water lagoon range from 6.8 to 7.55 m AOD over a 3 year period.

Hydrogeology

- 5.2.16 The Terraced Sands and Gravels, together with the alluvium, are classified by the Environment Agency as a Minor Aquifer being of moderate permeability and important for local water supply and for baseflows in rivers. The mudstones, silts and clays and the underlying Coal Measures are considered to form a low permeability layer (aquitard), restricting the movement of water through the Coal Measures and forming a perched groundwater system in the sands and gravels.
- 5.2.17 Groundwater at the Methley quarry site is found to lie between 5 and 7 m below ground level (7 and 9 m AOD). The original rest water level in the area of quarry site and the surrounding area would be between 9 and 10 m AOD but due to dewatering the water levels at the quarry site have been drawn down by approximately 2 – 3 m.
- 5.2.18 Water level contours show that a zone of dewatering influence exists within the area surrounding the quarry, with the Rivers Aire and Calder acting as sources of recharge to groundwater. Water levels in the Mickletown Ings are approximately 0.50 m lower than the level in monitoring well BH8, suggesting that the Ings could be in continuity with the aquifer.
- 5.2.19 Dewatering from a sump in Phase 9 at a rate of 3,000 m³/day takes place continuously during the winter, and occasionally during the summer months. The water is then discharged to the Methley Mires through the on-site water circulation system.

5.2.20 The BGS Minor Aquifer Properties Report (WD/00/04, 2000) provides hydraulic conductivity values for the Coal Measures ranging between 10^{-2} and 10^{-4} m/day. Grain size analysis data for sand and gravel samples taken from the Methley Quarry site were been used to calculate values for the hydraulic conductivity of the material using the Hazen formula⁴. The calculated values suggest that the permeability of the material is quite varied across the area, ranging between 9 and 310 m/day for the sands and gravels with a geometric mean of 73.25 m/day.

5.3. The Groundwater Model

5.3.1 The software used for the model was MODFLOW run under the Groundwater Vistas user interface. The finite difference grid was set with a cell size of 50 m by 50 m, refined in the area of the recharge trenches to a 1 m by 2 m spacing. The grid was orientated along the line of the recharge trench, allowing the dimensions of the trench to be modelled more accurately and the head levels in the area surrounding the trench to be monitored with greater detail.

5.3.2 The aquifer unit in the model comprised the Terraced Sands and Gravels, and Alluvium. The base of the sand and gravels was marked by the low permeability mudstones and clays of the Carboniferous Coal Measures (no flow boundary).

5.3.3 Different zones of the groundwater model were assigned different values of hydraulic conductivity according to the relative proportions of sand and gravel versus alluvium across the area, or where worked out phases had been backfilled with material containing higher proportions of silt and clay. Porosity and storage coefficients were estimated from reference texts (see separate report for further information).

5.3.4 The northern and the eastern boundaries of the aquifer were formed by the line of the River Aire and was represented by MODFLOW river cells (a head-dependent flow boundary condition). The southern boundary of the aquifer was the line of the River Calder, also represented by MODFLOW river cells.

5.3.5 The western boundary of the sands and gravels was represented in the model in two ways. The northern and the southern portions of the boundary were formed by the natural extent of the sands and gravels approximately 2 km west of the quarry site. These boundaries mark where the deposits thin and the Coal Measures outcrop were represented by no flow boundaries.

5.3.6 Between these two no flow boundaries the sands and gravels extend away from the quarry site towards the south-west and follow the course of the River Calder. As this natural boundary would prove difficult to model, a constant head boundary, with the head set at 10.5 mAOD.

5.3.7 The Mickletown Ings SSSI were represented using the MODFLOW general head package, allowing water levels in the ponds to be assigned and for the ponds to act as either a flow sink or source for groundwater depending on the head of groundwater in the surrounding sands and gravels, while enabling the conductance of the boundary to be specified. The lagoons of the Methley Mires to the south of the site were considered to be in continuity with groundwater, and were also represented by a general head boundary.

5.3.8 The water circulation system at the quarry site includes four silt lagoons and a clean water lagoon. Only three of the silt lagoons are currently used and the beds of these lagoons were visibly silted, restricting continuity with groundwater. Information on water levels is only available for the final silt lagoon, which is maintained at 8.24 m AOD by the positioning of the overflow pipes that transfer water to the clean water lagoon.

⁴ $K = C(d_{10})^2$. Where K is the hydraulic conductivity (cm/s), d_{10} is the effective grain size (cm) and C is a coefficient based on the type of material (Fetter, 1994)

- 5.3.9 The first two silt lagoons appeared to be nearly full, with only a shallow depth of water observed during a site visit (19/11/2003). These lagoons are unlikely to provide any impact on the groundwater model and have been ignored in the model. The final silt lagoon, which would be expected to contain the least amount of silt, was modelled using the MODFLOW general head boundary. The hydraulic conductivity of the bed of the lagoon is low, with a value of 10^{-4} m/day considered realistic. The bed of the lagoons was estimated to be at approximately 6 m AOD.
- 5.3.10 The clean water lagoon is situated in the previous, un-restored extraction phases. The water that reaches the clean water lagoon has a low silt content and the bed of the lagoon appears to be quite gravelly. It is likely that this lagoon is in continuity with the groundwater. Therefore an appropriate value for the hydraulic conductivity was considered to be between 1 and 10 m/day. Through calibration of the flows between the clean water lagoon and the Methley Mires a value of 1 m/day was determined. This clean water lagoon was represented using the MODFLOW general head boundary in the model, with the elevation of the bed estimated to be 6 m AOD.
- 5.3.11 Values for the weekly rainfall recharge to the groundwater have been calculated by taking into account the rainfall over the area; soil moisture deficit (SMD); the actual evaporation (E_t) and surface runoff. Considering the relatively flat topography and the sand and gravel material making up the aquifer it is considered that only 10 percent of the rainfall would be lost through surface runoff. Therefore the recharge to the groundwater was estimated using the equation:
- Equation 9: Recharge = 0.9 (Rainfall – $E_{t\text{catchment}}$ – SMD_{catchment})**
- 5.3.12 The value for recharge in the model was taken as the average recharge over the 20 year period for which rainfall and evaporation data had been obtained. This produced a value of 3.8×10^{-4} m/day. However recharge is likely to be retarded by the alluvium that overlies the sand and gravel and will be restricted by areas of land with impermeable surface, mainly the town of Mickletown. Therefore the flow domain in the groundwater model was divided into 3 zones. Zone 1 was where the alluvium was found to be thin, Zone 2 where the alluvium was thicker than 2 m and Zone 3 with impermeable surfaces.
- 5.3.13 The dewatering operation in the current extraction phase (Phase 9) acts to maintain the groundwater at a level that will allow the extraction of dry material. A topographic survey of the site shows the level of the base of the extraction to be at 7.16 m AOD. For this reason it was considered appropriate to represent the area of dewatering as a constant head boundary, with a head level set at 7.16 m.
- 5.3.14 The model was created as a steady state simulation allowing the model to be calibrated with the most recent groundwater level data imported into the model as calibration targets. This was then converted to a transient model, with the recharge trench included and with time step durations of one day, allowing the impact of the recharge trench over time to be investigated.
- 5.3.15 The transient model was run for three separate conditions, a normal period, a dry period and drought period. The normal conditions were based on conditions that had been monitored just prior to the on site experiment, with the results from these model simulations used as a comparison to the results from the experiment. It was considered that the recharge trench would most likely to be required for periods when either dry conditions or drought conditions are experienced, so these conditions were used in transient simulations, investigating the impact of the recharge trench. For this purpose steady state simulations were created with reduced recharge and water levels in the surface water boundaries that would be expected during such periods.
- 5.3.16 The design of the recharge feature was based around the design for the on-site experiment (Figure 5.2). This design involved separating the existing trench into two sections, each 50 m long. Trench 1 was left in its original state, where the trench is vegetated and is likely to provide a lower conductance, and is blocked off by clay bunds to retain the water in the trench. Trench 2 was designed to provide a comparison to the first trench, being cleaned out and deepened so that the two trenches are the same width and depth. Water was pumped to the trenches and water level maintained at a constant level by overflow pipes.

5.3.17 The trenches were represented in the groundwater model as general head boundaries, maintaining the head at a constant level of 10 m AOD. The general head package allowed the conductance of the bed of the trenches to be varied. Trench 2 had a moderately high conductance value (10 m/day), as the trench had been cleaned out allowing water to flow easily into the sand and gravel. The conductivity of vegetated Trench 1 was more uncertain, and therefore it was modelled in three separate simulations, with the conductivity value each time taken as a percentage of the value used for Trench 2. Values of 5 m/day, 2.5 m/day and 1 m/day, were used.

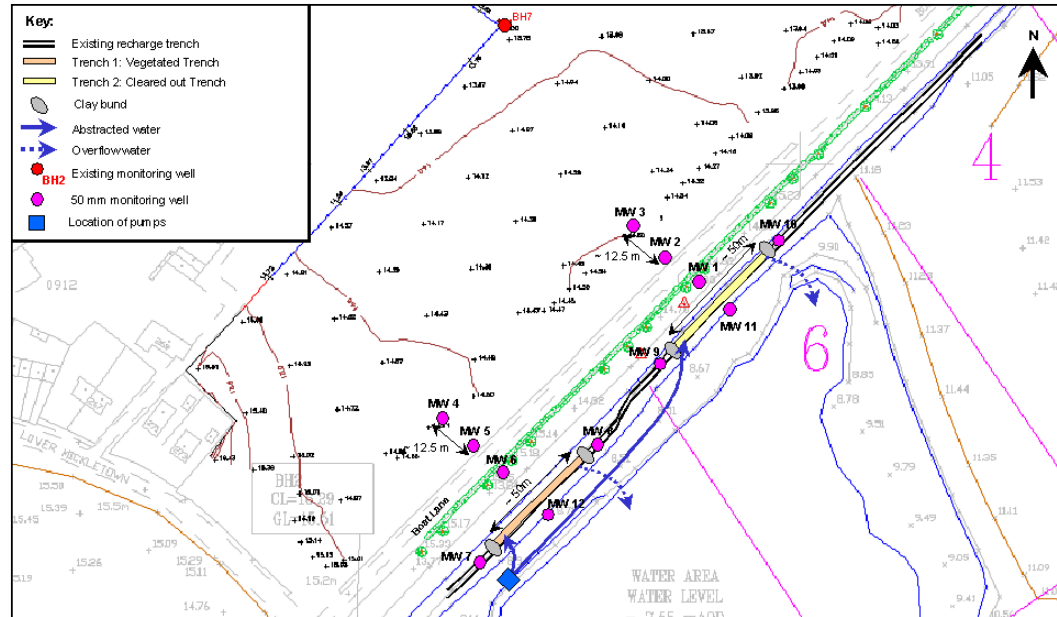


Figure 5.2: Methley Quarry recharge experiment

5.4. Model Simulations

- 5.4.1 The normal conditions steady state model was calibrated using data from the monthly groundwater monitoring from Methley quarry, together with consideration of the water mass balance. Results showed a reasonable correlation between the observed and the modelled levels, with an Absolute Mean Residual of 0.61 m.
- 5.4.2 The water circulation system on site has water transferred to the clean-water lagoon from the silt lagoons and the area that is being dewatered. The water in the clean-water lagoon is then pumped to the Methley Mires. The pump that transfers the water from the clean-water lagoon to the Methley Mires operates at approximately 3,900 m³/day.
- 5.4.3 The calibrated steady state model was converted to a transient simulation with 2 stress periods. The first stress period, consisting of ten daily time steps, before the recharge trench was active and the second stress period, consisting of 90 daily time steps, when pumping to the recharge trenches was active, allowing the response of the groundwater level to reach a steady condition.
- 5.4.4 As discussed above, there was some uncertainty as to the likely value of hydraulic conductivity that should be used for the vegetated recharge trench (Trench 1). Therefore three transient model simulations were created, keeping the conductance of Trench 2 constant at 10 m/day and varying the conductance of Trench 1 between 1, 2.5 and 5 m/day.

- 5.4.5 The recharge trench is likely to be used in dry conditions or when the area is experiencing a drought. Therefore the calibrated steady state model was adjusted to simulate the area surrounding Methley quarry during these periods that experience drier conditions. This was done by reducing the areal recharge and the head of water in the rivers and lakes to levels that were shown by historic data to have been experienced during such periods.
- 5.4.6 Only one trench was active during the transient model, allowing these investigative simulations to examine the impact of changing the depth of the trenches, the internal surface area, the effects of reduced hydraulic conductivity and the volumes of water that would be required to be pumped into the trench during recharging.
- 5.4.7 The impact of changing these factors, all require the conductance of the general head boundary to be altered in the model. The hydraulic conductivity of the sides and base of the trench were interpreted to reduce logarithmically as fines act to clog the trench walls. The impact of reducing the conductivity was examined using separate simulations which had different conductance values for the general head boundary.
- 5.4.8 To model both the effects of changing the hydraulic conductivity and the size of the trench, five values for the conductance of the trench were selected to be used in different simulations. These values were 1, 2.5, 5, 10 and 20 m/day. An example of how changing the hydraulic conductivity and the depth and width of the trench altered the conductance is shown below.

Hydraulic Conductivity (m/day)	Depth of trench (m)	Width of trench (m)	Conductance (m ² /day)
5	1	1	5
5	1	2	10
5	2	1	10
5	2	2	20
1	1	1	1
2.5	1	1	2.5
5	1	1	5
10	1	1	10
20	1	1	20

Table 5.1: Variation in conductance term modelled

5.5. Model Results

Normal Conditions

- 5.5.1 The model results showed an immediate response in the groundwater level on commencement of recharging. The modelled well hydrographs (Figure 5.3) of head levels in the monitoring wells near to the trench showed most of the rise in head occurred within the first 20 days after recharging began, although the groundwater levels didn't reach a steady condition until approximately 60 days after recharging began.
- 5.5.2 As the distance from the trench increased the results showed the response of the groundwater to be progressively less, with a time delay on the groundwater level rise.
- 5.5.3 The monitoring wells near to the trench showed a large and immediate response to recharging from the trench, with MW 1 showing a rise of 0.4 m and MW 6 a rise of 0.2 m after the first day. As the distance from the trench increased the modelled response of the groundwater was delayed with the first head change in BH 8, approximately 500 m from the trenches, seen after 30 days (0.01 m).

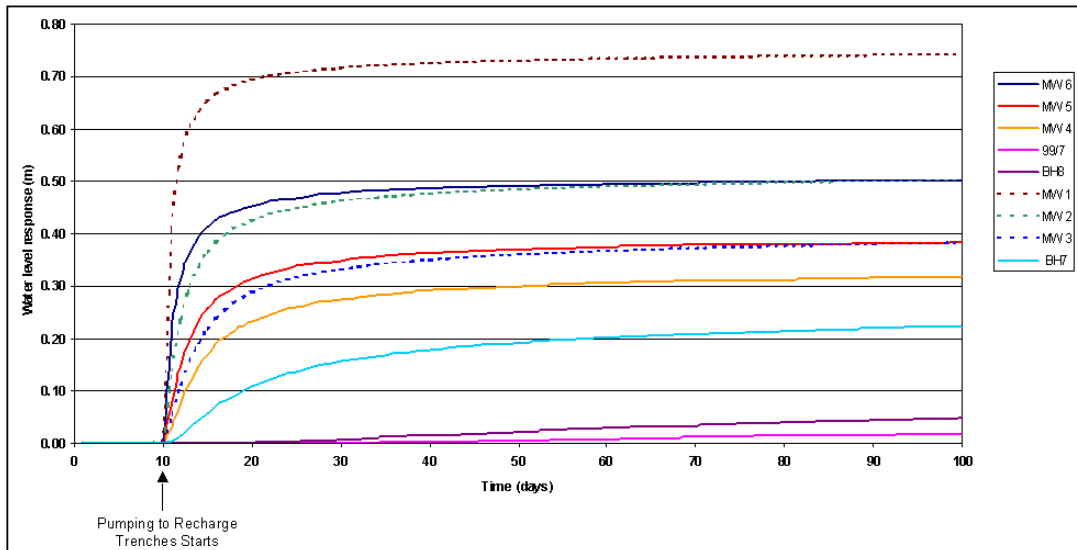


Figure 5.3: Model hydrographs

5.5.4 The impact due to the difference in the conductance value was clearly shown by the modelled groundwater levels, in the monitoring wells near to the trench, when the results of the three transient simulations were compared. Figure 5.4 shows the levels in MW 1 for the 3 simulations. The immediate response of the groundwater levels was almost directly proportional to the conductance value of the trench, as the rise in head levels increased by a factor of approximately 1.8 as the conductance of the trench was increased by a factor of 2. Over the longer term as the head levels reached a steady state this changed with the head level rise increasing by a factor 1.5 as the conductance was increased by a factor of 2.

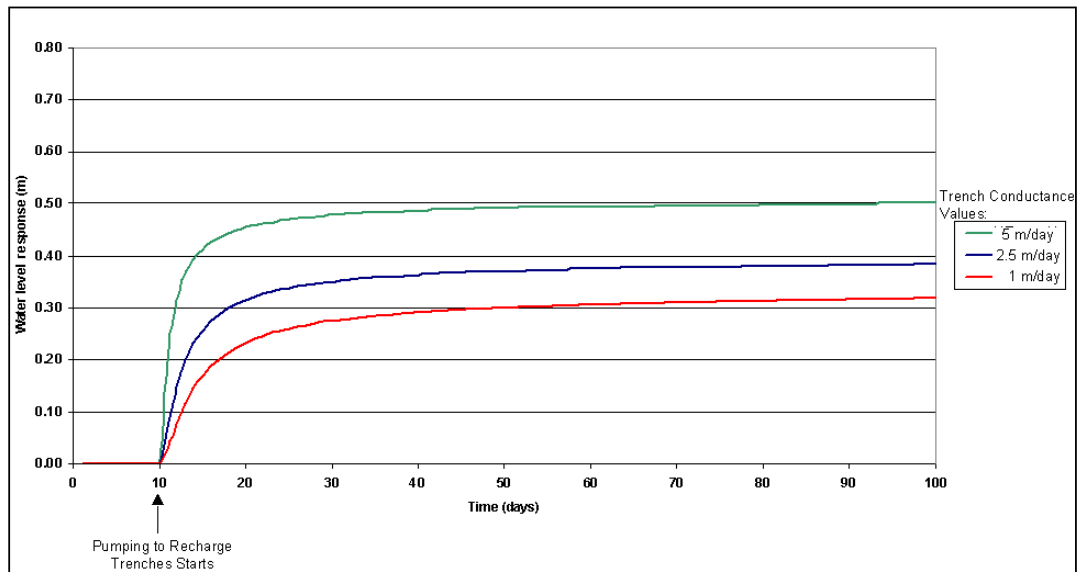


Figure 5.4: Modelled response of groundwater levels in MW1 for different trench conductance values

5.5.5 The mass balance for the general head boundaries that represent the recharge trenches allows the volumes of water that need to be pumped to the trench to be examined. It was found that approximately 1,000 m³/day was needed to be pumped into the trenches in order to maintain the modelled 0.5 m rise.

5.5.6 The mass balance results (see below) also showed that volumes of water seeping from the trench into the aquifer reduced. This was because initially, groundwater levels rose as water is taken into storage. The long-term steady state condition required no further water for storage change, with the recharge features acting only to maintain the head level.

Model Simulation	Trench 1			Trench 2		
	Conductance (m/day)	Volume of water (m ³ /day)		Conductance (m/day)	Volume of water (m ³ /day)	
		Day 11	Day 40		Day 11	Day 40
MTrans 11	5.0	379	350	10.0	612	549
MTrans 12	2.5	201	190	10.0	612	557
MTrans 13	1.0	84	80	10.0	612	556

Table 5.2: Model mass balance results showing initial volumes and steady state volumes

- 5.5.7 The on-site experiment involved water being pumped from the clean water lagoon up to the recharge trenches. A proportion of this water was expected to return directly, via groundwater, to the clean water lagoon. The results of the model mass balance showed that initially approximately 30% of the water pumped into the trench returned to the clean water lagoon. This meant that up to 70% (approximately 613 m³/day) of the water pumped to the trench would have been recharged to groundwater and flow in the general direction of Mickletown Ings.
- 5.5.8 However with time, as groundwater levels rose and reached a steady state condition the amount of water returning, via groundwater, to the lagoon increased. After 30 days the model mass balance showed that up to 80 % (approximately 700 m³/day) of the water pumped to the trench would be expected to return, via groundwater, to the lagoon. Therefore only a net volume of 200 m³/day of recharged groundwater would flow in the direction of the Ings after 30 days.
- 5.5.9 The mass balance also confirmed the impact of reducing the conductance of the trench, with the volumes of water seeping from the trench to be reduced by approximately 40 % as the conductance was halved.
- 5.5.10 The model results also showed that the recharging through the trenches had no effect on the Mickletown Ings SSSI. The groundwater monitoring well 7/99, located near to the edge of the Ings, showed only a small increase in the groundwater level after 90 days (0.01 m increase).

Dry and Drought Simulations

- 5.5.11 The dry and drought simulations were used to examine the likely response of recharging through the trenches during drier periods where the groundwater level would be expected to be lower. These simulations were also used to examine in more detail the depth needed to prevent perching of the water in the trench, the effects of changing the size of the trench, different values for hydraulic conductivity of the trench base and sides and the volumes of water required to achieve the modelled response.
- 5.5.12 Imposing the dry and drought conditions in the model lowered the initial groundwater levels. In the area near to the dewatering constant head boundary and the location of the recharge trench, the initial head in the monitoring wells was only slightly lower than the normal conditions, with the heads in MW 6 being 8.15 m AOD (normal), 7.94 m AOD (dry) and 7.89 m AOD (drought).
- 5.5.13 Further away from the quarry site, especially near to the Mickletown Ings SSSI, the change in head between the different conditions was greater. Initial water levels in the monitoring well 7/99 show the initial water levels to be 9.96 m AOD (normal), 9.60 m AOD (dry) and 9.50 m AOD (drought). Most significantly the groundwater level in BH8 fell below the trigger level of 9.40 m AOD for both the dry and the drought models, showing that conditions are suitable for mitigation measures used to raise the groundwater level.

- 5.5.14 The model hydrographs for the dry and drought model conditions showed lower initial groundwater levels, but a similar response to the recharging and a greater volume of water flowing from the trench into the aquifer.
- 5.5.15 The comparison of the water levels between the three different conditions in MW 6, where a conductance of 5 m/day was applied to Trench 1, showed water levels, after 30 days of recharging, to increase by 0.41 m in the dry conditions and 0.43 m in the drought conditions, rising to 8.35 m and 8.32 m AOD, respectively. This was compared to the rise of 0.49 m for the normal conditions simulation rising to 8.54 m AOD, although this water level may have shown some influence from Trench 2.
- 5.5.16 The head levels in the monitoring wells in the drier simulations showed the response to recharging to reach a steady state level much sooner than in the normal conditions models. Where the groundwater levels for the normal models was showing a steady state after 60 days, the dry models reach a steady level after 40 days and the drought conditions after only 30 days after the commencement of recharging.
- 5.5.17 The monitoring wells at a greater distance from the recharge trenches again showed a delayed response to recharging, with only very small, if any, rise in head. In the majority of the dry and drought simulations very little response was observed in monitoring well 7/99, with a maximum head change of 0.02 m (MTrans 21 and MTrans 31), only marginally greater than in the normal condition models.
- 5.5.18 The modelled groundwater levels in BH8 failed to recover to a level above the trigger level for any of the simulations for either the dry and drought periods, suggesting that the recharge trench at Methley quarry, at its current location, would not be adequate to mitigate the falling low groundwater levels at such a distance from the trench. However, in reality the site is not continuously dewatered during the summer, and hence such conditions are unlikely to occur.
- 5.5.19 Table 5.3 shows this response in terms of increasing either the depth or the width of the recharge trench, by comparing the groundwater response after 30 days of recharging. The conductance value was varied, whilst maintaining a constant hydraulic conductivity. Each of the conductance values showed either the width or the depth of the trench to have been doubled. The head values in each of the monitoring wells shows that by doubling the size of the trench the response in the groundwater levels, in the monitoring wells close to the trench, increased by approximately 60 %.
- 5.5.20 This same pattern was shown by the mass balance for the recharge trench. The volume of water flowing from the trench into the aquifer also increasing by approximately 60 % as the size of the trench (the depth or width) is doubled.
- 5.5.21 It is not possible to accurately determine whether the water in the trench would become perched above the groundwater in a one layer model. Looking at the response of the water table below the trench there is no evidence that water would become perched.

Conductance (m ² /day)	Hydraulic Conductivity (m/day)	Depth (m)	Width (m)	Water level (m AOD)			Model recharge volume (m ³ /day)
				MW 6	MW 5	MW 4	
Dry							
5	5	1	1	0.41	0.26	0.18	355
10	5	1	2	0.68	0.43	0.31	620
10	5	2	1	0.68	0.43	0.31	620
20	5	2	2	1.03	0.67	0.48	1008
Drought							
5	5	1	1	0.41	0.26	0.18	372
10	5	1	2	0.68	0.43	0.31	647
10	5	2	1	0.68	0.43	0.31	647
20	5	2	2	1.03	0.67	0.48	1049

Table 5.3: Impact of increasing recharge trench size on modelled groundwater levels

5.5.22 Table 5.4 below shows the response to changing the conductance of the trench with respect to the hydraulic conductivity of the base and the walls of the recharge trench, with the hydraulic conductivity varying and the size (width and depth) of the trench kept constant.

5.5.23 The range of the conductance values used in the model has provided a good assessment of the maximum and minimum levels that will provide a response in the groundwater level. The model simulations with a conductance value in the trench of 20 m²/day showed a large and immediate response in the groundwater level, while the models with a low conductance value of 1 m²/day showed very little change in the groundwater levels in the monitoring wells.

Conductance (m ² /day)	Hydraulic Conductivity (m/day)	Depth (m)	Width (m)	Water level (m AOD)			Model recharge volume (m ³ /day)
				MW 6	MW 5	MW 4	
Dry							
1	1	1	1	0.10	0.06	0.04	82
2.5	2.5	1	1	0.23	0.14	0.10	193
5	5	1	1	0.41	0.26	0.18	355
10	10	1	1	0.68	0.43	0.31	620
20	20	1	1	1.03	0.67	0.48	1008
Drought							
1	1	1	1	0.11	0.06	0.04	86
2.5	2.5	1	1	0.24	0.15	0.10	203
5	5	1	1	0.43	0.27	0.19	372
10	10	1	1	0.70	0.45	0.32	647
20	20	1	1	1.06	0.70	0.51	1049

Table 5.4: Impact of increasing the hydraulic conductivity of the recharge trench on model groundwater levels

5.5.24 Altering the level of head in the general head boundary can control the volumes of water that are flowing from the recharge trench into the aquifer. Three levels for the head in the boundary were selected: 11 m, 10.5 m and 10 m AOD. The mass balance for the boundary showed that the impact of lowering the head from 11 m to 10.5 m AOD reduces the volume of water flowing out of the boundary by 15 %. Reducing the head between 10.5 m to 10 m AOD, acts to reduce the volume of water by a further 20 % (i.e. a reduction in volume by 35% for a 1 m drop in head level within the trench).

- 5.5.25 The mass balance results showed that the drier the conditions the larger the volume of water that was required to achieve the modelled groundwater response.
- 5.5.26 The modelled water levels in the monitoring wells near to the trench showed that the groundwater response is directly proportional to the volumes of water seeping from the trench. The results showed that reducing the volume of water by 20 % reduced the increase in the head in the monitoring wells by 20 %.
- 5.5.27 The mass balance, for both the dry and drought models, shows a proportion of the water that flowed out of the trench returned directly, via groundwater, to the clean water lagoon in the excavation area. This proportion was similar to that in the model for the normal conditions, with initially 30 % of the water returning to the lagoon, increasing to 80 % as the groundwater reached a steady level.

5.6. Experiment

Overview

- 5.6.1 The aim of the Methley quarry experiment was to collect actual quantitative data as to how an existing zone of dewatering influence responded to recharging. This data was then used as a comparison to the model results to determine the accuracy of the short-term predictions.
- 5.6.2 The existing recharge trench at the site was over 200 m in length, and since being excavated a number of years ago had become silted and overgrown with vegetation. The trench was subdivided into two sections, with clay bunds at each end to separate each section from the rest of the trench. In order to quantify the influence of vegetation and siltation, Trench 1 was left in its current overgrown state whilst Trench 2 was cleared such that its base was once again within the sands and gravels. The section of the trench used for Trench 2 was originally shallower than Trench 1 and so was deepened and widened so that the two sections of trench were of similar dimensions.
- 5.6.3 The experiment involved pumping water to the recharge trench from the nearby clean water lagoon for a two week period, with water levels in the trench controlled using overflow pipes, that discharged any excess water to the nearby open water lagoon. Groundwater levels were continuously monitored (within monitoring wells screened over the thickness of the sand and gravel aquifer) along with discharge rates and the water level inside the trench.
- 5.6.4 Figure 5.2, shows the location of the recharge trench sections and the position of the monitoring wells. The two trench sections were 50 m in length. The south-easterly boundary of the trench comprised a sand embankment, where the excavation of sand and gravel had been completed to within a couple of metres of the trench location.
- 5.6.5 Pumping to the trenches used two 6-inch diesel driven pumps with regulators to help to control the flow rate, allowing discharge rates of 6 l/s to be achieved which were monitored by flow meters attached to the pipe line leading up to the trench. Water was pumped to the trench from the nearby open clean water lagoon. As the water level in the trenches reached the maximum level the pumping rate was reduced to help to maintain a constant water level in the trench.
- 5.6.6 Overflow from the trenches was achieved by inserting pipes just below the top of the sand embankment. The pipe allowed water to return to the nearby open water. Overflow from the trenches was kept as low as possible by altering the flow rate on the pumps.
- 5.6.7 Some operational difficulties were experienced while pumping to the trenches, which resulted in periods where pumping had to stop. When pumping initially started in Trench 1 the clay bund at the north-east end of the trench was found to be leaking, after only 1 hr 45 mins. Pumping stopped until this leak could be repaired. Pumping to the trench restarted two days later only for a failure to occur in the sand embankment around the position of the overflow pipe. This resulted in a 3 m wide section of the embankment collapsing and the trench having to be abandoned. Photos of the failure can be seen in Appendix B.

5.6.8 This may have been due to the fact that it is possible that water entered the embankment flowing back towards the lagoon area, particularly below the overflow pipe, became saturated and thus the slope was no longer stable and failure occurred.

Experiment Results

5.6.9 Although pumping to Trench 1 (the vegetated trench) only proceeded for two short periods, the hydrographs from the monitoring wells near to the trench showed that this was enough to have some impact on the groundwater levels.

5.6.10 The hydrographs from the six nearby monitoring wells show two peaks in the water level as a result of the two periods of pumping (Figure 5.5). The first period of pumping occurred for 2 hours with an almost immediate response in the groundwater levels in monitoring wells MW 6, MW 7, MW 8 and MW 12 with peak groundwater levels approximately 40 cm above the initial levels, following approximately 12 hours later (a rate of 3.3 cm/hr). In monitoring wells MW 4 and MW 5 the response is more delayed, with a peak coming approximately 18 hours later, and only a rise in water levels of 20 cm (MW 5) and 15 cm (MW 4).

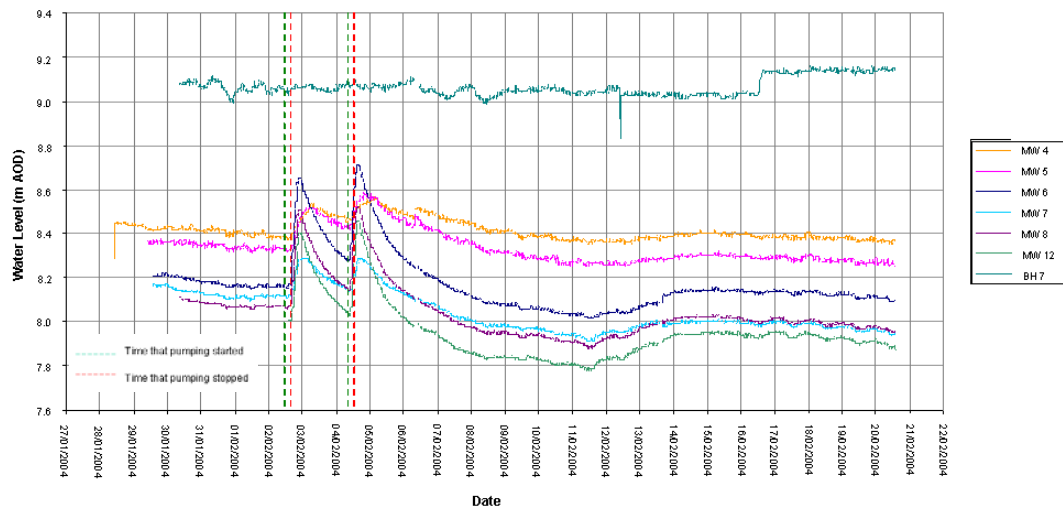


Figure 5.5: Experiment hydrographs of monitoring wells near to Trench 1

5.6.11 Pumping to Trench 2 (the cleared out trench) occurred continuously for the two week period, only stopping for a short period of 6 hours while the position of the overflow pipe was adjusted.

5.6.12 The hydrographs in the monitoring wells surrounding Trench 2 show the groundwater levels to respond almost immediately to recharging, with water levels rising by 30 to 40 cm after 24 hours (a rate of 1.7 cm/hr) in the wells nearest the trench (MW 1, MW 9, MW 10 and MW 11). Again the monitoring wells at more of a distance (MW 2 and MW 3) showed a slightly delayed and smaller response (Figure 5.6).

5.6.13 In all of the monitoring wells near to Trench 2 the rate of the rise in the water levels slowed and got close to a steady state level after 3 days of recharging. The impact of stopping the pumping during the second day wasn't obvious in the hydrographs, apart from possibly in MW 3, where a dip in the water level could be seen to follow soon afterwards.

5.6.14 The steady state water levels were observed to be between 8.6 and 8.8 m AOD, below the pre-dewatering background level of between 9 and 10 m AOD

5.6.15 After pumping to the trench stopped water levels began to decline in the boreholes within 12 hours, and decrease at a similar rate to the initial response to pumping. Water levels were found to return to original levels within seven days, and had begun to fall below the original levels in some of the monitoring wells.

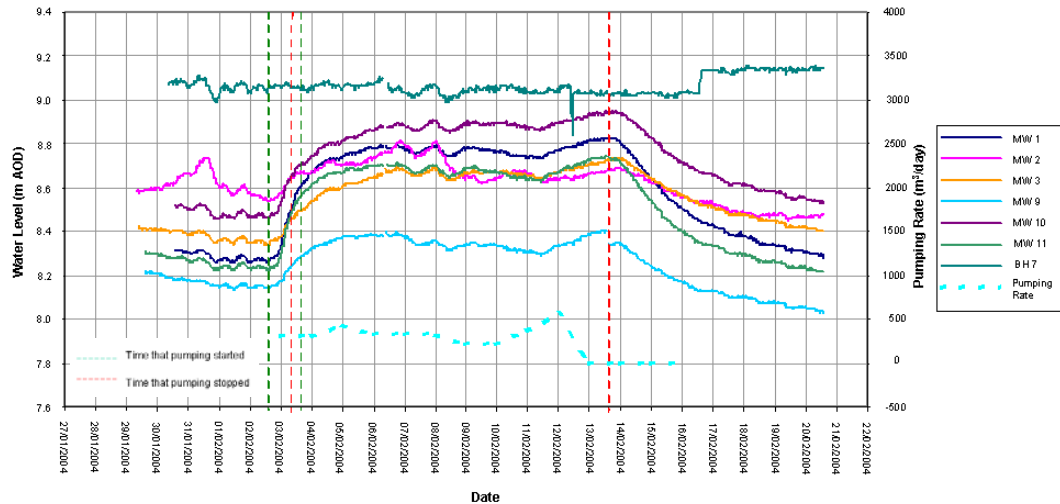


Figure 5.6: Experiment hydrographs of monitoring wells near to Trench 2

5.6.16 Water levels in BH 7, approximately 50 m away from the trenches, were also monitored. The hydrograph for this borehole showed no obvious response to recharging to the trenches for the period of the experiment. Only fluctuations attributed to natural environmental factors could be seen, suggesting that the influence of the trench was a localised effect.

5.7. Comparison of model and experimental results

5.7.1 Figures 5.7 and 5.8 show the comparison of the hydrographs from the groundwater model and from the experiment for monitoring wells MW 4, MW 5 and MW 6 (Trench 1) and MW 1, MW 2 and MW 3 (Trench 2).

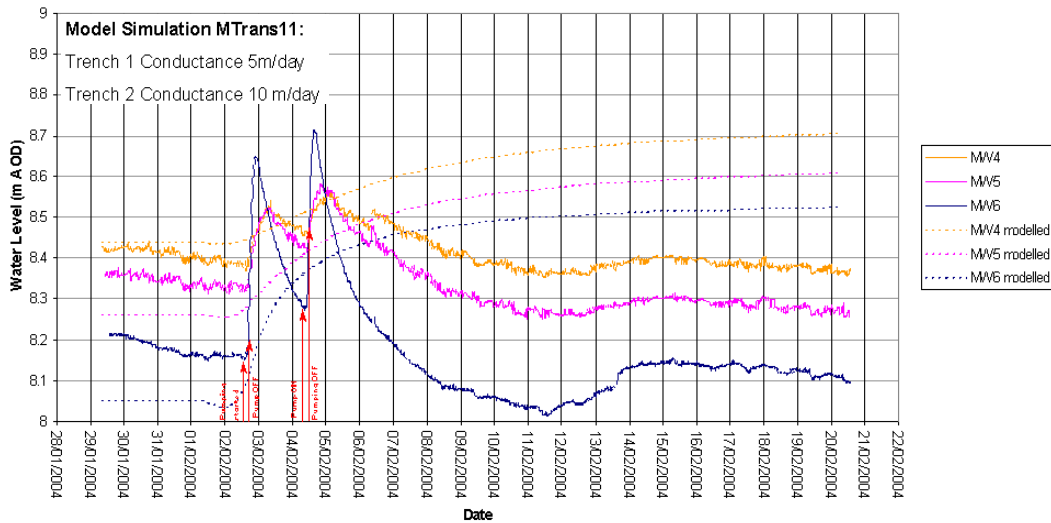


Figure 5.7: Comparison of Trench 1 model results with experimental results

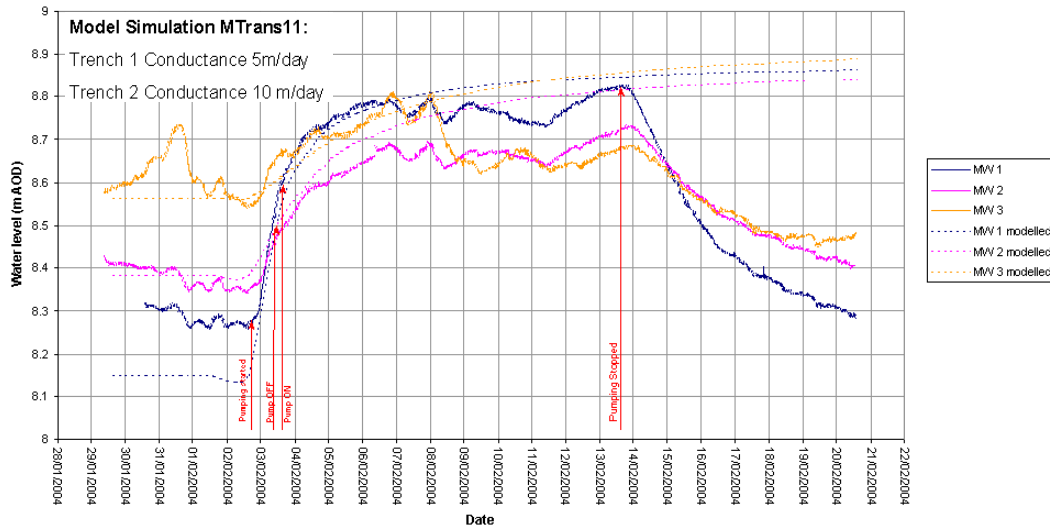


Figure 5.8: Comparison of Trench 2 model results with experimental results

- 5.7.2 The hydrographs for the monitoring wells near to Trench 2 show quite a close correlation to the modelled results with the water level rise seen to occur at a similar rate. While the rate of water discharging to the trench compared reasonably well to the mass balance volumes infiltrating through the base of the trench.
- 5.7.3 The model results showed a fairly accurate prediction of the rates at which the water levels would increase following the commencement of recharging. The predicted water levels, following recharging, were less accurate. The modelled initial head for MW 1 was found to be lower than the experimental data by approximately 10 cm, although for MW 2 and MW 3 the initial data showed a better correlation. The model hydrographs also showed the total rise in head to be greater than the experiment results, by up to 10 to 15 cm. This may however be due to the rise in the water level in the experiment being restricted by variations in the pumping rate.
- 5.7.4 The comparison of the results for the monitoring wells near to Trench 1 is more difficult due to the failure of the trench wall and the subsequently limited dataset. By comparing the initial 12 hour response that was observed in the monitoring wells for the first period of pumping it can be seen that the model predictions are less accurate than for Trench 2.
- 5.7.5 The model hydrographs are taken from the simulation MTrans 11, where the hydraulic conductivity of the trench was set as 5 m/day (the highest value used for Trench 1 in normal condition models). The initial heads, before recharging, were less accurate, although all within 10 cm of the real data. The main inaccuracy is shown by the rate of the initial head rise, with the real data responding at a greater rate than the model results, suggesting that the vegetation didn't have as large an influence on the efficiency of the trench as was considered in the model.
- 5.7.6 The water levels in this first 12 hour period of the experiment also showed the head in each of the wells to rise above what was predicted in the model, which is exemplified by MW 6, which shows the water level after 12 hours to be approximately 20 cm greater for the experimental data than the maximum steady state head that had been predicted by the model.
- 5.7.7 Figure 5.9 shows the comparison between the modelled and experimental data in BH 7. The monitoring well was located approximately 50 metres away from the position of the two trenches. No response to the recharging, in the experiment data, could be seen in BH 7 during the period that water was being pumped to the trench. However the model results predicted a delayed response, with up to a 5 cm rise in the head level, in the borehole within the duration of the experiment.

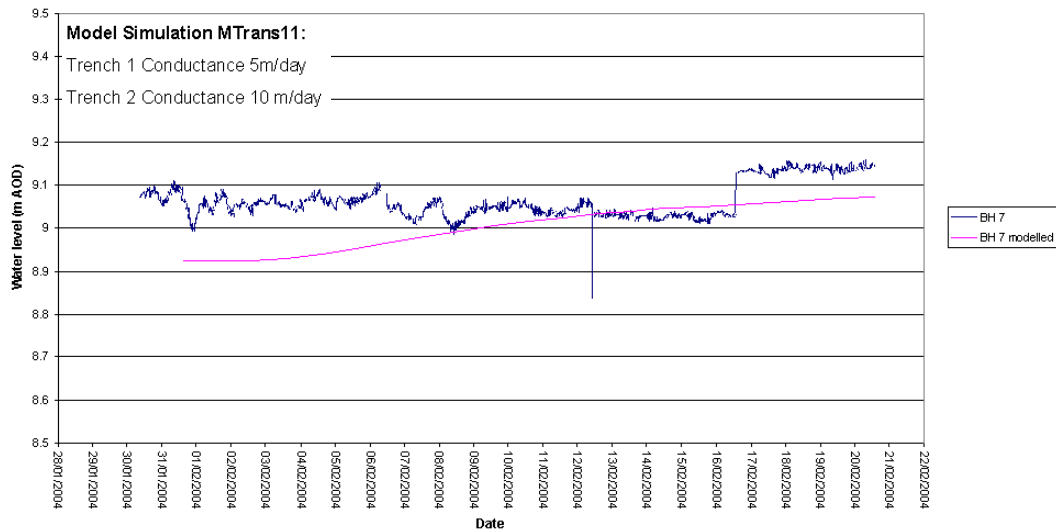


Figure 5.9: Comparison of model results and experimental results for BH7

5.7.8 This suggests that the model is less accurate at a greater distance from the trench, over estimating the influence that the trench would have.

5.8. Experiment 2 Summary

5.8.1 Both the experiment results and the model results showed that groundwater responded almost immediately to the commencement of recharging, with the majority of the rise in groundwater levels occurring within the first few days. The onsite experiment showed water levels to have risen by up to 0.5 m and reached what appeared to be steady state level within the two week experimental period. However the water levels failed to reach the pre-dewatering background levels.

5.8.2 The model results for the normal conditions did provide a good comparison to the experimental results for Trench 2, predicting a similar rate that the water levels would raise, and was within 15 cm of the steady state water level. The amount of water that would be required to be pumped to the trench to obtain the observed response was also predicted within the same order of magnitude.

5.8.3 The impact of recharging through the trenches is modelled to have a relatively localised effect on the groundwater levels. The water levels in the monitoring wells close to the trenches showed quite a large response with groundwater levels rising by up to 0.7 m above the original levels. However this response diminished with distance, with only a small response modelled in monitoring wells BH7 and an almost insignificant response in BH8 and 7/99.

5.8.4 This response of the groundwater at distance was predicted to be greater than what was actually observed in the experimental results. Water levels in BH 7, 50 m from the position of the recharge trench showed no response in the experimental data, compared to a delayed response and a 10 cm rise in head predicted by the model.

5.8.5 These results would suggest that, in isolation, the recharge trench, in its current location and of its current size, would potentially not be adequate to mitigate any impact on the Mickletown Ings SSSI if the quarry dewatering were to cause the water levels to fall below the trigger levels. However, it is likely that the Methley quarry is at a great enough distance not to impact the water levels in the SSSI. The dewatering at the quarry site has never been proven to have an impact on the Mickletown Ings, with previous low water levels in the ponds being due to the opencast coal excavation to the north of the area. Were the quarry dewatering found to effect the SSSI, then the recharge trench would not be used as the only mitigation measure but as part of a layered mitigation strategy.

- 5.8.6 The position of the trench at the site is not directly between the main area of dewatering and the Mickletown Ings SSSI, although the clean-water lagoon in the model does act as a sink to the groundwater. Changing the position of the trench in the model is a recommendation for further work, allowing the optimum position of the trench to be determined.
- 5.8.7 The limited data that was obtained from the experiment for Trench 1, would suggest that the vegetation in the trench wouldn't have as much of an influence as had been expected when the model was constructed. This is taken from the large response that was observed following only two short periods of recharging.
- 5.8.8 The effect of changing the conductance of the trench, in the groundwater model, has shown that the modelled groundwater responses were quite sensitive to small changes in the trench properties. The response of the groundwater changes almost proportionally to changing the internal surface area of the trench (depth and width) and to changing the hydraulic conductivity of the base and the sides of the trench. The range of hydraulic conductivity values show that by reducing the hydraulic conductivity from 10 m/day to 1 m/day, the groundwater response changes from a large response of 0.5 m rise in the water levels to a small insignificant change.
- 5.8.9 The range of response of the groundwater to different volumes of water was also considerable, with the rise in the groundwater level changing proportionately to the change in the head level at the boundary. The volumes of water that were required to be pumped to the trench were simulated as only a small fraction of the volumes of water that can be drawn from the groundwater through the dewatering.
- 5.8.10 The results showed a large portion of the water that was flowing from the trench into groundwater was returning directly to the excavation area of the quarry, with up to 80 % of the water returning after 30 days of recharging. Over the long term recharging the trench acts to maintain the increased water levels in the direction that is required (towards the SSSI) however large amount of water will return to the excavation.
- 5.8.11 The experiment highlighted issues concerning the design and operation of recharge features. The excavation of material to within a few m of the trench left the sand embankment unstable and a collapse occurred. The collapse of the sand embankment resulted in that 50 m section of the trench having to be abandoned, while safety issues for any personnel working near to the trench were addressed. The original design of the trench allowed for the provision of a clay barrier to support the embankment, mainly to restrict the water flowing back into the excavation. Such a barrier should help to restrict the risk of such a collapse occurring.
- 5.8.12 Further detailed information may be found in Symonds Group's report (2004b).

6. LEGISLATION, RESPONSIBILITIES AND CONSENTS

6.1. Legislation

- 6.1.1 Various pieces of environmental legislation provide mechanisms to restrict the extent to which any form of development (including surface mineral working and associated features) is permitted to affect the water environment.
- 6.1.2 Key UK legislation includes the Water Act 1989; Environmental Protection Act 1990; the Water Resources Act 1991; the Water Industry Act 1991; the Environmental Protection (Duty of Care) Regulations 1991; the Land Drainage Act 1994; the Environment Act 1995; the Groundwater Regulations 1998; Water Supply (Water Quality) Regulations 2000; the Landfill (England and Wales) Regulations 2003; and most recently the Water Act 2003 together with the Water Environment (Water Framework Directive) (England and Wales) Regulations 2003.
- 6.1.3 Forthcoming European directives which are currently in preparation, include daughter directives to the Water Framework Directive for 'groundwater' (currently in draft) and 'priority substances' (due in draft by the end of 2004).
- 6.1.4 Additional legislation concerning designated nature conservation sites may also be relevant where impacts on the water environment could have an indirect 'knock-on' effect on natural habitats. Directives 79/409/EEC on the conservation of wild birds, and 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (the Habitats Directive) are particularly important in this respect. In Great Britain the requirements of this EU Directive are implemented through the Conservation (Natural Habitats) Regulations 1994. Sites which are designated as (candidate) Special Areas of Conservation (cSACs) or Special Protection Area (SPAs) are afforded the highest levels of environmental protection.

6.2. Responsibilities and Consents

- 6.2.1 The primary responsibility for protecting the water environment within England (& Wales) is that of the Environment Agency. The statutory powers of the Agency with respect to controlling impacts on the water environment are restricted, however, with their main direct powers being the licensing of:
 - (i) Groundwater and Surface Water Abstractions (which currently exclude quarry dewatering, but this will change in 2005 – see below);
 - (ii) Discharges (to both groundwater and surface water); and
 - (iii) Waste disposal / waste management operations.
- 6.2.2 Indirectly, the Environment Agency can also exert control through its role as a Statutory Consultee within the Town and Country Planning System. By this means, the Agency is able to provide advice to Local Planning Authorities regarding whether or not specific plans and proposals are acceptable, in their view, in terms of potential impacts on the water environment, and what conditions (and/or 'Section 106' legal agreements) may need to be attached to planning permissions in order to avoid or minimise those impacts if the proposed development were to go ahead. Local Planning Authorities generally accept such advice but they are not obliged to do so, since other material considerations, including the basic need for mineral extraction, may be seen to outweigh the Agency's concerns in some cases.
- 6.2.3 At present, the Agency relies on its role as a statutory consultee to exert control on quarry dewatering and, for the majority of recharge features proposed for use in the past, that have been identified in this research, Section 106 legal agreements have been used to define both the proposals for these and certain aspects of their operation.

- 6.2.4 In most cases, the operation of a recharge feature (whether it be a trench or an injection well) will also require a discharge consent to be issued by the Environment Agency in accordance with Section 85 of WRA 1991, and the Groundwater Regulations 1998. The regulations cover discharges to groundwater and surface water and require 'List I' substances to be prevented from entering the water environment in discernible quantities (i.e. above detection limits). They also require concentrations of 'List II' substances to be minimised to prevent pollution. Under the Groundwater Regulations, should List I substances be present in the abstracted groundwater, then they may be authorised for disposal into groundwater, after prior investigation, if the water is re-injected into the same aquifer from which it was originally pumped⁵.
- 6.2.5 From 2005, the implementation of the Water Act 2003 will give the Environment Agency greater direct control of both abstraction (including quarry dewatering) and discharge, through the use of 'water transfer licenses'. These will take account of the way in which the abstracted water is used and, in particular, whether or not it is returned to the same or a different 'source' after being abstracted. **Recharge features, which are specifically designed to return the water to the source from which it is abstracted, offer clear advantages in this regard.**
- 6.2.6 A further consequence of the Water Act 2003 is that, from 2005, 'Section 32' consents will be required when undertaking a pumping test as part of a hydrogeological investigation leading to an abstraction license application.
- 6.2.7 For development within the floodplain (where recharge features are commonly proposed), there may additional requirements for Land Drainage consents, issued by the Environment Agency under the Land Drainage Act 1994. This applies especially to features, such as mounds of excavated material, which could restrict or divert the flow of floodwater. Even small quantities of material that are stored on the floodplain – for example during the experimental trials of a proposed recharge feature – are likely to require such consent.
- 6.2.8 It is important for mineral operators to consult with the Environment Agency at the earliest possible stage in order to establish the exact nature of any licences and supporting information that may be required. This should be done at least 6 to 9 months in advance of when a recharge feature may be required. Considerably greater periods may be required to allow for supporting site investigation and baseline monitoring work if this has not already been obtained: again, it is advisable for such requirements to be discussed with the Agency in advance.

⁵ This will change as a result of the Water Framework Directive in 2012

7. IMPLICATIONS OF THE RESEARCH FINDINGS: TECHNICAL CONSIDERATIONS

7.1. Introduction

- 7.1.1 This research has brought together existing information on the theory of artificial recharge (largely from published literature on Aquifer Storage Recovery (ASR) and drainage design) with case studies on the implementation of recharge features to mitigate the effects of quarry dewatering and with the findings of two preliminary experiments to investigate how the effectiveness of such features can be optimised. It has also looked into some aspects of the planning and legislative background.
- 7.1.2 Very little information has hitherto been published on this subject. The ASR work, though very useful in respect of some of the design issues associated with injection wells and recharge trenches, is concerned more with optimising the volume of groundwater which may be stored rather than restoring and maintaining specific groundwater levels.
- 7.1.3 Similarly, the theory of soakaway design is primarily concerned with optimising the volume of water which can be discharged. When used to mitigate the drawdown induced by quarry dewatering, it is important to understand the volumes and rates of flow involved, but the main emphasis has to be on groundwater levels.
- 7.1.4 Despite the collation of new case study information from mineral operators, there is still very little clear evidence on the extent to which recharge features have actually succeeded in their objective (in some cases, the proposed features were never actually used, since no adverse impacts of the dewatering were detected).
- 7.1.5 The two preliminary experiments carried out as part of this research have therefore been invaluable in highlighting some of the practical issues involved in both gaining acceptance of the proposed use of such features as a mitigation measure and in optimising their efficiency.
- 7.1.6 In addition to the experiments and the field monitoring data, the steady state and transient groundwater modelling has made it possible to run a number of scenarios in which some of the potential key factors influencing the efficiency of recharge features (i.e. trench dimensions and the permeability of trench basal deposits) are varied.
- 7.1.7 There is still some way to go before all of the necessary issues have been explored but a number of useful implications are now beginning to emerge. This Chapter deals with some of the scientific issues that have been identified, and Chapter 8 deals with other important practical issues, including planning and licensing.

7.2. Groundwater chemistry, biology & suspended solids content

- 7.2.1 The main concern expressed in published literature, and reference design guides, related to the potential reduction in infiltration capacity with time as a result of clogging with fines, micro-organisms, or precipitates as a result of exposing groundwater at the surface and mixing waters of different chemistries.
- 7.2.2 Consideration of the groundwater chemistry has been shown to be important. In the case of Eversley Quarry, trial recharge trenches became rapidly clogged with iron oxide deposits within the space of only a few days as a result of low pH groundwaters, with high iron concentrations, being discharged at surface.

- 7.2.3 Experiments undertaken at the Rocky Mountain Arsenal in the early 1990s found that sedimentation and microbial fouling tended to be restricted to the gravel filled trench and that it had not progressed far into the aquifer. It was observed that 100 days (over 3 months) after recharging of the trench with water laden with sediment and micro-organisms significant reductions in recharge rates were observed. However, when only sediment laden water was injected into the gravel filled trench, a reduction in recharge rates was only observed after 160 days (nearly 5 months).
- 7.2.4 This suggests that precipitation of chemical oxides is likely to have a greater immediate impact on recharge rates, whilst micro-organism growth will lead to a reduction in infiltration capacity over a period of a few months. In the case of sediment laden water, however, it may be suggested that infiltration capacity is unlikely to be affected for a number of months (up to 6 months potentially). This is supported by the fact that few examples of clogging of soakaways were reported in either technical or academic press (Pratt, 2001).
- 7.2.5 This suggests that regular maintenance to prevent the build up of sediment allows trenches to operate successfully for considerable periods of time. Indeed where this has been undertaken in some case studies (such as Efford Landfill) no such clogging problems have occurred.
- 7.2.6 It has not yet been possible to investigate these long-term clogging issues in the field experiments, since these were of limited duration. In the case of Methley Quarry, however, groundwater modelling using differing scenarios with increasingly lower permeability values for the base of the trench, was used to simulate the effects of clogging. It was found that when permeability values were increased by a factor of 10, recharge volumes to the underlying aquifer increased by a factor of 7.5. Overall it was found that regardless of permeability, a similar immediate response was observed in the groundwater levels near to the trench, although the eventual rise in head is very much dependent on the permeability of the trench base.

7.3. Groundwater level response – short term

- 7.3.1 In both experiments undertaken as part of this research project it was observed that groundwater levels responded swiftly at the start of discharging to the recharge trenches, suggesting that there was very little delayed response. With pre-recharging groundwater levels less than one metre below the base of the trenches (and even less when the height of the capillary fringe is taken into account) it may be seen that the intervening sand and gravel deposits reached field capacity almost instantaneously allowing recharge water to drain under gravity immediately.
- 7.3.2 At Chamberhouse Farm, given that the deposits had only recently been drained of groundwater, it is not unexpected that the retained moisture content may still be high or near field capacity. In the case of Methley Quarry, where a zone of dewatering influence had been established for a number of years, this was not the case.
- 7.3.3 The groundwater levels were seen to rise by 0.5 m to 0.6 m, within the space of a few days, for both of the experiments. It might have been expected that the trench at Methley Quarry, being significantly larger than at Chamberhouse Farm, would have discharged a greater volume of water to the ground, resulting in a greater observed rise in the water level. However, similar volumes of water, discharged through the trenches, were achieved at the two sites, highlighting the importance of the hydraulic conductivity of the base of the trench, which is discussed further in Section 7.5.

- 7.3.4 In the case of both experiments, the majority of the rise in groundwater levels occurred within the first few days after recharging commenced. Following this the water level would have continued to rise at a slower rate as the recharging moved towards a steady state situation. Both of the experiments were conducted over a relatively short duration of 2 weeks and it is possible that a greater increase may have been seen if the experiments had continued for longer. Over a longer period it might be possible that the groundwater levels beyond the recharge trench are able to recover further from natural inputs of water, with the trench acting to 'shield' the effects of dewatering, but this can not be confirmed without running further experiments for a longer duration.
- 7.3.5 In the Chamberhouse Farm experiment, although the trenches used weren't able to recover the water levels to the pre-dewatering level they were observed to have mitigated the total drawdown created by pumping. This response is illustrated by Figure 4.12, where the recharging is superimposed on the drawdown curve, resulting in a reduced total drawdown in the surrounding aquifer. Theoretically locating the recharge feature closer to the protected feature, where the drawdown will be less, this response may be more effective in helping to maintain the groundwater levels.
- 7.3.6 The Methley Quarry experiment demonstrated that the localised influence of the recharge trenches extended to no more than approximately 50 m, although this is likely to be dependent on the permeability of the aquifer material. It also demonstrated that slope stability problems can arise when the recharge trench is located very close to the margins of the dewatered excavation. Both of these observations suggest, once again, that the trench would have been more beneficial if it had been located much closer to the protected feature. However, issues such as land ownership and consideration of the design and cost of a water delivery system may make this an unviable option, in this particular case, and an on-site alternative (such as a low permeability barrier to restrict the zone of dewatering influence) may need to be considered instead, if any adverse impacts on the protected feature are ever detected.
- 7.3.7 An alternative to using a recharge trench very close to a protected feature would be to discharge the water directly into that feature. This could work where the feature involved is an existing lake or surface watercourse or (in some cases) a wetland habitat, providing that the chemistry of the waters is compatible, and subject to careful control of both suspended sediment and potential scouring.

7.4. Groundwater level response – long term

- 7.4.1 Modelling of the Methley Quarry experiment indicated that the majority of groundwater level rise occurred within the first 20 days, with steady state recharged groundwater levels being reached after 60 days (a maximum predicted increase of 0.7 m).
- 7.4.2 This indicates that, although absolute groundwater level rises may be lower than required, they tend to occur in a short period of time following the start of recharging. Some delayed, but lower, response was observed at distance suggesting the propagation of a recharge front.
- 7.4.3 Both the Chamberhouse Farm and Methley Quarry experiments were characterised by relatively shallow groundwater levels comparatively closer to the base of the trench, which may explain this rapid response. In any future work it would be interesting to undertake similar experiments in a deeper water table aquifer setting to see what contrast there may be.

7.5. Trench efficiency

- 7.5.1 In the case of the Chamberhouse Farm experiment, representing an unsteady state scenario in the short term, Trench 1 was found to be more efficient, overall, than Trench 2 (i.e. a higher proportion of water discharged to Trench 1 returned to the ground rather than overflowing). The potential factors controlling this can be explained by examining Darcy's Law (Equation 4).

- 7.5.2 Darcy's law states that the rate that water flows through a porous medium is dependent on the hydraulic conductivity of the material, the cross sectional area and the hydraulic gradient. The two trenches at Chamberhouse Farm had a similar internal surface area and similar hydraulic conductivities, however, prior to recharging, there was a greater depth of unsaturated zone below the base of Trench 1.
- 7.5.3 As recharging commenced and the unsaturated zone beneath the trenches became progressively saturated, Trench 1 is likely to have developed a greater hydraulic gradient and hence discharged a greater volume of water into the aquifer.
- 7.5.4 The comparison for the two experimental sites show that, although the trench at Methley Quarry (172 m²) had a larger internal surface area than at Chamberhouse Farm (32 m²), similar volumes of water were being discharged through the trenches, resulting in a similar rise in groundwater levels in the near vicinity of the trenches. However the aquifer material at Methley Quarry was much less permeable than at Chamberhouse Farm, restricting the discharge of water from the trench into the aquifer.
- 7.5.5 As the hydraulic conductivity will be determined by the aquifer material at the specific site, in order to decrease the amount of water overflowing from the trench, and hence increase the efficiency of the trench, consideration should be given to spreading the discharge volume over a greater area, over which infiltration could occur, or increasing the hydraulic gradient between the water level in the trench and groundwater level by increasing the head level in the trench, which could be made possible by raising the sides of the trench above ground level.
- 7.5.6 This may become an important consideration if a recharge trench were to be located further from the excavation and nearer to the sensitive feature, where the drawdown of the water table will be less, hence it may be more difficult to obtain the necessary hydraulic gradient.
- 7.5.7 Modelling undertaken for Methley Quarry indicated that water levels and volumes entering the aquifer both increased by approximately 60% when the size of the trench (the internal surface area) was doubled (for the same permeability and hydraulic gradient values). This would suggest that the practice of increasing the surface area of the trench is only 60% efficient and should be taken into consideration.

7.6. Water balance

- 7.6.1 Results of the Chamberhouse Farm experiment show that a significant proportion of the water discharged to the recharge trenches was lost as overflow.
- 7.6.2 In order to enable a greater proportion of the water to enter the aquifer it may be necessary to either discharge to a trench with a significantly larger internal surface area (as discussed above), increase the depth of water stored within the trench (e.g. by bunds to raise water levels above ground level) in order to increase hydraulic gradients, or it may be necessary to store the abstracted water for periods when it may be required more (for example during the summer months) so that it is delivered at a more efficient, regulated rate.
- 7.6.3 Figure 7.1 shows the development of water balances during the dewatering and recharging processes, using results from both the Chamberhouse Farm and Methley Quarry experiments. The unsteady state zone of dewatering influence (a) represents the process that was found to have occurred at Chamberhouse Farm, where a continual decline in groundwater levels was observed. In this scenario the outputs are still significantly greater than the inputs and water is taken out of storage to compensate (with the associated drop in the groundwater levels). However, as discussed previously, the superposition of the recharging onto the effects of dewatering would result in less water being taken out of storage, limiting the extent of the zone of dewatering influence, compared to a scenario where there was no recharging taking place.

- 7.6.4 The commencement of recharging where a zone of dewatering influence was previously in steady state (Figure 7.1, b and c) represents the process that occurred at Methley Quarry. In this scenario the input of water into the area increases. This input of water will, in part, contribute to increased storage of water giving the resultant rise in groundwater levels and will also result in some increased outflow from the zone. Some of this increased outflow is likely to be back directly towards to the area being dewatered, resulting in a greater recycling of water. For example, the transient modelling of Methley Quarry indicated that during the early stages of recharging approximately 70% of water was going into storage, with the remaining 30% returning to the excavation.
- 7.6.5 With time, as the recharging approaches a steady state situation, the groundwater will stabilise at a new, higher equilibrium, with no further water going into storage. Figure 7.1c, represents a later time, where the recharging is beginning to approach a steady state, where approximately 20% of the recharged water goes into storage, with the majority (80%) returning to the quarry, creating a localised cycle of abstraction and recharging.
- 7.6.6 As previously noted, this inefficient re-circulation would be greatly reduced if the recharge feature were further away from the excavation: the situation at Methley represents a worse case scenario in this respect, but one that will, nevertheless, be encountered from time to time. In such circumstances, the amount of recirculation could be reduced by installing a low permeability barrier in between the excavation and the recharge feature. This option was modelled for Lafarge by Symonds at the Stonecastle Farm site (see Case Study 5) but further experimental work could usefully be done to assess the practicalities of this solution.

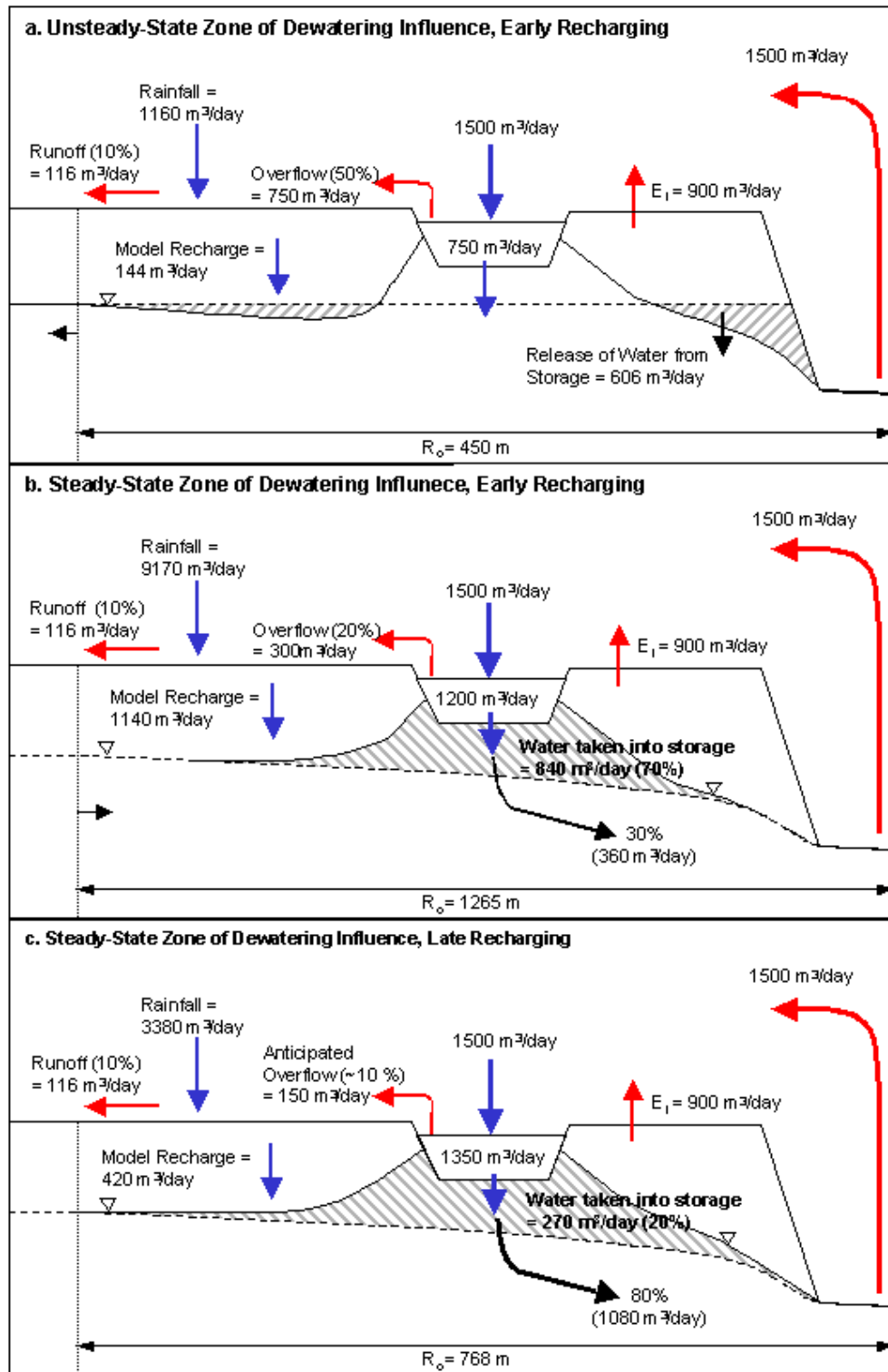


Figure 7.1: Water balance

7.7. Summary

- 7.7.1 Drawing on information from existing literature, newly documented case studies and the findings from two new field experiments, this research has been able to shed light on many of the factors that influence the efficiency of recharge features.
- 7.7.2 Whereas previous literature has focused largely on the way in which efficiency can be reduced, over time, due to the effects of 'clogging' with suspended sediment, the new experiments have allowed the short term behaviour of recharge features to be examined in more detail, in order to elucidate some of the essential design considerations.
- 7.7.3 Both experiments demonstrated that the recharge features are able to at least partly reverse the drawdown induced by dewatering. They also demonstrated that groundwater levels begin to respond as soon as recharging commences, although a delay may be expected at sites where the water table is at greater depth or the deposits are less permeable. Neither of the experiments was able to achieve a full recovery of the water table to pre-dewatering levels, but this was due partly to the limited duration of the trials and partly to the limited size of the trenches that were used.
- 7.7.4 In both cases, the response achieved was seen to be very localised, though this again is likely to have been affected by the time constraints, and a wider zone of response may be expected if the recharging were continued for longer. Once steady state conditions have been established, the width of this zone will depend on the permeability of the deposits.
- 7.7.5 In view of this, locating a recharge feature as close as possible to the stream, wetland or other feature requiring protection will clearly improve the chances of success in the early stages of mitigation. In the longer term, when recovery results from natural as well as artificial recharge (see para. 3.2.4, above), it may be less important to do this, but there are two other practical reasons for doing so.
- 7.7.6 Firstly, if the trench is located a long way from the quarry, a more limited increase in groundwater levels will be needed and the gradient towards the quarry (once recovery has been achieved) will be considerably reduced (thus reducing the rate of flow back towards the excavation); for both of these reasons, less water will need to be recharged. The reverse obviously pertains if the recharge feature is located very close to the quarry, when very high rates of flow can be induced, necessitating higher rates of dewatering.
- 7.7.7 Secondly, as clearly demonstrated in the Methley experiment, locating a recharge feature too close to the margins of the quarry may create a significant risk of both slope failure and catastrophic flooding. These issues would need to be considered as part of the routine Geotechnical Assessments carried out under the Quarry Regulations 1999.
- 7.7.8 Further improving the efficiency of a recharge feature may entail increasing the internal surface area or increasing the driving head by using bunds to raise the sides of the feature above ground (though this again would be subject to Geotechnical Assessment). The groundwater modelling undertaken at Methley has suggested that increasing the internal surface area may not be an entirely efficient process.
- 7.7.9 In situations when a recharge feature may not be fully suitable to mitigate the impact of dewatering alternative mitigation measures, or a combination, may need to be considered. For example the combined use of a low permeability barrier (in order to prevent the majority of the zone of dewatering influence evolving) and a recharge trench scheme to sensitively manage the input of abstracted water into the ground near to the feature to be protected.
- 7.7.10 Other combinations which may be considered include dewatering in smaller cells (in order to minimise the radius of dewatering influence) in combination with recharge features (trenches or injection wells). The correct design and approach will depend upon the site specific circumstances of the feature (whether ecological or man-made) to be protected.

- 7.7.11 Numerical modelling (as undertaken for the Methley Quarry experiment and in the Stonecastle Farm case study) may be a useful tool to explore the potential impact that some of these recharge features, or combinations of recharge features, may have in order to inform the design process.
- 7.7.12 Any future experimental work should consider looking at how combinations of mitigation measures may be employed.

8. IMPLICATIONS OF THE RESEARCH FINDINGS: DESIGN & PLANNING CONSIDERATIONS

- 8.1.1 The foregoing chapters have examined some of the technical issues relating to the use of artificial recharge features as a means of mitigating the potential adverse impacts of quarry dewatering. It is important to remember, however, that recharge features are only one of many techniques available and, more significantly, that potential impacts do not always occur. It will, therefore, not always be necessary to implement any specific measures, depending on local circumstances. Having said that, a prudent operator will normally take steps to assess potential impacts and to determine the best means of dealing with these, should they occur. The essential point is the mitigation works required of an operator should be 'fit for purpose' and designed to counter specific identified risks.
- 8.1.2 An essential first step in deciding what needs to be done is therefore to assess the potential risks through an understanding of the local groundwater and surface water system. Figure 8.1 outlines key aspects of the decision-making process that might be involved (for example in support of a planning application for quarrying below the water table).
- 8.1.3 Firstly, it is important to consider whether there are any vulnerable features (such as habitats, man-made structures, contaminated land, or groundwater resource needs) that may be affected by a reduction in groundwater levels or changes in groundwater flow paths. Secondly, the operator should consider whether dewatering is really necessary at the site (i.e. could wet working be a viable option)?
- 8.1.4 If dewatering is necessary and vulnerable features might be affected, then the next stage is to develop a conceptual model of the groundwater / surface water system, and to calculate a theoretical zone of dewatering influence from the excavation. If the vulnerable feature(s) requiring protection lies within the zone of potential dewatering influence, then calculation of the theoretical maximum drawdown of groundwater levels beneath the feature(s) should be undertaken.
- 8.1.5 As indicated in Figure 8.1, considerable effort may need to be devoted to the fundamental task of getting this understanding right, but it must also be remembered that natural systems are often complex and that no theoretical analysis can be expected to give absolute certainty in its predictions. In this regard, the expectations placed on mineral operators need to be reasonable, rather than excessive. Where uncertainties exist, conditions (or legal agreements) can always be attached to planning consents that require the operator to cease dewatering if unacceptable impacts are found to occur, until such time as these are remedied. This places a greater onus on the operator to gain the best possible understanding of the water environment at the planning stage and leaves the risk with him, rather than the vulnerable feature.
- 8.1.6 It will also be important to ascertain whether the predicted drawdown may lead to permanent or temporary impacts on the habitat or feature(s) concerned. This will depend upon the expected duration of the drawdown, including seasonal changes, and the tolerance of the feature to groundwater variations. The latter will normally require expert advice from ecologists (in the case of lakes, rivers and wetland habitats), from geotechnical engineers (in the case of earthworks and structures), and from or local water users, in the case of abstraction wells.
- 8.1.7 Determination of the maximum permitted drawdown will inform the decision making and design process for the construction and implementation of mitigation features, whether they be recharge trenches in isolation or in combination with alternative measures (e.g. low permeability barriers, dewatering in cells, or seasonally restricted dewatering).
- 8.1.8 Numerical groundwater modelling may be a useful tool to aid in the decision making process, and to inform the design of whatever method of mitigation is chosen, but this should be undertaken only if necessary, and if an adequate conceptual understanding has been gained from empirical monitoring data.

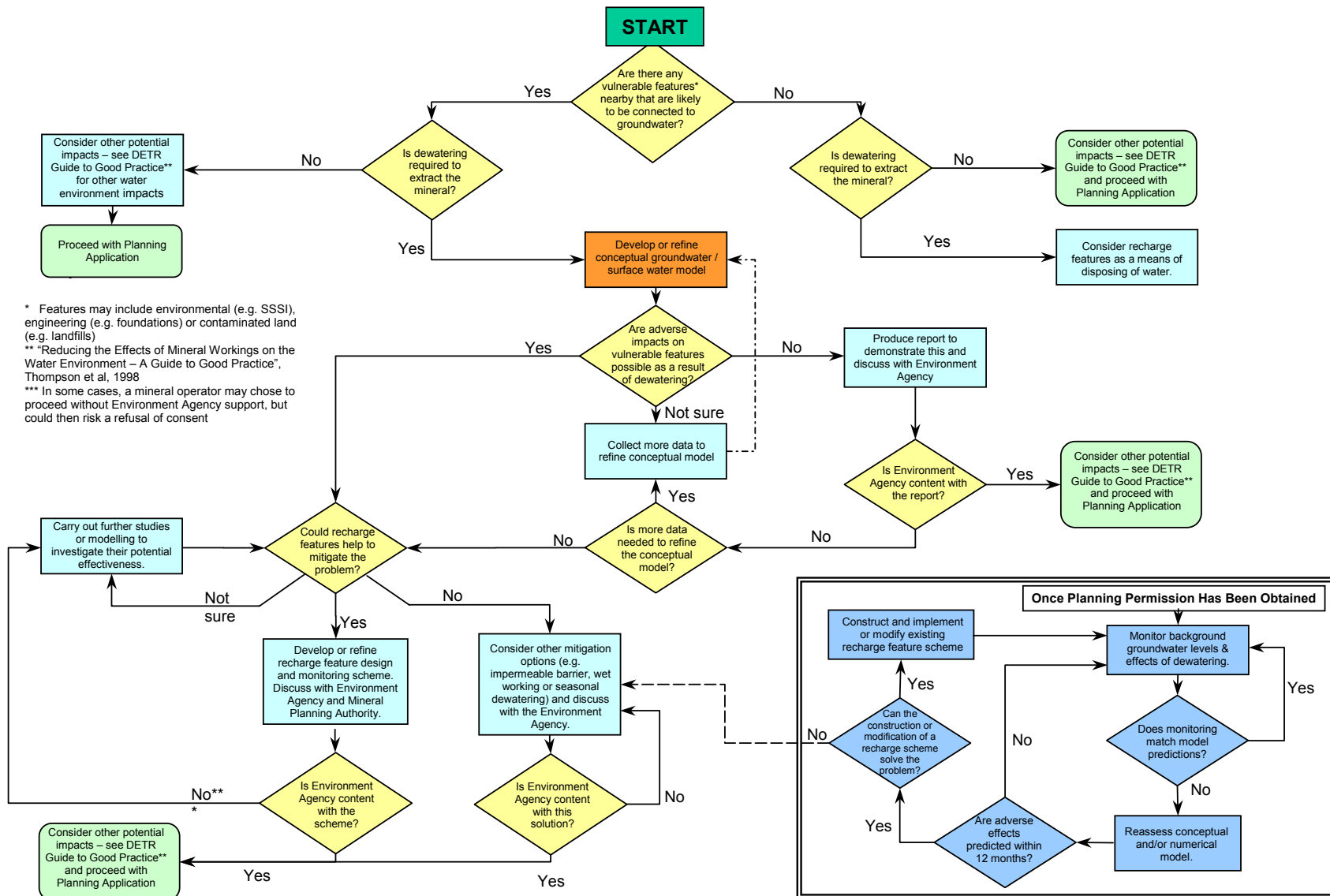


Figure 8.1: Flow chart

- 8.1.9 Attention will also need to be paid to the groundwater chemistry of the system and sediment load in order to identify ways (through operation and maintenance of the system) in which clogging and precipitation of minerals on mixing of recharge waters with groundwater can be minimised.
- 8.1.10 Having considered all of the above, if a recharge feature (either alone or in combination with another mitigation measure) is still considered the best way forward, the Environment Agency should be consulted with an outline method / design in order to ascertain whether they are satisfied with the proposed approach, and to determine which consents should be applied for (Chapter 6). This should be undertaken at the earliest opportunity given that the application preparation and determination process may take anywhere between 6 months and 9 months.
- 8.1.11 In the detailed design of any recharge feature scheme, it is important to consider the geotechnical stability of the feature (particularly when saturated), health and safety issues, and ways in which any excess discharge water may be accommodated.
- 8.1.12 Results of this research illustrate that there are still gaps in our knowledge as to the optimum design for a recharge feature in different settings. Site specific circumstances mean that the design of any measure taken to mitigate the impacts of dewatering will be different. In addition theoretical predictions of the extent of a zone of dewatering influence, or the volumes of water which may be recharged to ground, may vary from the reality of the actual situation.
- 8.1.13 It is therefore important to have a staged response approach to monitoring and construction of a recharge feature. Groundwater levels, both within and outside of the radius of dewatering influence, should be regularly monitored and compared to model predictions.
- 8.1.14 If predictions and reality are found to be significantly different, the conceptual and / or numerical model should be reviewed. Following re-assessment, if unacceptable adverse impacts on the habitat or structure are predicted within the next 12 months then the proposed recharge feature should be constructed and implemented, and the cycle of monitoring and validating model predictions continue.

9. RECOMMENDATIONS FOR FURTHER WORK

- 9.1.1 The review and collation of available information on the use of recharge features to mitigate the impacts of quarry dewatering has been useful in ascertaining some of the factors (such as clogging and long term behaviour) that influence recharging efficiency.
- 9.1.2 The experiments undertaken at Chamberhouse Farm, and Methley Quarry (including the numerical modelling) have enabled some elucidation of the key factors which may influence recharge trench efficiency, however there are still a number of areas, outlined below, where further investigation would be beneficial and enable more detailed guidance on the design of mitigation measures for quarry dewatering to be produced.
- 9.1.3 The short term nature of the Chamberhouse Farm experiment meant that only unsteady state behaviour could be studied. As part of any future work it would be useful to undertake an extended period of experimentation (such as 6 to 12 months) in order to ascertain the long term behaviour of such a system, enabling quantification of the impacts of clogging due to sedimentation, vegetation build up, or chemical precipitation.
- 9.1.4 Both experiments were undertaken during winter months. In contrast, it would be useful to undertake similar experiments during summer months in order to investigate whether there are any design or operational considerations that may be different to operations during winter months.
- 9.1.5 In any future investigations it is recommended that recharge trenches be placed closer to the feature to be protected in order to ascertain what impact this may have. In addition it would be useful to commence recharging at the same time as dewatering is started in order to ascertain whether this would, or would not, have had a significant impact on the scale and rate of development of a zone of dewatering influence.
- 9.1.6 As part of any further work, it is recommended trialling of ways to achieve greater input of recharge water into the aquifer should be focused on. In addition, consideration of ways in which greater volumes of water could be introduced to the aquifer in order to generate a reversal of depressed groundwater levels would be a useful area of research.
- 9.1.7 As well as the use of recharge trenches, it would be useful as part of any additional practical work to undertake a range of mitigation measures at the same site (trenches, injection wells, low permeability barriers) or combinations, in order to ascertain the pros and cons of each method (or combination of methods) in order to inform the design process in the future.
- 9.1.8 This research has provided a useful starting point in the review of the use and application of recharge features. It is recommended that this research, together with the further research work recommendations outlined above, be used to produce a more comprehensive guidance in the future.

10. REFERENCES

- British Geological Survey (2002): *ASR – UK: Elucidating the Hydrogeological Issues Associated with Aquifer Storage and Recovery in the UK*. UKWIR report reference 02/WR/09/2. BGA report no. CR/02/156/N.
- Building Research Establishment (1991): *Soakaway Design*. Digest 365, BRE, London.
- CIRIA (1988): *Control of Groundwater for Temporary Works*. Special Publication 113, CIRIA, London.
- CIRIA (1996): *Infiltration Drainage – Manual of Good Practice*, Report 156, CIRIA, London.
- Cliff M and Smart P (1996): *The Use of Recharge Trenches to Maintain Groundwater Levels*. Proceedings of the Extractive Industry Geology Conference 1996 – Groundwater Problems in Extraction. Applied Geoscience 15 – 18 April 1996.
- Domenico P.A. and Schwartz F.W. (1997): *Physical and Chemical Hydrogeology*. 2nd Edition, John Wiley & Sons Inc.
- Driscoll F (1986): *Groundwater and Wells*. U.S. Filter / Johnson Screens, St Paul, Minnesota 55112.
- English Nature (1994): *Hydrology and Mineral Workings: Effects on Nature Conservation*. English Nature, Peterborough.
- Fetter C.W. (1984): *Applied Hydrogeology*. 3rd Edition, New York
- Kruseman G.P. and de Ridder N.A. (1994): *Analysis and Evaluation of Pumping Test Data*. Second Edition. International Institute for Land Reclamation and Improvement. The Netherlands.
- National Rivers Authority (1992): *Policy and Practice for the Protection of Groundwater*.
- Pratt (2001): *SUDS – A Review of Published Material on the Performance of Various SUDS Devices*. CIRIA, London
- Shaw E.M. (1994): *Hydrology in Practice*. Chapman and Hall, London.
- Symonds Group Ltd (2004a): *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering – Chamberhouse Farm: experiment overview and findings*. Symonds Group, East Grinstead.
- Symonds Group Ltd (2004b): *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering – Methley Quarry: experiment and groundwater modelling*. Symonds Group, East Grinstead.
- Tarmac Quarry Products Ltd (1998): *Chamberhouse Farm, Thatcham – An assessment of the impacts upon the water environment of proposed mineral extraction at Chamberhouse Farm, Thatcham, near Newbury, Berkshire: The Groundwater Flow Model*. Interim report (no. 2).
- Thompson A; Easton P.H; Hine P.D; & Huxley C.L. (1998): *Reducing the Effects of Surface Mineral Workings on the Water Environment: A Guide to Good Practice*. Report to the Department of the Environment, Transport and the Regions. Symonds Travers Morgan (part of Symonds Group Ltd), East Grinstead.
- Warner J et al (1994): *Sediment and Microbial Fouling of Experimental Groundwater Recharge Trenches*. Journal of Contaminant Hydrology, volume 15, p. 321 – 344.
- Wardrop D.R., Leake C.C., and Abra J. (2001): *Practical techniques that minimise the impact of quarries on the water environment*. Transactions of the Institution of Mining and Metallurgy (Section B: Applied earth science), 110, Jan – Apr 2001

Wu F.C and Huang H.T (2000): *Hydraulic Resistance Induced by Deposition of Sediment in Porous Medium*. Journal of Hydraulic Engineering, July 2000 p. 547 – 551.

Appendix A

Case Studies

Case Study No. 1 – Efford Quarry and Landfill Site, Hampshire

Protected Feature: Pennington & Keyhaven **Mitigation Method:** Low Permeability Barrier and Saltmarshes



Statistics:

Grid reference 431505, 094505
Groundwater depth ~1m-2 m below ground level
Recharge Rate ~ 5000m³ per month

Geological Setting:

Topsoil and subsoil (0.3 m)
River Terrace Gravels (~4-8 m)
Oligocene Headon Beds (~50 m) (clay and silt)
Eocene Barton Sands (30 m-60 m)

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

This leaflet is one of a series produced as part of the MIRO research project; *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering*, which aim to illustrate the application of recharge features either exclusively or in combination with other mitigation measures in a range of different environmental and geological situations.

The environmental and structural conditions of a working area together with secondary land uses, may have a significant impact upon the surrounding area particularly with respect to groundwater sensitive habitats. This case study focuses on the effects of dewatering for mineral extraction combined with waste disposal in worked out cells on an expansive area of protected marshland adjacent to the site. It also highlights the use of recharge features as a mechanism to manage variations in groundwater levels for the benefit of certain habitats.

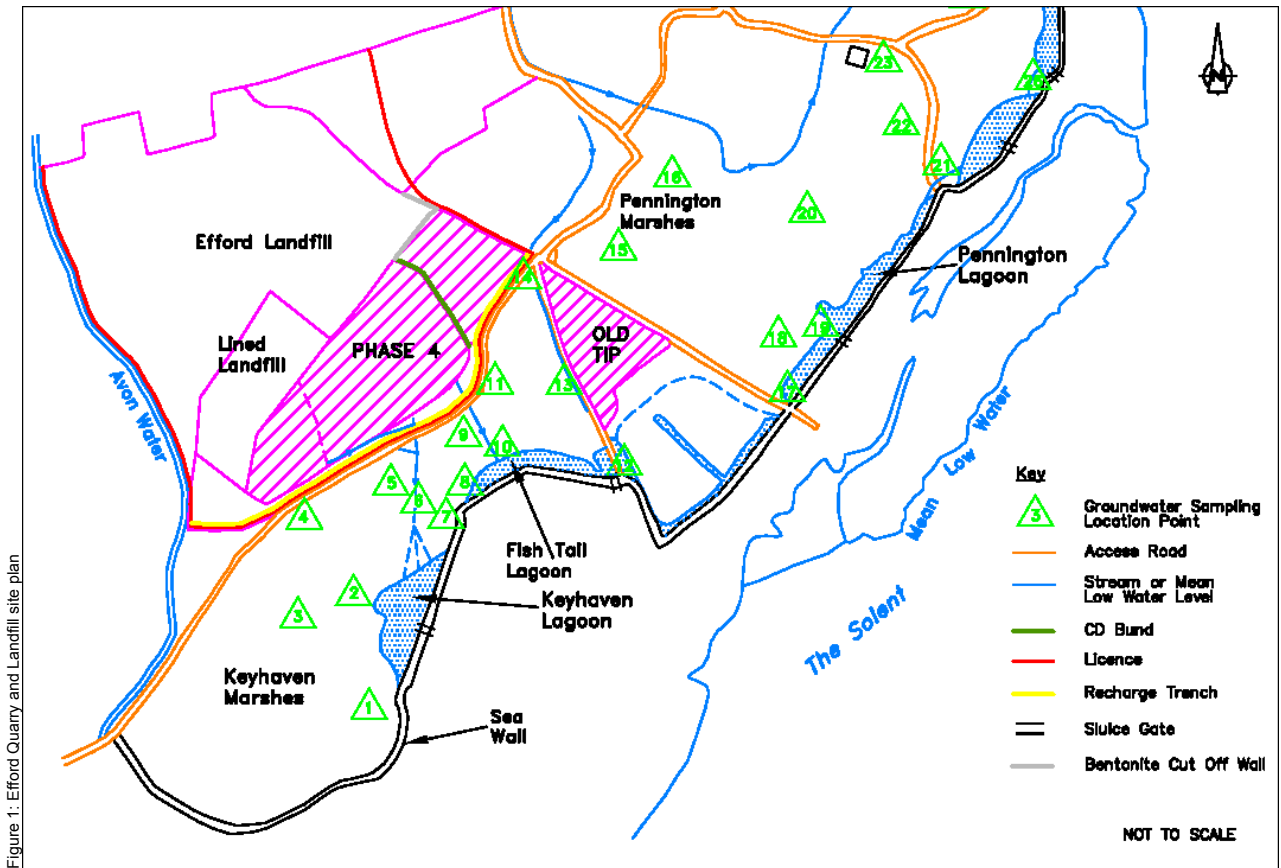
Background

Efford Quarry and Landfill site is situated on Manor Farm, 1.5km south west of Pennington, South Hampshire. Sand and gravel is an important mineral resource for the region and this site has been owned and worked by New Milton Sand and Ballast (NMSB) for over 30 years. Much of the worked out area, leased by Hampshire County Council (HCC), comprises restoration to inert and domestic landfill.

Directly adjacent to the southern border of the site are the Keyhaven and Pennington marshes, which are designated as a Site of Special Scientific Interest (SSSI) and as a Special Protection Area (SPA) for its birds and a Special Area for Conservation (SAC) for its saline lagoons. The site is owned and managed by HCC as a coastal nature reserve. Although created under anthropogenic influence, as indicated by the area of former salt workings (salt pans) dating from the medieval era, these habitats, particularly Keyhaven and Fishtail lagoons, are sensitive to alterations in lagoon water levels and salinity. As dewatering of quarry workings continues and the structure of the landfill evolves, a complex water management scheme monitors groundwater movement quality and surface water features, and seeks to maintain the sensitive habitats and species of the marsh.

Background (cont.d)

The groundwater recharge scheme was proposed as mitigation measures in connection with the renewal of planning permission, granted under the Review of Minerals Permission and subject to an Appropriate Assessment under the Habitats Regulations, for the continuation of mineral working at Manor Farm (Efford). A 'Water Management Scheme' was required as a condition of the permission. The scheme was prepared by Patrick Johnston Associates as Consultant Engineer and subject to discussions between Hampshire County Council as Planning Authority, Hampshire County Council Waste Management Group, Environment Agency, Onyx Environmental Group, New Milton Sand & Ballast and English Nature and the managers of the nature reserve



Geology

River Terrace Gravels, Recent or Pleistocene in age, are found across most of the area varying in thickness from 4 m to 8 m. The gravel deposits unconformably overlie Oligocene Headon Beds (up to 50m thick) composed predominantly of clay and silt, beneath which 30m to 60m of Barton Sands occur.

Borehole data indicates that the Terrace Gravels are fairly laterally uniform, with some silt / clay lenses and extend beneath the marsh to the south in a seaward direction. The marshes are formed on a thin overburden of topsoil and mixed alluvium. Borehole data and historical excavation records indicate that a clay ridge runs west-east across the site although the lateral extent cannot be confirmed.

Hydrology and Hydrogeology

Numerous natural and man made surface water features are present over the site indicating variable topography and groundwater levels. Background groundwater levels across the marshes are close to the surface, with flooding in the winter. The groundwater levels fluctuate seasonally by approximately 2m.

Groundwater flows from north west to south east towards the coast, along a hydraulic gradient of approximately 1:16. Although the marshes evolution has been influenced by anthropogenic activity, namely the salt pans and recently reconstructed seawall. Close to the seawall the groundwater beneath the marshes is in continuity with the groundwater beneath the sea and the lagoons are fed by percolation through these gravels. The majority of the marshes overlie lower permeability alluvium deposits above the sand and gravel resulting in a freshwater perched wetland system interacting with the saline influences of the seawater percolation into the lagoons and surrounding low lying marshland.

A network of freshwater seepages and surface drainage ditches run across the marshes collecting, and carrying, surface water flows due both to rainfall and inputs from land drainage north of the marshes. Ponding of surface water over parts of the marshland reflects the natural flow of both groundwater and surface to the coast. The Avon Water River flows north to south along the western boundary of the site discharging to the sea via a sluice at Keyhaven. The river is not connected to the marshes.

Hydrology and Hydrogeology (cont.d)

The new seawall, constructed in 1992, allows the discharge of fresh water from the Marshes through a number of discharge pipes with stop board/penstock and tidal flap controls. These are seasonally controlled by the reserve rangers to manage the discharge of fresh water from the back of the marshes and the salinity of the percolation fed lagoons.

Sand and gravel extraction and associated dewatering has been occurring on the Manor Farm site for more than 30 years. As working has progressed to the south towards the marshes the impact of the dewatering on groundwater levels has steadily increased. During the late 1980's and 1990's, prior to installation of mitigation measures, quarrying and dewatering along the southern boundary resulted in several metres of drawdown across areas of the marsh.

The impact of dewatering in the 1990's resulted in groundwater fed features at the back of the marshes drying more readily and particularly impacting on the internationally important percolation fed saline lagoons which are adjacent to the sea wall. This resulted in seasonally reduced salinity levels within the saline lagoons and drying of some areas. Discharge of dewatering water onto the back of the marshes drained directly to Keyhaven Lagoon assisting in maintaining groundwater levels but further reducing salinity levels particularly during winter months.

In addition, the earlier areas of gravel extraction have been backfilled with domestic waste causing a leachate plume within the local unworked areas of the gravels. This was restricted to the Manor Farm site by the influence of the dewatering. The quality of dewatering has contained low levels of ammonia and other leachate associated determinands however dilution has ensured these have remained below consent levels.

The Challenge

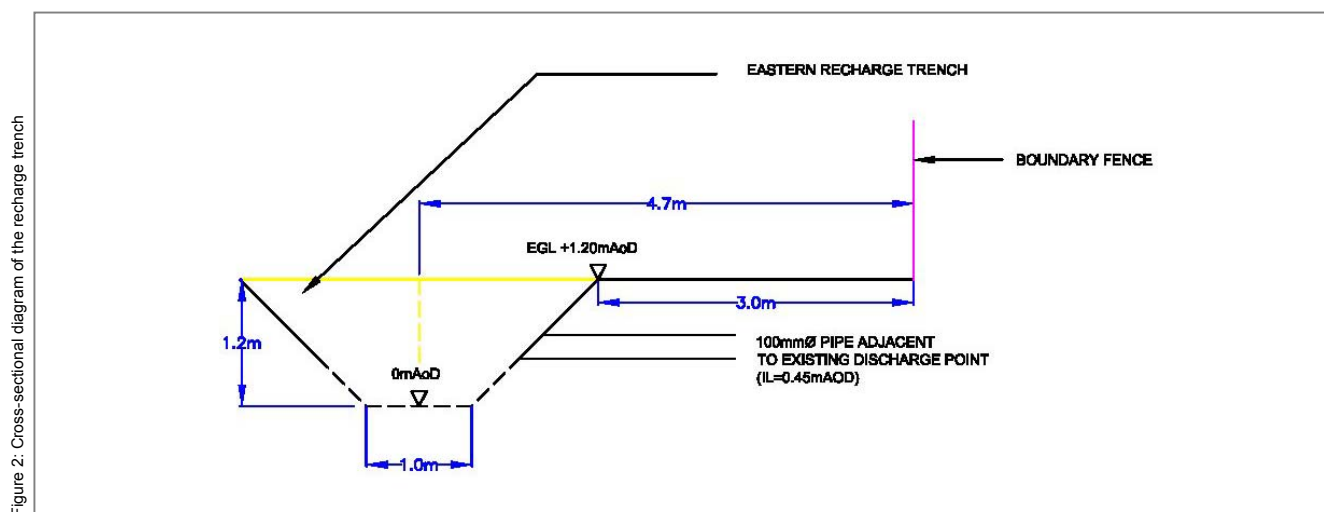
Concern was expressed by Hampshire County Council and English Nature regarding the potential impact of quarry dewatering on the natural hydrological characteristics of the adjoining coastal marshes nature reserve and SSSI. In addition concerns for surface water quality, related to potential contamination of groundwater from the 'dilute and disperse' Efford landfill to the north of the site or potential breaches of landfill containment were raised.

Historically the main concern was the impact of dewatering on groundwater levels beneath the marshes and particularly the impact on the internationally important saline lagoons. The mineral was worked dry and the natural background hydrology of the marshes was being disrupted. There was clear evidence that areas of marsh and the saline lagoons were drying out as a result of the cone of depression created by dewatering.

Theoretical groundwater modelling indicated that dewatering of up to 8 m below ground level within the quarry adjacent to the southern boundary would result in a drawdown at the edge of the marshes of approximately 6 m with a theoretical sphere of influence across the marshes extending up to 700m. A theoretical drawdown of up to 1m is estimated beneath the percolation fed saline lagoons.

There was also concern that a number of unlined landfill phases presented a contamination risk to groundwater quality and therefore potential contamination of marshes to the east and Avon Water River to west either via groundwater or contaminated surface water discharge. The integrity of liners within contained cells were also a concern.

Proposed Mitigation Measures



In order to address the above concerns detailed hydrogeological assessment and modelling was undertaken to assess the performance of a number of mitigation measures. This identified the requirement for an impermeable cut off wall around the area of dewatering to prevent the effects of dewatering extending beneath the marshes, and a recharge trench to replace lost groundwater recharge that prior to working flowed beneath the boundary of Manor Farm to the marshes.

Proposed Mitigation Measures (cont.d)

Installation of a temporary impermeable clay barrier between the marshes and the active mineral working in Phase 4c and the unworked area of Phase 4D was proposed to prevent dewatering impacting on groundwater levels beneath the marshes and to mitigate against any spread of potential contamination through groundwater from the unlined landfill areas. Since the low permeability barrier would affect the natural supply of groundwater and surface water flow to the marshes, which, in combination with the new sea wall, was affecting the hydrology and natural salinity levels of the marshes and lagoons, a scheme was drawn up to restore the marshes to 'favourable conditions' through management of the marsh habitat by means of an artificial irrigation system.

The scheme proposed included the construction of a recharge trench, designed to emulate natural groundwater inflow, and the introduction of surface water through the redirection of land drainage onto the marshes at three locations. Annual maintenance of the trench was proposed in the form of desilting in order to maintain infiltration capacity.

Although the fresh water features at the back of the marshes would dry out naturally in summer months, the aim was to replicate the groundwater recharge lost from the Manor Farm Site and to replace lost seasonal surface water drainage onto the back of the marshes. To facilitate the maintenance of water levels in the recharge trench, the management scheme proposed the collection and storage of water within balancing ponds on site particularly during winter and spring months in order to feed the recharge trench during seasonal lows. The proposed scheme included the maintenance of the saline lagoons through restoration of groundwater levels and the control of input of freshwater where at times of flood the excess could be directed away from the marsh.

Where landfill phases had no engineered liners or the containment was felt inadequate remediation measures were proposed. These included the capping of Phases one and the installation of a submerged bentonite wall in Phases two to contain the former 'dilute and disperse' landfills. A strategy for management of the landfill included regular monitoring for stability and the installation of gas and leachate abstraction wells.

An extensive network of monitoring wells was installed in the marshes and along the southern edge of the site, between the recharge trench and the marshes, to monitor groundwater levels and quality. Weekly monitoring of the groundwater levels in the marshes was proposed and loggers were installed in monitoring wells 4, 9 and 14 to automatically record groundwater level data. In addition flumes were placed in longitudinal soakaways leading into each end of the recharge trench and out of the recharge trench at the consented discharge point to measure surface water input.

In addition to monitoring of the hydrological conditions of the marshes a comprehensive ecological survey and monitoring programme was undertaken by HCC. This included assessments of the changes to plant communities, rare plants, invertebrates, both terrestrial and lagoon specialist, and to over-wintering and breeding birds.

The Reality

The cut off wall along the southern boundary of the worked areas was constructed in 1999 and a temporary bund (C/D bund) installed dividing the unworked areas. This was effective in rapidly allowing groundwater rebound beneath the marshes. The recharge trench was excavated in 2000 (eastern area) and 2001 (western area) and includes flow control structures to monitor surface flows in and out and therefore groundwater recharge. The trench location is shown on the plan in Figure 1 and a cross section in Figure 2. The trench was excavated into the sand and gravel deposit with the base level throughout. Due to site operations the trench quickly became silted requiring desilting by scraping using an excavator in 2003. This is considered an essential annual operation during the period Manor Farm continues to be a development site with high silt runoff.

Monitoring of the recharge trench has indicated that recharge seasonally varies depending on underlying groundwater levels and the hydraulic gradient. In summer months when groundwater levels fall below the base of the trench recharge increases to a maximum of about 5000m³/month. In winter months groundwater levels rise close to water levels within the recharge trench reducing the head difference and therefore resulting in a "topping up" of groundwater only.

A temporary failure of the C/D bund in 2002 resulted in the requirement for emergency dewatering within the unworked gravel area outside of the C/D bund. Dewatering water was discharged into the recharge trench between the dewatered area and the marshes but this was not effective and drawdown of up to 2m resulted in groundwater levels beneath the marshes.

Subsequently in 2003 a bentonite cut off wall was installed around the remaining site boundary within the unworked gravels. This will allow the sand and gravel to be extracted across the remainder of the permitted area without directly impacting groundwater levels or water quality beneath the marshes.

There is a requirement to provide a supply of water to the recharge trench during summer and dry winter periods from storage ponds located on the Manor Farm. The construction of these so as to provide a gravity feed on a level site such as Manor Farm is problematic although a proposed water management scheme has now been prepared.

Ecological monitoring has proved to be a good method of observing changing environmental conditions such as salinity on the marshes. Changes in conditions were reflected in variations in the size and occurrence of populations of species of flora and fauna from previously surveyed values. For example a reduction in *Chaetomorpha linum* in the Keyhaven Lagoon was observed indicating a decrease in salinity levels. This may have been as a result of dewatering during the installation of the bentonite cut-off trench.

Post excavation

Mineral extraction and landfilling are permitted until 2007 when the site will be restored. New Milton Sand and Ballast have obtained planning permission to extract mineral on an area of Lower Farm, in the north east of the site. They have also proposed the installation of a recharge trench in order to return water as a result of quarry dewatering to groundwater thereby reducing the discharge to surface water and reducing the need for discharge consent.

Final restoration of the site requires careful consideration and engineering to effectively manage the landfill and to produce surface contours designed to prevent increased surface run-off which could develop potential flood risk areas and disrupt the balance of surface water input to the marsh areas.

Conclusions

Quarry dewatering associated with the extraction of sand and gravel at Manor Farm over a period of many years resulted in significant drawdown in groundwater within the beneath the adjacent internationally protected marshes. In the late 1990's assessments confirmed this impact and Hampshire County Council required site operators to install mitigation measures. The main mitigation measure has been the construction of a combination clay and bentonite cement barrier. This has been effective in preventing the direct impact of quarry dewatering on groundwater levels beneath the marshes. A recharge trench has also been installed along the boundary between the sand and gravel workings and the marshes. This "tops up" the gravel aquifer beneath the marshes with the objective of replicating the lost recharge and groundwater flow from the Manor Farm site. In order to provide an adequate supply of water to the recharge trench in summer and dry winter periods storage ponds are required which allow a gravity feed.

The use of a recharge trench, combined with balancing ponds for storage, should also allow the prudent management of surface water to ecologically sensitive areas of the marshes. The whole scheme represents a good example of the degree of cooperation that is required to successfully protect the natural environment. The programme of water management with the objective of mitigation and improvement of groundwater and surface water conditions in the Pennington and Keyhaven Marshes requires ongoing co-operation and project management from members of the Efford Working Group and the Efford Marshes Group comprising Hampshire County Planning Authority, Hampshire County Council Waste Management Group, Environment Agency, English Nature, Onyx Environmental Group, New Milton Sand & Ballast, HCC Nature Reserve Wardens together with consultants Marcus Hodges Environmental and Patrick Johnston Associates.

Further information

All figures and photographs are reproduced with the approval of Hampshire County Council.

Further queries on Efford Quarry should be directed to:

Jeff Edwards
Hampshire County Council
Environment Department
The Castle
Winchester
Hampshire
SO23 8UD

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU.

Tel: 01342 327161.



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Recharge Features Case Studies

Case Study No.2 – Condover Quarry, Shropshire

Protected Feature: Bomere Pool (SSSI)

Mitigation Method: Proposed Recharge Trench

Plate 1: Condover Quarry and Bomere Pool RAMSAR site & SSSI



Statistics:

Grid reference	349700, 307800
Total quarry area	37 ha
Dewatered area	8.5 ha
Groundwater depth	54 – 75 mAOD
Dewatering rate	Previously 1150 – 1585m ³ /day At present <1000m ³ /day

Geological Setting:

Soils, Boulder Clay and Peat (1m - 18m)
Quaternary glacial sand and gravel (20m & up to 50m in the north east) with clay lenses (10m)
Upper Carboniferous Keele Beds (red marls and sandstone)

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

This leaflet is one of a series produced as part of the MIRO research project; *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering*, which aim to illustrate the application of recharge features either exclusively or in combination with other mitigation measures in a range of different environmental and geological situations.

Upon dewatering and subsequent extraction it may become evident that the impacts on protected habitats in the vicinity may be mitigated by insitu geological controls such as is the case at Condover Quarry. Therefore a precautionary approach to monitoring and implementation of a recharge feature is sometimes advisable.

Background

Located approximately 5km south of Shrewsbury, mineral extraction for sand and gravel at Condover Quarry has continued since the early 1970's. In 1982 the site was acquired by ARC (and subsequently Hanson Aggregates). The old workings and Extension A were largely worked out, and planning permission to extract mineral from Extension B was granted in August 1999 (Ref: MS98083284). The site will eventually be restored to agricultural land, woodland and lakes, as agreed with the Mineral Planning Authority.

Located approximately 60m north east of the site lies Bomere Pool, a RAMSAR wetland site covering 16ha and the surrounding Bomere Wood, a designated Site of Special Scientific Interest (SSSI).

Geology

A complex sequence of glacial sands, gravels and clays varying in thickness from around 20m to up to 60m in the north eastern part of Extension B, overlie a sequence of red marls and sandstones of the Upper Carboniferous Keele Beds. The base of the glacial deposits generally dips to the north east, steepening towards Bomere Pool.

In Extension A, a ridge of Quaternary clay (up to 10m thick), aligned north north west to east south east, was identified above the Carboniferous base.

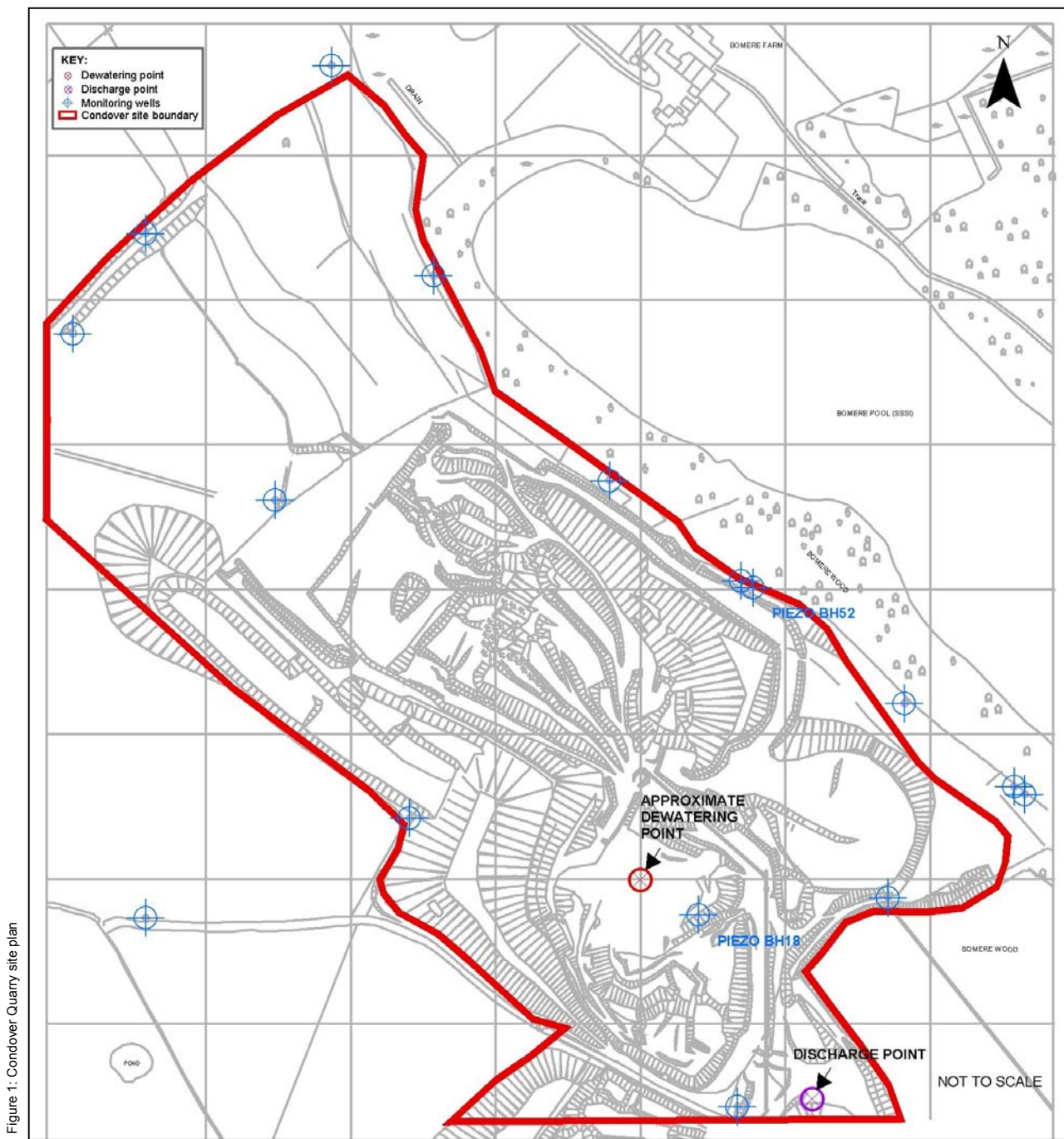


Figure 1: Condover Quarry site plan

Hydrology and Hydrogeology

Groundwater levels across the site drop steeply at a gradient of 1:12 from around 70-75 m AOD in the south western corner of Extension A to around 55 m AOD in the north eastern boundary of the site. Groundwater generally flows to the north east.

Water levels in Bomere Pool have been recorded to be on average approximately 75.7m AOD with seasonal fluctuations of approximately 0.3m.

The Challenge

The Mineral Planning Authority was concerned by the potential impact of dewatering on groundwater levels beneath Bomere Pool and Bomere Wood, and what knock-on impacts the lowering of groundwater levels may have on these sensitive sites.

Subsequently a Section 106 agreement, associated with the planning permission, required that Bomere Pool water levels be monitored monthly and if levels were found to fall below 75.4m AOD, approximately 0.3m below background levels, then monitoring would be increased to fortnightly and a report explaining the potential cause and effect of the drop in water level submitted to the Planning Authority.

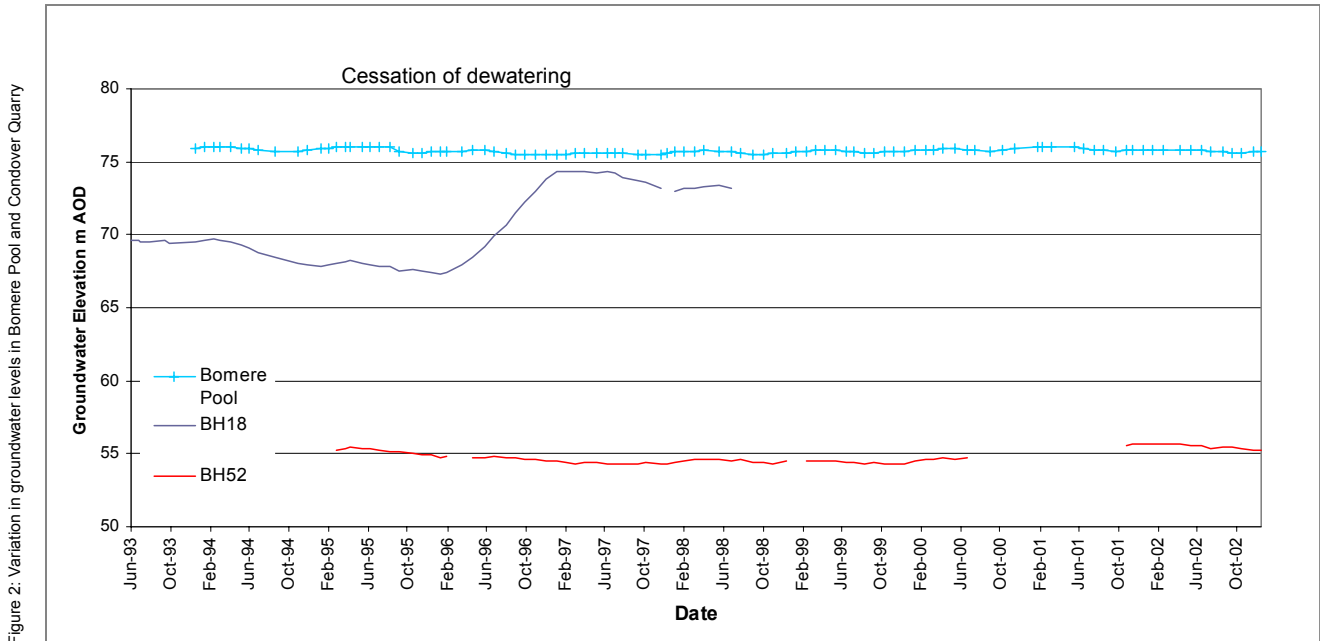
Should levels then fall to below 75.1m AOD, Hanson were required to cease dewatering and monitor weekly until it had been established that failure was not due to quarry dewatering operations. A remediation scheme would then be proposed should this prove to be the case. In addition, a 30m stand-off between the working excavation and Bomere Wood was stipulated in the conditions of planning permission.

The Reality

Condover Quarry (Extension A) was dewatered from a sump to the south west of the Quaternary clay lens between 1994 to 1996. From groundwater hydrographs it may be seen that levels within boreholes to the south west of the Quaternary clay lens (BH18) were observed to be affected by dewatering, showing a maximum drawdown of approximately 7m and subsequent recovery following cessation of dewatering in March 1996.

However groundwater levels to the north east of the clay lens (BH52) remained stable suggesting that the low permeability clay lens potentially acted as a barrier to groundwater flow, thus preventing the spread of the cone of depression to the east and hence mitigating any reduction in groundwater levels.

In relation to Bomere Pool, groundwater levels in the vicinity (BH52) were recorded to be over 20m lower than levels recorded in the pool; and showed no variation that could be attributed to dewatering. This suggested, and was supported by work undertaken by the Institute of Hydrology on behalf of English Nature, that Bomere Pool represents a perched surface water system and therefore is not fed by groundwater flow. Comparisons of water levels within the pool and evaporation indicates a strong correlation between the pool and climate.



Conclusions

Laterally extensive Quaternary clay lenses within the mineral deposits acted as natural low permeability barriers to groundwater flow minimising the lateral extent of the cone of depression associated with the dewatering of Condover Quarry. This resulted in no significant lowering of groundwater levels within the sands and gravels below Bomere Pool.

Further information

All figures and photographs are reproduced with the approval of Hanson Aggregates.

Further queries on Condover Quarry should be directed to:

Matt Uttley
Hanson Aggregates
Ashby Road East
Shepshed
Loughborough
Leicestershire
LE12 9BU

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU.
Tel: 01342 327161.



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Recharge Features Case Studies

Case Study No. 3 – Colne Fen Quarry, Earith, Cambridgeshire

Protected Feature: Fishery Lakes

Mitigation Method: Clay Cut-off Trench



Plate 1: Day Lake Fishery

Statistics:

Grid reference 538000, 276000

Total quarry area 98 ha

Dewatered area 9.5 ha

Groundwater depth ~ 2 m AOD

Drawdown depth ~ 5 m

Dewatering rate Variable

Geological Setting:

Overburden (~ 1m)

River Terrace Gravels (~ 6 – 7 m) with clay interburden (~ 0.5m)

Amptill Clay

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

This leaflet is one of a series produced as part of the MIRO research project; *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering*, which aim to illustrate the application of recharge features either exclusively or in combination with other mitigation measures in a range of different environmental and geological situations.

Low permeability barriers can be utilised in order to negate the need for a recharge feature by preventing the spread of the cone of depression. This case study focuses on the use of a clay cut-off trench to minimise the potential for dewatering to affect nearby privately owned fishery lakes.

Background

Colne Fen Quarry, Earith is located approximately 17 km north west of Cambridge in a region of low lying fen land across which many superficial sand and gravel deposits have been historically exploited for mineral. Wholly owned by Hanson Plc (formerly ARC), the quarry is situated on the floodplain of the Great Ouse river, which has an average elevation of approximately 3 m AOD.

Former workings have been allowed to flood and restored to amenity areas such as lakes and fisheries including Day Lake, approximately 20 m south of the current site boundary, and Coots Lake, a further 20 m south. At the southern end of site, there is an area that had been partially worked in the 1960's. Having remained dormant under the Environment Act 1995, sufficient reserves remain to warrant working out of the remainder of this area in two phases.

Geology

Aggregate worked at Earith consist predominantly of undifferentiated River Terrace Gravels, principally of Terraces One and Two which outcrop at Colne and Earith continuing northwards beneath the overlying Fenland Peat deposits. The mineral has an average composition of 60% medium fine sand, 30% gravel of <20mm and a low silt content of approximately 5-8%. A thin layer of topsoil and silty overburden (approximately 1m thick) overlies mineral extending to depths of 7-8m. Amptill Clay underlies the sand and gravel.

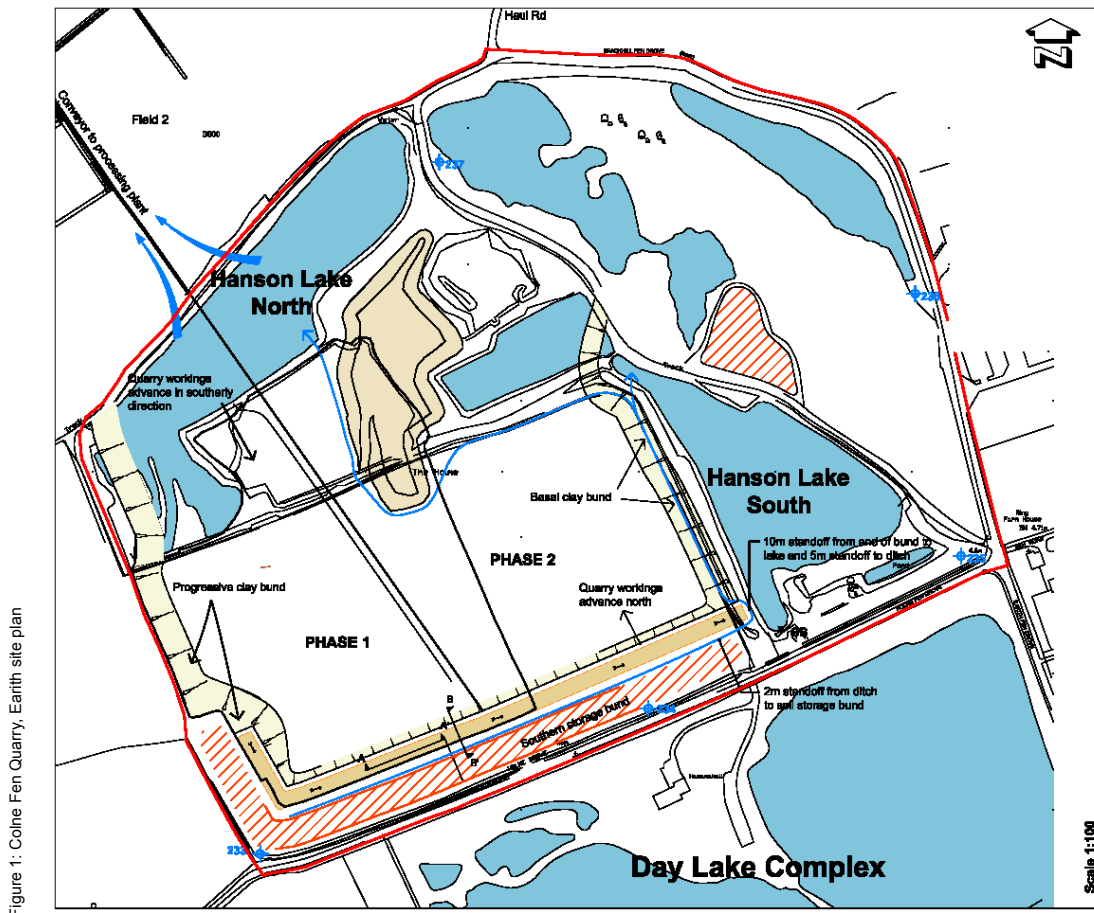


Figure 1: Colne Fen Quarry, Earith site plan

Hydrology and Hydrogeology

Groundwater levels across the area are, on average, between 2m and 2.5m below ground level (bgl), approximately 2m AOD and decrease in an easterly direction on a shallow gradient as indicated by historical monitoring. Groundwater level data also indicates that Day Lake, south of the working area and Hanson Lake South, to the west of the proposed working area, exhibit comparable seasonal fluctuations in groundwater levels suggesting a probable hydraulic connection. In addition Coots Lake demonstrates similar variations although of smaller amplitude and slightly lower levels to those of Hanson Lake South. From this it can be inferred that there is a hydraulic connection between the lakes and groundwater and the sand and gravel aquifer which is likely to behave as a homogenous unit.

Calculations using Hazen's formula indicate that the mineral deposits have a moderate permeability of 20 – 50m / day. In the vicinity of the site there are a series of west to east man made and natural drainage channels and dykes contributing to drainage of surface water run off from the site.

The Challenge

Approximately 20m south of the proposed area lie former workings, namely Day Lake and Coots Lake, now restored to fishery lakes and local amenity areas. Day Lake is a privately owned fishery for which concern was expressed regarding the potential impact on water levels of dewatering the adjacent proposed working area.

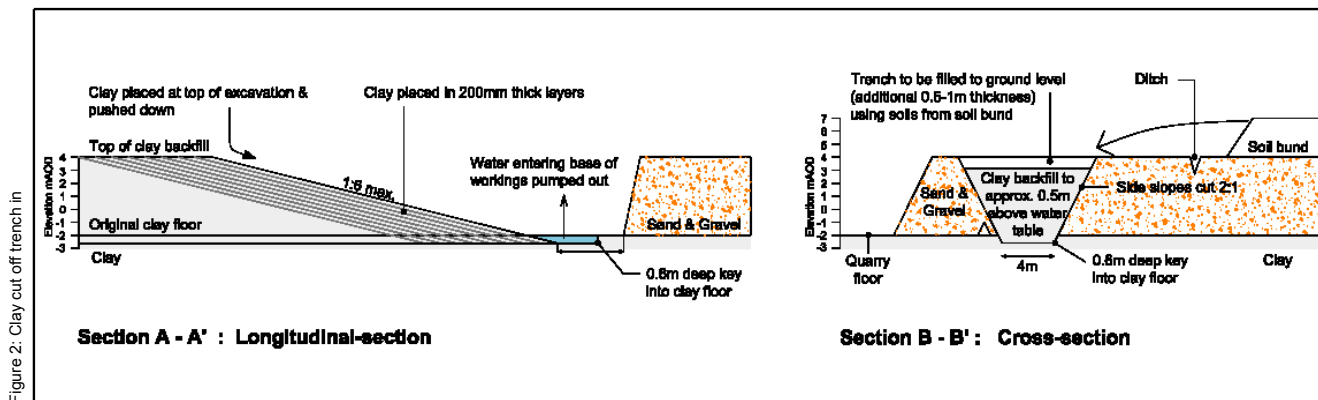
In order to work the mineral dry, groundwater levels will be drawn down to the base of the mineral (approximately 8m bgl, a drawdown of approximately 6m) and the sphere of dewatering influence has been calculated to be ~350m which encompasses both Day Lake and Coots Lake. An independent groundwater consultant estimated that it would take approximately a year from the start of dewatering in the north western corner of the proposed working area for the cone of depression to reach the fisheries lakes.

Since the initial proposals of mitigation measures, it has not been possible to monitor water levels in Day Lake. However, Coots Lake, on the far side of Day Lake can still be accessed and therefore is used as an indicator of groundwater levels in Day Lake.

Proposed Mitigation Measures

The main aim of the proposed mitigation scheme was to mitigate against effects caused as a direct result of dewatering of the working area upon the Day Lake system. An independent groundwater consultant, determined that a recharge feature sited between the dewatered working area and the protected feature would not be feasible as, it was considered that to be effective, it would need to be very deep for the base of the trench to be in contact with lowered groundwater levels caused by dewatering. Therefore a clay infilled trench (Figure 2) was to be constructed in as short stages as was feasibly possible to limit the exposure time to potential impacts.

Proposed Mitigation Measures (continued)



The clay filled trench, to be keyed 0.6m into the clay floor, was to be progressively excavated along the southern margin of the proposed working area (Figure 1). Point dewatering at a limited distance from the exposed working face would be undertaken to facilitate the backfilling of compacted clay.

Abstracted water would then be transferred, via a ditch dug deep enough to extend a short way into the sand and gravel (approximately 1m), to a pump in Hanson Lake North and subsequently pumped to the worked out quarry void. The ditch had the ability to behave as a recharge trench, potentially assisting in maintaining groundwater levels whilst the trench was under construction. During excavation regular maintenance of the ditch was to be undertaken to prevent any build-up of silt and allow continued recharge to the aquifer.

Phase 1 of mineral extraction will commence in the north and move progressively south. Upon completion of Phase 1, Phase 2 will commence at the southern end and work northwards leaving a 10m margin of unworked mineral between the worked out area and Hanson Lake South.

As the working face progresses in both phases, basal clay will be pushed up against the western and eastern sidewalls respectively of the working area to minimise groundwater seepage into the excavated area. In addition a margin of unworked mineral will be left between the clay trench and the working area to maintain the structural integrity of the clay barrier.

Throughout construction of the clay trench daily monitoring took place of monitoring wells 233, 234, 235 that were installed between the site and the fisheries, and also of the gauge board installed in Hanson Lake South. Monitoring is to be ongoing throughout excavation. Results will be supplied to the Environment Agency and Cambridgeshire County Council. Monitoring will be reduced to weekly once the Environment Agency are satisfied that water levels in Day Lake have not been significantly impacted.

Based on the evidence that the aquifer behaves as a uniform homogenous body, it has been proposed that should water levels of Hanson Lake South fall below the trigger level of 1.6m AOD, water from dewatering would be discharged to the ditch to restore groundwater levels or discharged to the lake directly.

The Reality

Background groundwater levels indicate seasonal variations with comparable fluctuations in groundwater levels in each monitoring well reflecting the homogenous hydraulic nature of the aquifer.

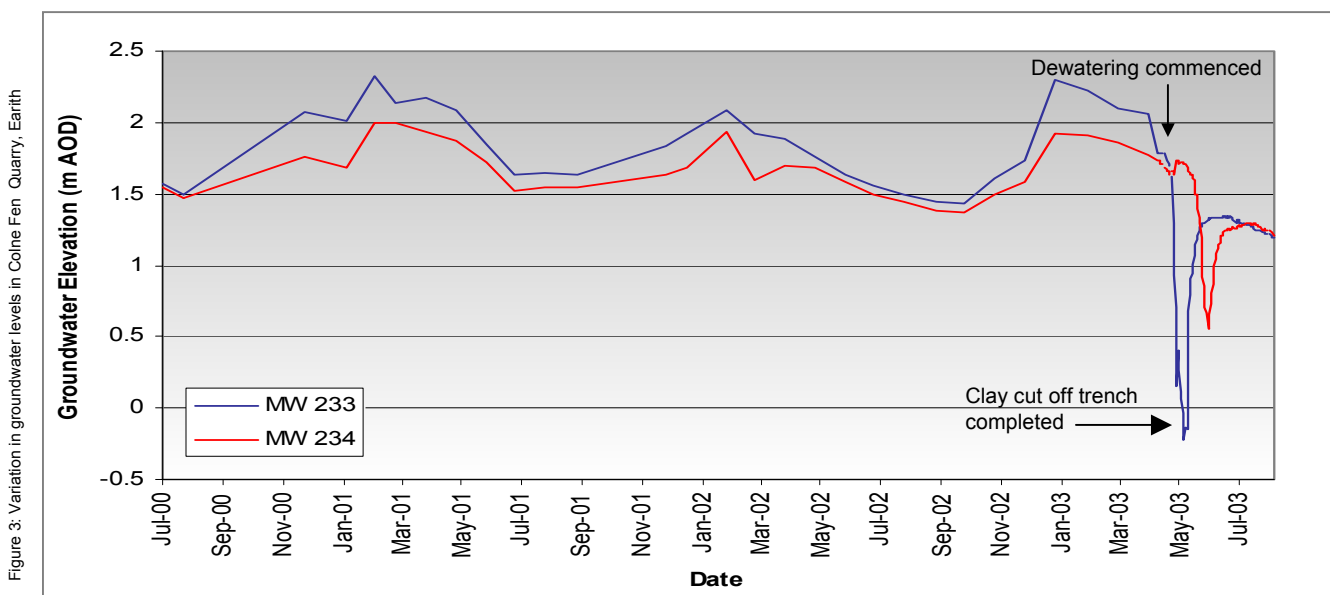
Hanson Lake North was dewatered via a sump for a period of two weeks in May 2003. Upon completion, the construction of the clay cut-off trench and point dewatering in the zone of working began adjacent to monitoring well 233 with extracted groundwater discharged to Hanson Lake North via a ditch. Work advanced in the direction of 234 along the southern margin of Phase 1 towards Hanson Lake South and was completed in a period of four weeks.

The hydrograph below indicates a sharp reduction in groundwater levels immediately following commencement of localised dewatering as reflected in water levels in 233; the closest monitoring well to the point of dewatering. Following completion of the clay cut off trench in the vicinity of 233, groundwater levels were observed to recover rapidly although background levels were not reached.

The hydrograph also illustrates that moving eastwards along the southern margin, groundwater levels were affected by dewatering but to a lesser extent and experience a time delayed reaction reflecting the easterly progression of point dewatering with continued construction of the clay bund as well as increased distance from the initial dewatering. Again recovery is observed once the trench was infilled with clay.

Gauge board readings showed that water levels in Hanson Lake South were unaffected due to its distance from the point of dewatering.

The Reality (continued)



Conclusions

Although the clay cut off trench was observed to limit the effects of dewatering, background groundwater levels were not seen to have been restored. Since trigger levels for additional remediation action are based upon the water levels in Hanson Lake South, no supplementary action has been required at the present time.

A more extensive low permeability barrier may act to further mitigate the reduction of groundwater levels. The use of a recharge trench between the low permeability barrier and the protected feature may also provide greater mitigation of the effects of dewatering.

Determination of the effectiveness of the installed mitigation measure is limited due to the inability to access Day Lake, thereby making accurate monitoring difficult and affirmative action, should Day Lake begin to suffer adverse effects, unachievable.

Further information

All figures and photographs are reproduced with the approval of Hanson Aggregates.

Further queries on Colne Fen Quarry should be directed to:

Bob Woodbridge
Hanson Aggregates
Ashby Road East
Shepshed
Loughborough
Leics
LE12 9BU

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU.

Tel: 01342 327161.



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Recharge Features Case Studies

Case Study No. 4 – Stanwick Quarry, Northamptonshire

Protected Feature: A6 Viaduct

Mitigation Method: Recharge Trenches



Plate 1: A6 Viaduct, restored workings Stanwick Quarry

Statistics:

Grid reference	495200, 271000
Total quarry area	61 ha
Dewatered area	48 ha
Groundwater depth	0.3m – 2m bgl
Drawdown depth	3m bgl
Dewatering rate	6000m ³ /day

Geological Setting:

Overburden (~1.5 – 2.0m)
Alluvial clays (~2.0m)
River terrace gravels (2m - 2.5m)
Oxford clay

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

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Mitigation measures used to protect natural habitats work equally as well for the protection of man made structures from the effects of lowering the ground water level as a result of dewatering.

Background

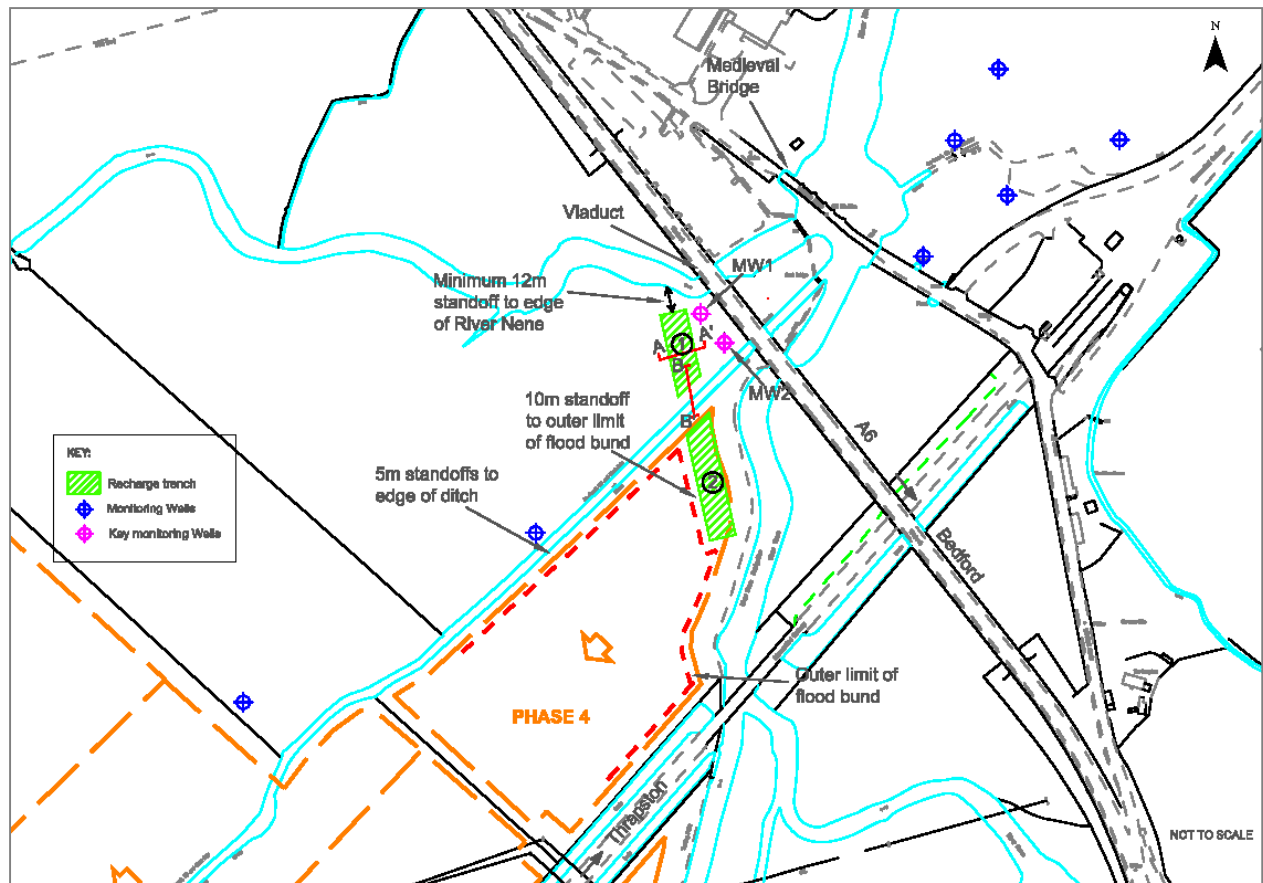
Stanwick Quarry, wholly owned by Hanson Plc, is situated on the River Nene floodplain. Historically extraction of mineral has occurred extensively across the region with restoration to open water.

Economic deposits include alluvial sand and gravel; First, Second or Third Terrace River Gravels and discrete deposits of glacial sand and gravels. The quarry site, located approximately 13km from Kettering, opened in 1985. Extraction in the area south of Irthlingborough town commenced in late 1991. Having completed Phases 1-4, extraction first moved upstream, then to the area adjacent to the plant and weighbridge and is due to be completed by 2005.

Geology

Drift deposits predominate across much of the area due to the floodplain setting. Overburden of approximately 1.5m, consisting of topsoil and alluvial clays, overlie economic deposits of first terrace river gravels which range in thickness from 2.0 to 2.5m. These are not laterally continuous and tend to deteriorate in thickness and quality to the north and south of the excavation area adjacent to the viaduct. Upper Lias Clay underlies the mineral.

Figure 1: Stanwick Quarry site plan



Hydrology and Hydrogeology

The flat, low lying nature of the area and the presence of the River Nene and several secondary water courses, man-made ditches and other surface water features denote that a near surface water table prevails over much of the site.

Groundwater levels are on average approximately 35m AOD varying between 0.5m and 1m below ground level (bgl). Intermittent monitoring of background groundwater levels, undertaken since the initial planning application was submitted in 1991, established natural and seasonal groundwater fluctuations to be approximately +/- 0.5m.

With overburden of less than 2m at maximum, it was concluded that the sand and gravel within the extraction area lies beneath the water table as does a proportion of the overburden. Dewatering would therefore be necessary even during the stripping of overburden.

Throughout the four month Phase 4 excavation period, continuous dewatering occurred to a depth of approximately 3m. Concurrently groundwater levels in boreholes MW1 and MW2 were monitored for any deviation from established natural fluctuations in groundwater level.

The Challenge

The A6 viaduct over the River Nene, constructed in the 1960's, is at its closest 50m from Phase 4 of this stage of excavation at Stanwick Quarry.

Concerns that a reduction in groundwater levels below the viaduct as a direct result of dewatering may potentially lead to ground settlement and thereby undermine the integrity of the structure were addressed at planning application stage in 1991. Surveys, carried out at that time, concluded that dewatering could have a potential effect on the viaduct.

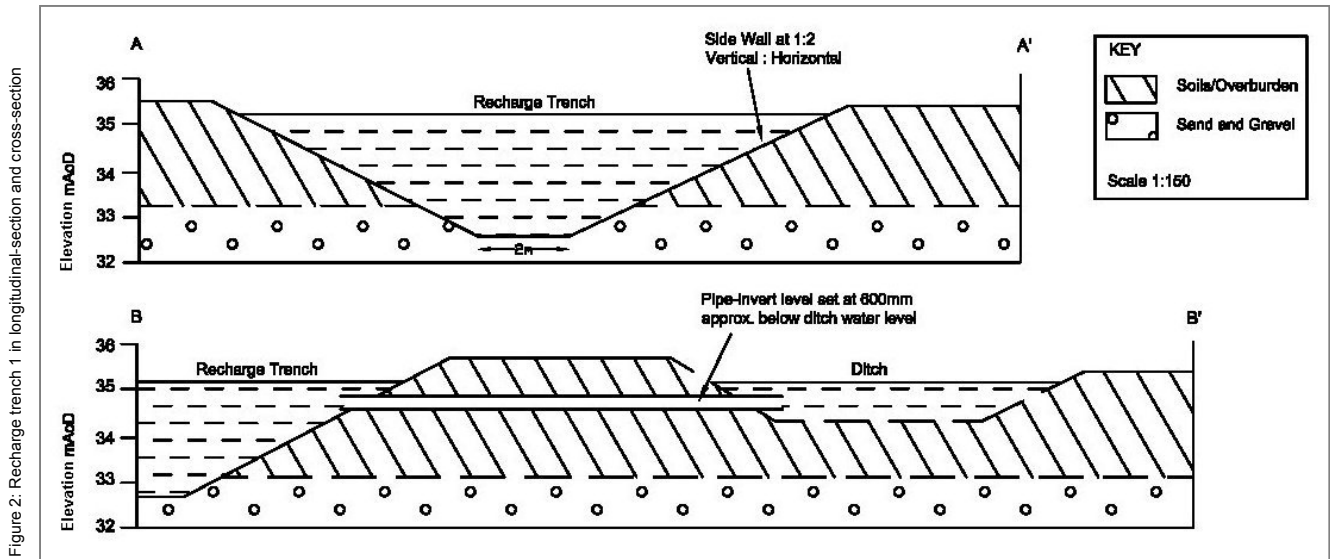
Two monitoring boreholes, MW1 and MW2 were installed at the northern end of the site between the bridge and the proposed working area to establish background groundwater levels.

In order to mitigate the lowering of groundwater levels below the viaduct, and hence any potential settlement of the viaduct, it was proposed that two recharge trenches would be installed between the viaduct and Phase 4 into which abstracted groundwater would be discharged. There were no trench maintenance requirements stipulated in planning conditions and therefore none was undertaken.

In addition it was proposed to install a clay sidewall lining during excavation of the working area.

A minimum 9m stand off between the River Nene and the recharge trenches was prescribed by Environment Agency consent in accordance with by-laws, although a 12m minimum width was assumed.

Proposed Mitigation Measures



Prior to stripping of overburden two intermittent recharge trenches (extending through the clay overburden up to 0.5m into the gravel) were constructed in July 2001 prior to the commencement of extraction in Phase 4. Both trenches, aligned NNW-SSE, orientated according to the boundary of Phase 4, were cut at right angles to a boundary ditch.

Located between 20m and 80m from the A6 viaduct, the recharge trenches were connected to the boundary ditch by pipe lengths, and flap valves were installed to control fluctuations in water head as a result of seasonal variations. A structural survey of the A6 viaduct was undertaken by independent consultants prior to commencement of dewatering and it was proposed that a further inspection and level survey would be carried out post excavation in order to ascertain the effects, if any, of quarry dewatering nearby.

Monitoring of groundwater levels continued with an increasingly extensive programme implemented as additional monitoring boreholes were installed to monitor impacts of dewatering on lake levels to the south west of Phase 4 and a site of nature conservation value north east of Phases 1 and 2.

The Reality

Dewatering, to the base of the mineral, of Phase 4 took place continuously for a period of three months from July to September 2001 during which overburden was stripped and mineral was extracted from the working area.

Upon commencement of dewatering monitoring data from boreholes MW1 and MW2 indicated a sharp reduction in groundwater levels as shown in the hydrograph below. Trigger levels were not predetermined or stipulated in planning conditions, however by August 2001 groundwater levels had fallen by over 1m. Although extreme seasonal fluctuations (i.e. drought) may have contributed to the drop in the water table, Hanson began to intermittently discharge water to the recharge trench at variable rates.

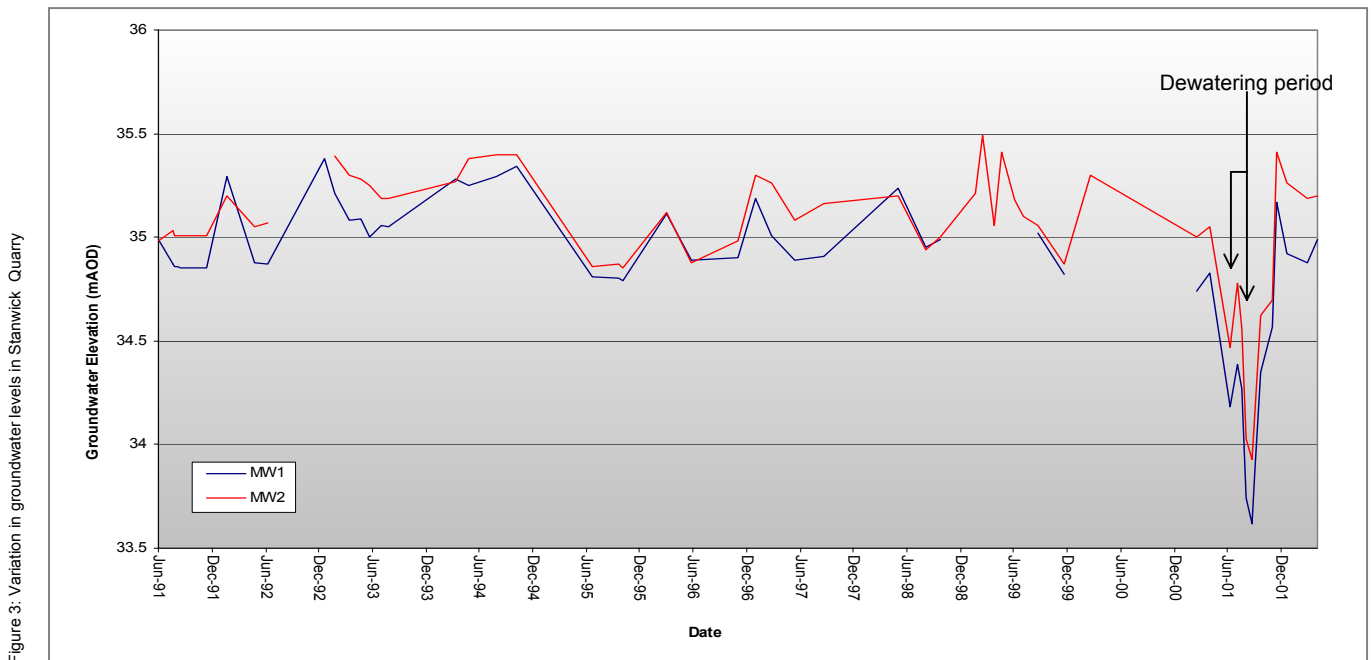


Figure 3: Variation in groundwater levels in Stanwick Quarry

The Reality (cont.d)

The monitoring data indicates that groundwater levels did not immediately recover as a result of the recharge and the increase reflected on the hydrograph coincides with the cessation of dewatering, with groundwater levels in MW1 and MW2 recovering rapidly.

Following dewatering and excavation, an inspection and level survey was carried out of the A6 Viaduct. The levels in October 2001 were all slightly higher than those recorded in the pre excavation survey undertaken in July 2001 and all within the expected tolerance. The post dewatering structural survey stated that since *'any movement of the structure owing to dewatering the foundation strata would be expected to be downwards not upward as recorded'* it can be concluded that *'there was no structurally vertical movement of the viaduct structure during the period of dewatering'*.

Post Excavation

Restoration took place on completion of all four phases of excavation, with the worked out phases 1, 2, 3 and 4b allowed to flood and left to develop as areas of nature. Phase 4a, the area in closest proximity to the viaduct and recharge trenches, was infilled with waste material extracted from Phase 4b and restored to grazing land.

Following completion of Phase 4, the area to the north east of the A6 viaduct was worked out in 2002. As a condition of the planning permission monitoring of the medieval bridge to the south of the area to be worked was necessary and should any effect of dewatering be noticed, a recharge trench as proposed in the planning application was to be installed. The fact that there was no effect on the viaduct as a result of Phase 4 excavation supported the proposed recharge trench design.

A secondary phase of excavation is currently being undertaken adjacent to the weighbridge office and although there is a scheduled monument site (Scheduled monument No. 13667 – Irthlingborough bowl barrow) within the working area no mitigation measures are required by the planning authorities as the barrow is unlikely to be affected from lowering of the groundwater levels.

Conclusions

Since the cessation of dewatering coincided with the recovery of groundwater levels, it is difficult to determine whether the recharge feature was successful in maintaining groundwater levels in the vicinity of the viaduct.

The potential inefficiency of the recharge trenches may have been contributed to by a number of factors. Maintenance of the trench to remove any accumulated silt deposits was not required nor undertaken. However, it was observed that 'water pumped into the recharge trench at one end was overflowing into the watercourse at the other' potentially implying that the rate of water discharge was greater than the infiltration rate of the trench. The intermittent discharge of water to the trenches may have also contributed to ineffectual recharge to groundwater.

Clay sidewall lining, as was proposed in the planning application may have prevented the potential for in water to flow down gradient into the excavation as well as towards the viaduct and thereby reducing the effective recharge volume.

Although there is no evidence to determine the degree of contribution from the recharge trenches in mitigating the effects of dewatering, and the contribution to groundwater made by surrounding water bodies, the recharge trench was deemed to be effective since no effect on the integrity of the viaduct structure was observed.

Further information

All figures and photographs are reproduced with the approval of Hanson Aggregates.

Further queries on Colne Fen Quarry should be directed to:

Bob Woodbridge
Hanson Aggregates
Ashby Road East
Shepshed
Loughborough
Leics
LE12 9BU

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU.
Tel: 01342 327161.



Recharge Features Case Studies

Case Study No 5. – Stonecastle Farm Quarry, Kent

Protected Feature: Hartlake Public Water Supply **Proposed Mitigation Method:** Recharge Trench

Plate 1: Dewatering excavations at Stonecastle Farm Quarry



Statistics:

Grid reference	565600, 146300
Total quarry area	60 ha
Groundwater	11–15 m AOD
Drawdown (approx.)	4m - 5m
Dewatering rate	variable
Consent to Discharge	10,000m ³ /d

Geological Setting:

Holocene Alluvium and Brickearth	1-2m
Pleistocene River Gravels	2.5 - 4m
Cretaceous Wealden Clays	

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

This leaflet is one of a series produced as part of the MIRO research project; *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering*, which aim to illustrate the application of recharge features either exclusively or in combination with other mitigation measures in a range of different environmental and geological situations.

Recharge features may be proposed for the mitigation of lowering groundwater levels at public water supply wells as a result of dewatering.

This case study focuses on a sand and gravel workings where recharge trenches were proposed as a mitigation measure, and groundwater modelling was used to predict their potential impact.

Background

Stonecastle Farm Quarry, operated by Lafarge Aggregates, is surrounded by low lying topography that is worked for river sand and gravel deposits. The quarry site is situated in the Medway valley, approximately 1.25km east of Tonbridge, between the River Medway and Hammer Dyke. Operational since the early 1980's, the quarry is extending excavations to the west in four phases over an estimated 10 year period.

Geology

The site is directly underlain by an overburden sequence of fine grained alluvium (comprising soft clay, mud and silt) and Brickearth, ranging in thickness from approximately 1m to 2m.

Below the overburden lies a 2.5m to 4m thick sequence of Pleistocene deposits consisting of alluvial, sub-alluvial and River Terrace Sands and Gravels. The gravels are interspersed with localised silt lenses, less than 0.5m thick.

In most areas, Lower Cretaceous Weald Clays lie beneath the sand and gravels.

Hydrology and Hydrogeology

Groundwater levels, at 11-15m AOD, are generally within the clay rich alluvium overlying the sands and gravels. Hydraulic conductivity of the gravels ranges from 24 m/d to 292 m/d indicating the variable silt content across the site. The regional hydraulic gradient is inclined gently (0.0007) from west to east.

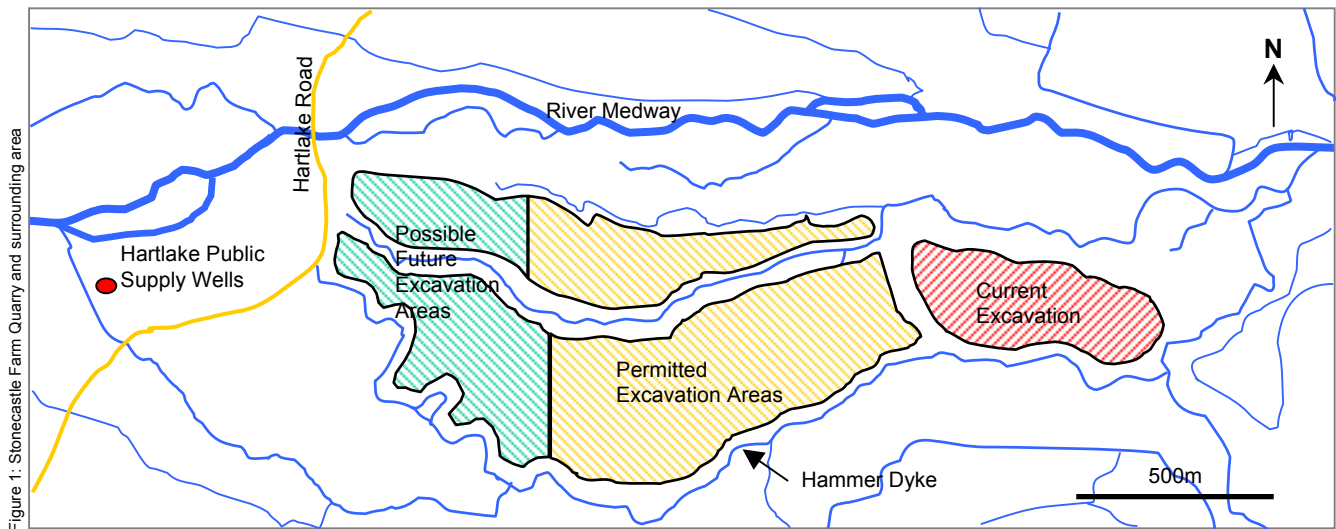
With groundwater levels only 1 to 2 m below ground level, the majority of mineral to be worked lies below the water table. In order to excavate the mineral dry, the quarry is dewatered creating a drawdown of up to approximately 4 to 5 m at the point of abstraction.

This has created a cone of depression in the water table which spreads laterally beyond the boundaries of the excavation and is superimposed on the regional hydraulic gradient

Stonecastle Farm Quarry is surrounded by a number of surface water bodies including the River Medway (200m north), Alder Stream, and Hammer Dyke (25-50m south). The connectivity between the river and the gravel deposits mean that the Medway has a strong influence on groundwater levels within the gravels.

Hammer dyke, a minor surface water channel, is thought to have limited connectivity with the gravels as its water level is usually above that of groundwater. Excess abstracted water, which is not recycled on site, is discharged to this dyke.

Both Hammer Dyke and Alder Stream can be sluice controlled by farmers to maintain soil moisture in local agricultural land.



The Challenge

Hartlake public water supply (managed by Southeast Water Company) consists of five boreholes, and is licensed to abstract 5000 m³/d. The supply wells are located approximately 1.5km to 1.8km west of the boundary of current excavations.

The original planned extension phases to the west of the existing quarry would have brought the excavation and dewatering point to within 500m to 800m of the supply wells. Concerns were raised that the cone of depression from dewatering in the quarry could potentially lower groundwater levels at the boreholes, and potentially affect the public water supply as a result.

In shallow workings, such as at Stonecastle, limiting the depth of excavation to minimise dewatering is not a feasible option. Working in cells minimises the area where dewatering is required and hence reduces the extent of any cone of depression, but other mitigation measures may be required.

Possible mitigation measures proposed for the Stonecastle Farm site included “wet working” – involving the excavation of material from below the exposed water table; the construction of a recharge trench; a low permeability barrier; and direct recharge to the public supply well.

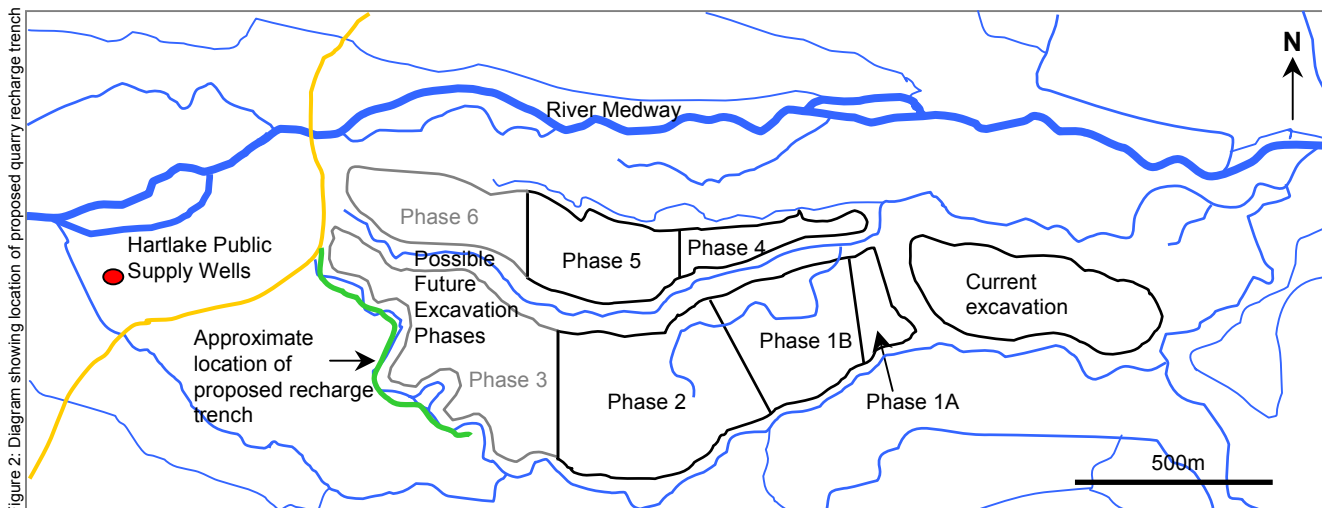
If a trench were emplaced between the extension workings and the supply wells, the input of abstracted water into the trench would enable the creation of a water mound that may assist in maintaining background water levels within the supply wells.

In order to ascertain the most appropriate mitigation approach, Lafarge Aggregates undertook groundwater modelling to quantify the potential effects of the planned quarry extension dewatering on the Hartlake public water supply, and to establish the potential impact of the proposed mitigation measure.

Groundwater modelling aims to represent reality by simulating current groundwater conditions and calibrating them against actual monitoring data. This base model can then be used to predict groundwater responses to alterations in the physical conditions.

In this case modifications to the base model were used to predict the potential impact of dewatering of future excavation on the Hartlake public supply wells. In addition, predictive runs were performed to assess the effectiveness of potential dewatering mitigation measures. One of these possibilities was the construction of a recharge trench.

Modelling of Proposed Mitigation Measures



The Base Model

A MODFLOW base model was set up in the Groundwater Vistas modelling package, and run in steady state – a non time-dependant method that represents the long term outcome, once the effects of changes in conditions have reached equilibrium. The gravel aquifer was represented as single layer model with varying gravel thickness, underlain by an impermeable boundary (Weald Clays). Dewatering in the current excavation was represented by an area of constant head (where water levels are fixed at a one height, here it was the water level within the excavation), that gave a dewatering rate in the same order of magnitude as was pumped from existing workings. Drawdown of surrounding water levels, creating a lateral spreading cone of depression, was modelled and compared to actual field data collected at monitoring wells on site.

Two model runs were performed, using natural recharge data from summer and winter conditions. The reduction in water levels due to decreased rainfall in summer months would be more likely to result in greater predicted drawdown at the public supply wells. Model runs using current working conditions and water level data showed that the base models had good calibration between observed water levels in monitoring wells and the water levels predicted by the computer model.

Scenario 1 – Quarry extension with no mitigation

Modified versions of the summer and winter base models were run, in steady state, to predict the potential effects of quarry extension, without any mitigation measures. Each phase was planned to be worked individually, with restoration of completed phases occurring as new phases were worked. The model was set up with different areas of conductivity depending on the development stage of each phase. Un-worked phases were given an average hydraulic conductivity of gravels (160 m/d), the open worked phases were given a hydraulic conductivity of 500 m/d. Restored areas were given conductivities of 1000 m/d if they were restored to open water or 5 m/d if they were filled with overburden.

As each new phase was modelled, the constant head cells (representing the dewatering point) were moved to within the working phase). It was assumed that dewatering in each working phase would be to within 20cm of the base of the gravels in that phase.

Scenario 2 – Quarry extension with recharge trench as mitigation

By controlling the amount of discharge into a recharge trench, and periodically clearing to maintain permeability, a recharge mound may be produced to compensate for drawdown in groundwater levels associated with dewatering. The trench was initially represented in the model by constant head cells at the trench location, which maintained constant water levels to represent a full recharge feature. It was later refined to be represented by a series of 'river' cells. The advantage of using 'river' cells is that recharge rates for water in the trench being returned to the groundwater, would alter when different heads were present in the cells.

The base of the recharge trench was located near the base of the gravels, and a low hydraulic conductivity applied to the base to represent channel bed silt. The cells representing the trench were given quite a low hydraulic conductivity to represent the potential future silting up of the recharge feature.

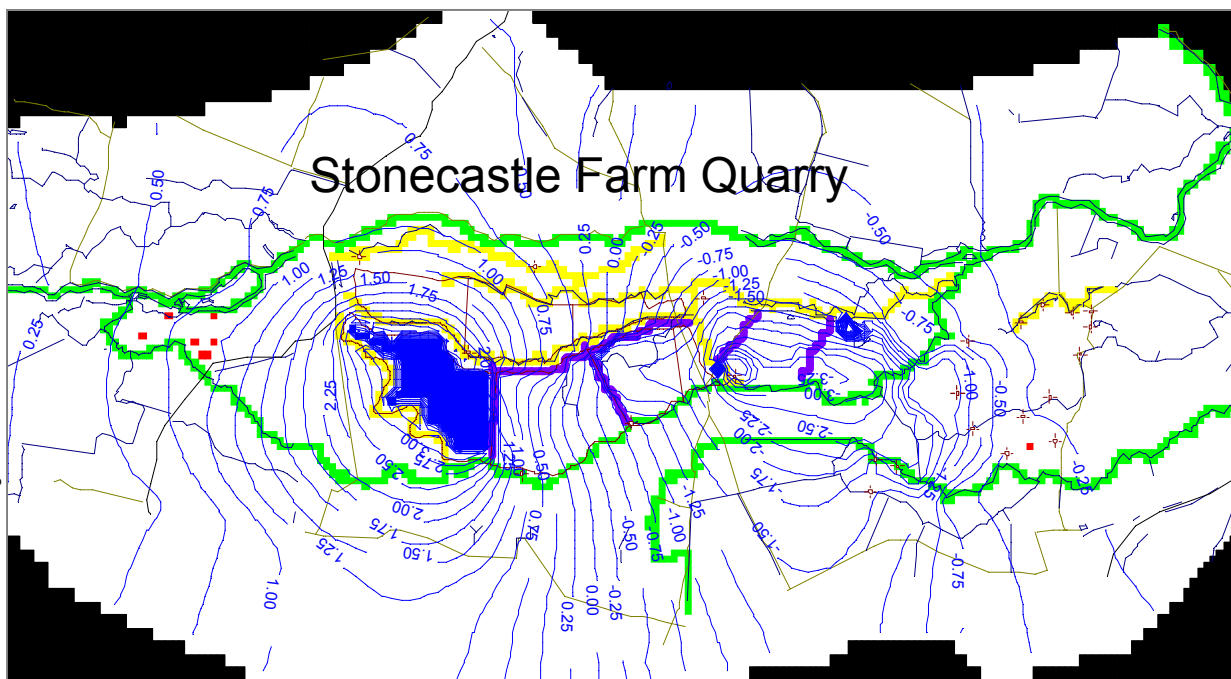
The Outcome

Results of model Scenario 1 (quarry extension: no mitigation) showed that, in general, dewatering had a similar or reduced predicted impact on water levels in winter months, when recharge from rainfall would be greater, than in summer month model runs.

Since the potential cone of depression caused by dewatering spreads laterally, those wells at Hartlake furthest from the point of dewatering would experience less effects from dewatering the excavation than those closest to the excavation (Figure 3). The greatest drawdown at the water supply wells was predicted when the phases closest to the wells (Phases 3 and 6) were excavated, although both of these phases were removed from the final planning application. In summer month model runs, the maximum predicted drawdown was 1.55m. Drawdown at the wells during other phases of excavation ranged from 0.05m to 0.5m.

Modelling of Proposed Mitigation Measures (cont.d)

Figure 3: Modelling output showing the potential drawdown caused by extracting Phase 3 (winter) with no mitigation feature. Predicted drawdown at the water supply wells during extraction of this Phase ranged from 0.5m to 1m.



Results of model Scenario 2 (recharge trench mitigation) suggested that, provided that the recharge trench was correctly set up and managed, water levels at the water supply wells could be sufficiently maintained or even increased.

In reality, since the excavation of material in the subsequent phases has progressed, groundwater monitoring data has shown that a significant groundwater divide is present between the extraction area and the public supply well, approximately following the line of Hartlake Road. The monitoring data also shows that the River Medway acts as the major contributor to aquifer around the Hartlake public supply wells

Conclusions

Groundwater modelling of future dewatering at Stonecastle Farm, without a mitigating recharge trench, indicated that some drawdown in the Hartlake water supply wells may be predicted (up to 1.55 m). Modelling of a recharge trench to the west of the site suggested that more water is recharged through the trench, and back to groundwater, when there is a high head in the trench, and less is recharged when heads are reduced. It was concluded from the model runs that using a recharge trench as a mitigation measure at this site could even be used positively to raise water levels at the Hartlake wells depending on how the work was carried out.

The result of the modelling is limited in that it is only a prediction of what could occur. Careful monitoring during excavation of the phases has been used to determine if any mitigation is actually required. In addition the modelling only predicts the long term outcome of the different scenarios. As the modelling was undertaken in steady state, no inferences can be made as to how quickly water level changes due to dewatering or the construction of a mitigating recharge feature may take place.

Further information

All figures and photographs are reproduced with the approval of Lafarge Aggregates.

Further queries on Stonecastle Quarry should be directed to:

Ian Mundy, Lafarge Aggregates Ltd, Minerals Resources, Panshanger Park, Hertford, SG14 2NA

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson, Symonds Group Ltd, Symonds House, Wood Street, East Grinstead, West Sussex, RH19 1UU. Tel: 01342 327161.



Recharge Features Case Studies

Case Study No.6 – Ellingham Hall, Norfolk

Protected Feature: Wild Fowl Farm Ponds

Mitigation Method: Recharge Lagoon



Plate 1: Recharge Lagoon, Ellingham Hall Quarry

Statistics:

Grid reference 635700, 292600
Total quarry area 13 ha
Groundwater depth 2m – 4.3m bgl
Drawdown depth 2m - 3 m
Dewatering rate 2000 m³/day

Geological Setting:

Glacial sand and gravel (~4.6m)
Pliocene Crag (20m)
(Fossiliferous beds of sand and marl)
Cretaceous Upper Chalk

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

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Quarry dewatering may be of concern for neighbouring habitats sensitive to changes in groundwater levels but it may also affect the larger scale, natural background hydrological / hydrogeological setting. This case study illustrates a scenario where recharge features were utilised primarily to manage discharge to within the consented volume, with monitoring of water levels in the duck ponds a secondary concern.

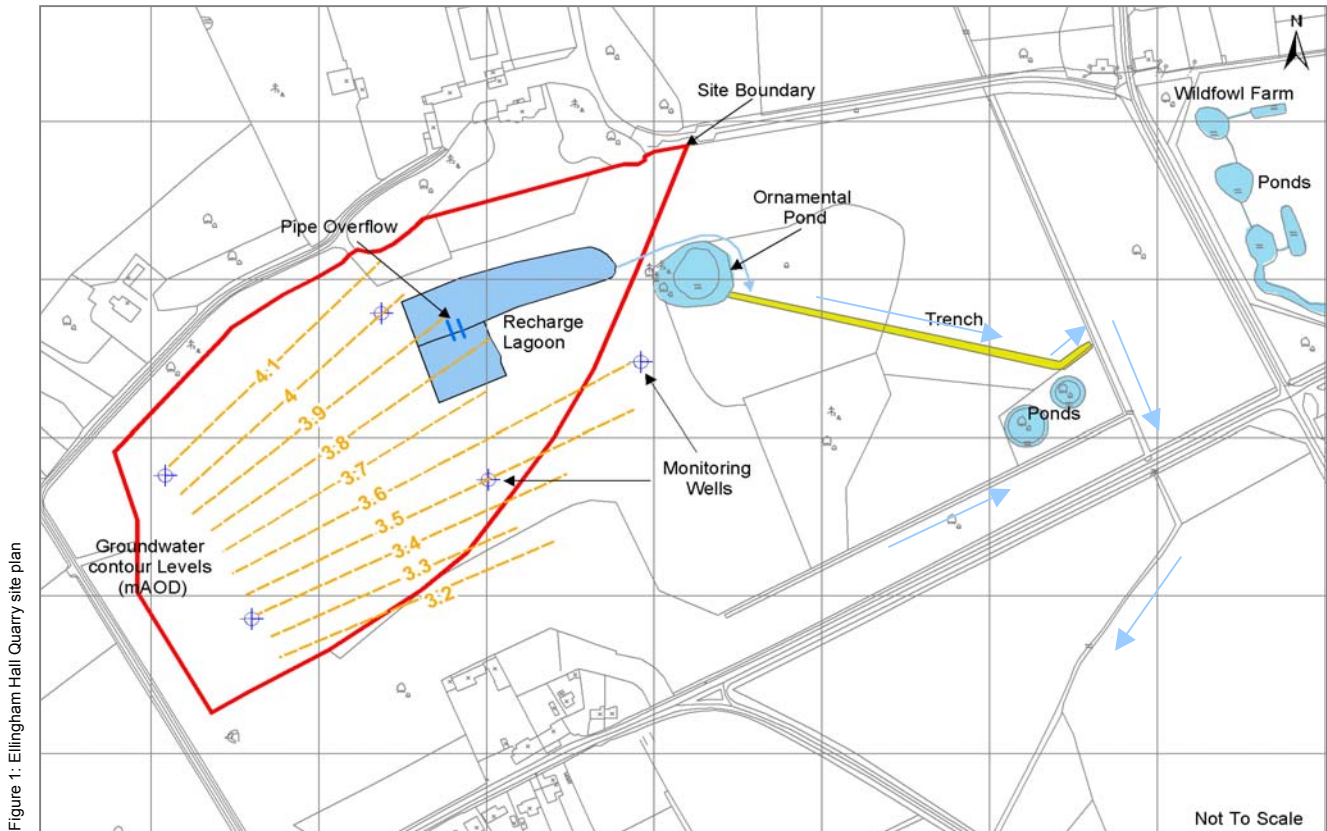
Background

Ellingham Hall, a former RMC Eastern operated quarry, is situated in the low lying region of The Norfolk Broads approximately 28km south east of Norwich. Surface topography varies from 3m AOD in the south east to 6m AOD in the north, with several water courses in close proximity to the site. Ellingham Hall is located 1.5km north of the River Waveney, above the floodplain on the north side of the Waveney Valley.

Planning permission (C/7/1998/7019) was granted in 1998, after the initial submission in 1995 was refused based on hydrological concerns. The quarry, operating since late 2001, completed excavation in 2002 and the site has now been restored to an open water body and returned to the private owners.

Geology

Glacial sand and gravel greater than 4.6m in thickness, overlies approximately 20m of Pliocene Norwich Crag comprising interbedded shelly sands and pebble beds. Cretaceous Upper Chalk, found beneath the Crag at approximately -30m AOD exhibits a shallow regional dip to the east. Thin overburden, consisting of approximately 0.3m - 0.6m of topsoil and subsoil overlies mineral deposits that were laterally continuous in thickness and quality across the site.



Hydrology and Hydrogeology

Groundwater levels decrease on a gentle hydraulic gradient of 1:400 in a north west to south easterly direction from approximately 4.1m AOD to 3.2m AOD (1m to 2m below ground level). Seasonal variations of approximately 0.5m were exhibited in groundwater levels and approximately 0.3m in surface water levels of the six existing ponds.

The overlying sand and gravel is considered to be in hydraulic continuity with the Crag, (a minor aquifer), and the Chalk, (a major regionally extensive aquifer). The absence of lower permeability horizons suggests that the overlying drift deposits are likely to be in hydraulic continuity with the underlying Upper Chalk.

Dewatering took place to the base of the mineral, (approximately 5m below ground level), giving a maximum drawdown of 3m. Ponds and other surface water bodies, located within the vicinity of the excavation, provide habitat for wild life in the area and considered to be direct expressions of the groundwater, thereby providing a good indicator of changes in groundwater levels.

The Challenge

Continuous dewatering of the mineral workings for periods of 3-5 days was followed by intermittent dewatering for 8 hours per day, resulting in the creation and maintenance of a cone of depression in groundwater levels. The radius of dewatering influence was theoretically estimated to extend to 200m from the point of dewatering.

Several ponds which may have been potentially affected by a reduction in water levels lay within this theoretical cone of depression. Theoretical drops in groundwater levels were estimated to be less than 0.13 m in all the ponds with the exception of the ornamental pond (which lies in closest proximity to the working area).

A discharge consent to a tributary of the River Waveney was issued by the Environment Agency. It was intended that any water for disposal would be pumped from the extraction area to the drain on the southern edge of the site where it would flow to the main drain to the east of the site and be discharged into the River Waveney. In practice it was found that the volume to be disposed of was greater than that anticipated (Figure 2).

As a result RMC had to find an alternative means of disposal, such as the return of any additional water to groundwater on site. A recharge lagoon and recharge trench system were proposed (Figure 1).

Proposed Mitigation Measures

A recharge lagoon, measuring 43m x 34m, was installed in the north east corner of the excavation site approximately 115m from the 'ornamental pond'.

The lagoon extended into the underlying sand and gravel deposits and was connected via an overflow pipe to a secondary excavated void. Should input to the recharge lagoon from quarry dewatering exceed infiltration rates then the water would overflow to the secondary void which was also available for recharge purposes. The secondary void was connected to a 200m long recharge trench which was constructed to the east of the site.

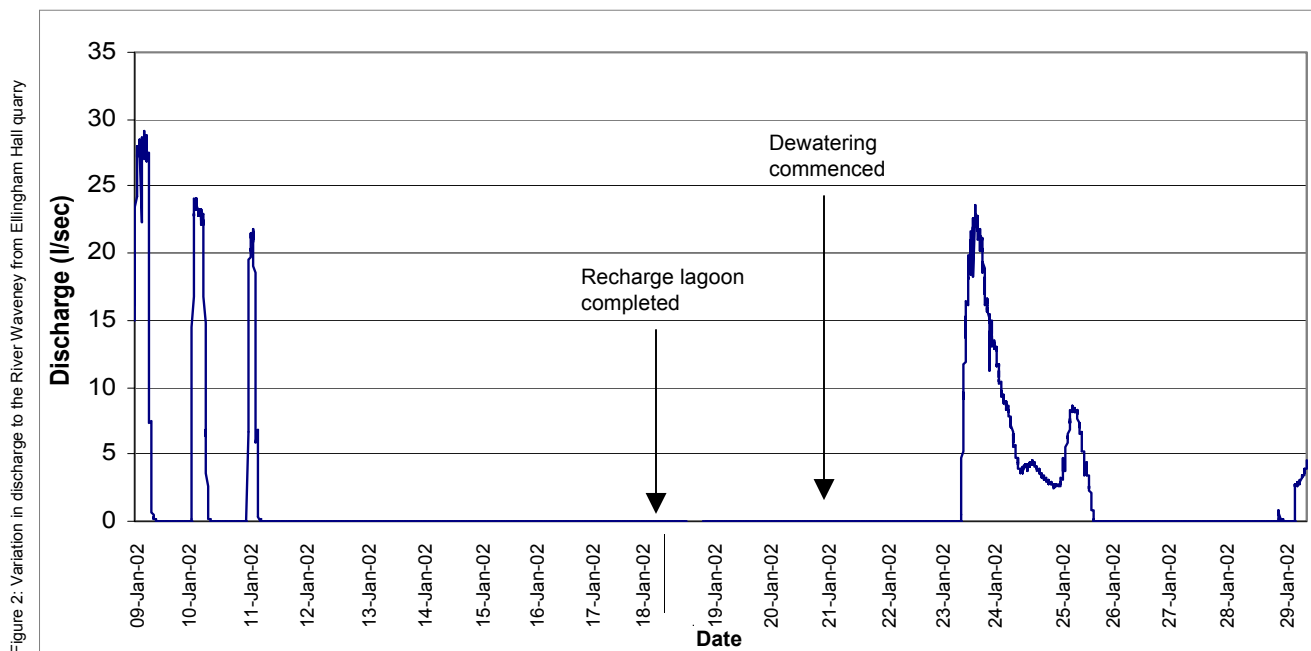
It was proposed that infiltration through the base and sides of the lagoon, the secondary void and the trench would reduce discharge from the site to the desired rate.

Monitoring wells were installed in five locations across the site and gauge boards in any pond that fell within the theoretical zone of influence of the lowered groundwater levels, as well as in the ponds of the wildfowl farm located 400m east of the excavation.

A plan of action was drawn up whereby should water levels in the ponds be affected as a result of dewatering, measures would be undertaken to restore levels by either 'topping up' the ponds or terminating dewatering and further extraction of the mineral in a 'wet' state.

The Reality

The mineral was worked dry following a programme of dewatering which took place in several phases, with periods of dewatering followed by periods of groundwater level recovery. Discharge from the site was monitored between the 9th January and the 29th January 2002. Following the completion of the lagoon on the 18th January 2002 dewatering commenced on the 21st January 2002. Pumping was carried out at an average rate of 25 l/s. Overflow from the secondary void started on the 23rd January 2002 and increased to a peak of 23.5 l/s which coincided with a period of rainfall. The subsequent rapid decline in discharge suggests that the recharge lagoon was effective in recharging the gravel. A smaller peak on the 25th January 2002 coincides with further rainfall.



Water was pumped from the excavation to the recharge lagoon throughout the day. It was observed that overnight the water would infiltrate into the underlying sand and gravels since lagoon water levels were reduced by the following morning with no discharge from the lagoon having taken place. Therefore it was found that the recharge arrangements resulted in a reduction in discharge but not by the desired amount.

Groundwater level data recorded in the monitoring wells was not available. However, visual observations, gauge board measurements and the fact that 'topping up' of pond water levels was not required (indicating that levels in the ponds were not significantly affected) would suggest that the recharge lagoon worked effectively.

Post excavation phase

Once the mineral was completely worked out the quarry site was restored to an open water body and the land returned to the custody of the owner of Ellingham Hall.

Conclusions

The recharge lagoon was only partially successful in reducing the discharge from dewatering the excavation. Water level readings recorded within the nearby ornamental pond (115m distance from the working excavation area) indicated no significant variation (beyond seasonal fluctuations of 0.3m). This suggests that the presence of the recharge lagoon led to the cone of depression being limited in its extent.

In the absence of an impact on the ponds and the wildfowl ponds, the recharge feature was deemed to be successful.

Further information

All figures and photographs are reproduced with the approval of RMC.

Further queries on Ellingham Hall Quarry should be directed to:

Chris Pointer
RMC (UK) Ltd
RMC House
Church Lane
Bromsgrove
Worcestershire
B61 8RA

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU.

Tel: 01342 327161.



Recharge Features Case Studies

Case Study No.7 – Eversley Quarry, Berkshire

Protected Feature: Private Residential Property

Mitigation Method: Recharge Trench and Well Point Injection System



Plate 1: Area of private housing and proposed location of trial recharge wells

Statistics:

Grid reference 480320, 161750

Groundwater depth ~1m –2m bgl

Drawdown depth ~ 4m

Dewatering rate 35 – 50 l/sec

Geological Setting:

Fluvial gravel (2m - 5m)

Bagshot and Bracklesham Beds (~7m)
(marine sands and clays with flint pebble beds)

London Clay

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

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Whilst geological setting can control whether mitigation against the effects of quarry dewatering is required, it can also influence which method of mitigation will be most effective.

This case study focuses on a site where, due to geochemical controls, recharge trenches were proved to be ineffective and trials of alternative measures are proposed with a view to use.

Background

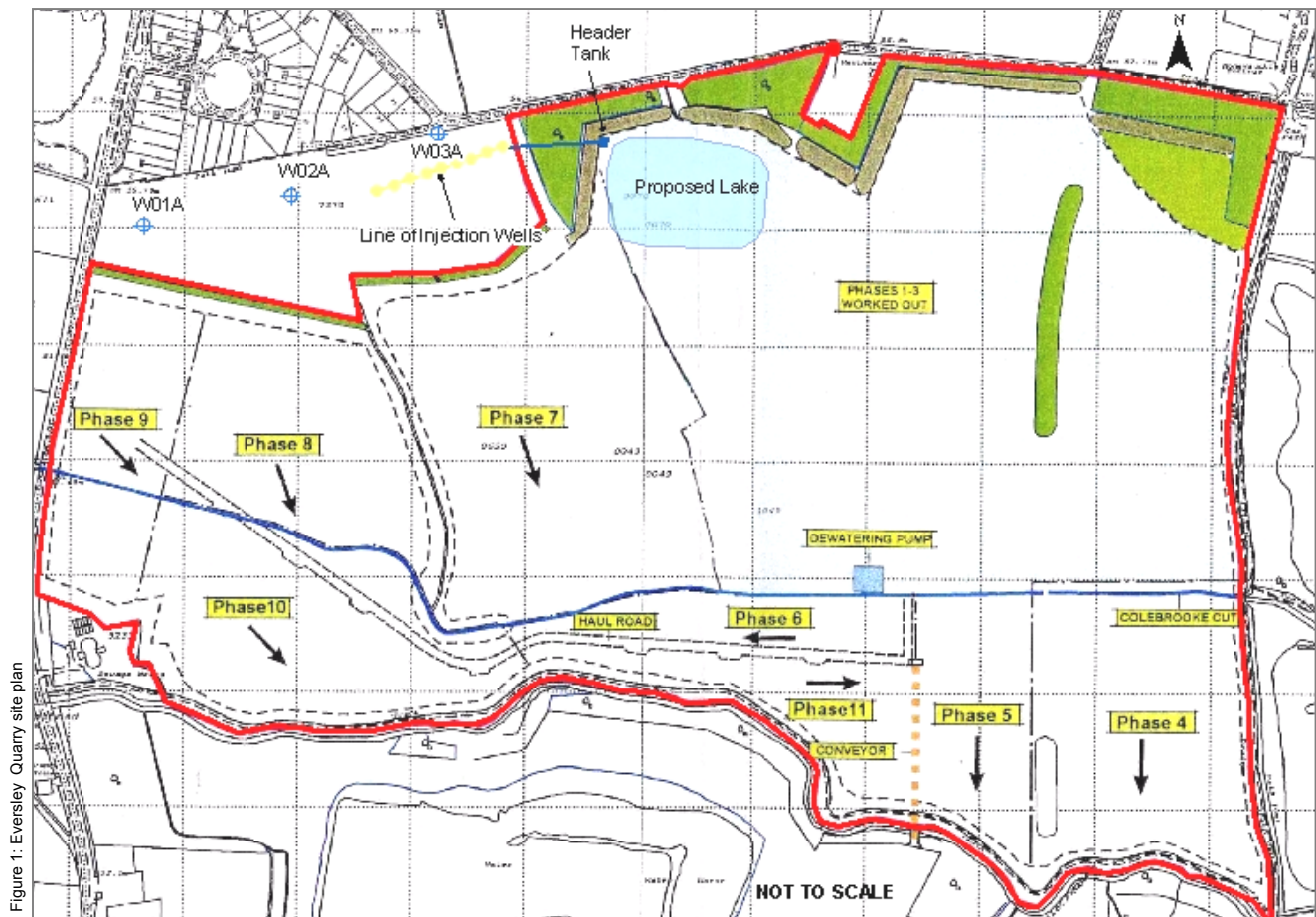
Quarrying has been undertaken along the River Blackwater Valley in Hampshire for approximately 50 years. Many of the workings are owned by RMC Aggregates, who acquired the area in question as an extension to their Eversley Quarry the mid-1990's.

Sited to the north of the river, the site is currently being worked from east to west, towards an area of private housing. Conditions of the planning permission require that potential settlement as a result of dewatering the sands and gravels be monitored and consideration be given to possible mitigation measures that may be implemented.

Geology

Shallow fluvial gravel deposits (2m – 5m thickness), overlain by little top soil and clay overburden, are underlain by the Bagshot and Bracklesham Beds Formation.

The Bagshot beds consist of micaceous sands with impersistent bands of flint, and the Bracklesham beds are a complex sequence of clays, marls and sands with a narrow seam of gravels composed of flint pebbles becoming increasingly pebbly towards the base. Within the Bracklesham Beds the predominant clay mineral is montmorillonite, a swelling clay. London Clay, a blue grey clay deposit containing nodules of pyrite that weathers to brown, forms the basal clay beneath the mineral.



Hydrology and Hydrogeology

The natural water table lies approximately 1m below ground level (bgl) in close proximity to the River Blackwater (forming the southern boundary of the Eversley site), increasing to 2-3m bgl towards the valley sides. At the point of dewatering, groundwater drawdown is estimated to be approximately 4m. This may generate a theoretical cone of depression in groundwater levels of up to 300m from the point of dewatering.

The river gravels and the Bagshot & Bracklesham Beds constitute a minor aquifer in the area with variable permeability. Although minor aquifers will seldom produce large quantities of water for abstraction, they are important for local supply. Several houses situated to the north east of the site, although on mains supply now, sourced their water from private supply wells during the earlier phases of quarrying.

Colebrook Cut, an artificial drainage ditch designed to drain the low lying agricultural land surrounding the site, was diverted by RMC in order to access mineral and better drain the working area. Planning permission was granted by the Mineral Planning Authority to the previous land owners, CAMAS and RMC intend to restore the ditch to its original course on completion of excavation.

The Challenge

Concerns were raised that dewatering of the working area may lead to groundwater levels being lowered beneath nearby housing, with settlement within the sand and gravels occurring as a result.

In addition, lowering of groundwater levels, and their potential for impact on nearby private water wells was of concern. As a result a Section 106 Agreement was entered into requiring that, at the appropriate time, a recharge trench would be installed in order to mitigate against possible subsidence.

Two recharge trenches were installed to the north east of Phases 1-3 (now completely worked out) to protect private well water supplies. These were constructed as trenches with a sidewall gradient of 1:2 and 1m wide at the base. The trenches were dug into the surface of the gravels and below dewatered groundwater level.

Although water levels were maintained, infiltration was found to be very slow from the outset and the recharge trenches were considered to be unsuccessful. Accumulated iron deposits and silt washed in from the sides of the trench are thought to have led to clogging of the trench reducing its infiltration capacity.

It is considered that peat deposits or sulphide mineralisation such as pyrite, found across the site is likely have resulted in acidic groundwater with pH readings of 2.5 recorded. At such low pH, iron present will be held in solution in groundwater. On exposure of groundwater to the atmosphere, iron will become oxidised leading to precipitation as iron oxide or oxyhydroxide.

Proposed Mitigation Measures

Results of the trench trial indicated that the oxidation of iron deposits, and subsequent clogging of the base of the trench was a problem. It has therefore been proposed to install a well point injection system which would allow abstracted groundwater to recharge directly to groundwater at greater depths and under greater pressures in order to obtain increased recharge.

To prevent the build up of iron, and subsequent decreasing of infiltration capacity, near neutral waters would be supplied to the recharge wells via an artificial storage lake to be constructed in the north of the site. The lake would be fed predominantly by water derived from surface run-off from the hills to the north which reduces the background acidity of surface and groundwater to around a pH of 6 from 3-4. At this pH iron will precipitate out of solution and be deposited in the lake, reducing the potential for iron accumulation in the jetting wells. It is thought that by jetting water into the aquifer at greater depths, the greater permeability would facilitate more effective recharge of the aquifer. In addition, if the water was directly injected into the saturated zone then oxidation of any residual Fe-rich minerals may be avoided.

The proposed site of the well point injection system is the privately owned land adjacent to the private housing located to the north west of the application area (Figure 1). It is planned to inject of water into a series of 33 recharge wells (at 3m centres along a length of 100m) drilled to a depth of 10m. This system was chosen as the area is situated off the floodplain, at higher topography than much of the application area, therefore the groundwater level is at greater depths. The geology differs to that of the working area in that the gravels are very thin and overlie Bracklesham Beds consisting mainly of silts, sands and clays with narrow seams of gravels, consequently it is considered that a greater degree of pressure would be required to recharge the aquifer.

The planned injection wells will be constructed with a 150mm diameter steel injection tube, into which a 32mm riser pipe with a perforated filter will to be placed. The riser pipe will to be surrounded by Sharp sand, after which the jetting tube would then be withdrawn leaving the recharge riser in position. The injection wells would be connected by a 150mm diameter header pipe.

Three monitoring wells (Figure 1) have been installed behind the line of proposed recharge wells set back from the northern boundary of the application area. Each monitoring well contains two or three 50mm diameter monitoring pipes which vary in depth from A – C, A being the shallowest at between 2.50m and 3.90m below ground level (bgl), and B or C being the deepest drilled to between 9.70m and 12.10m bgl.

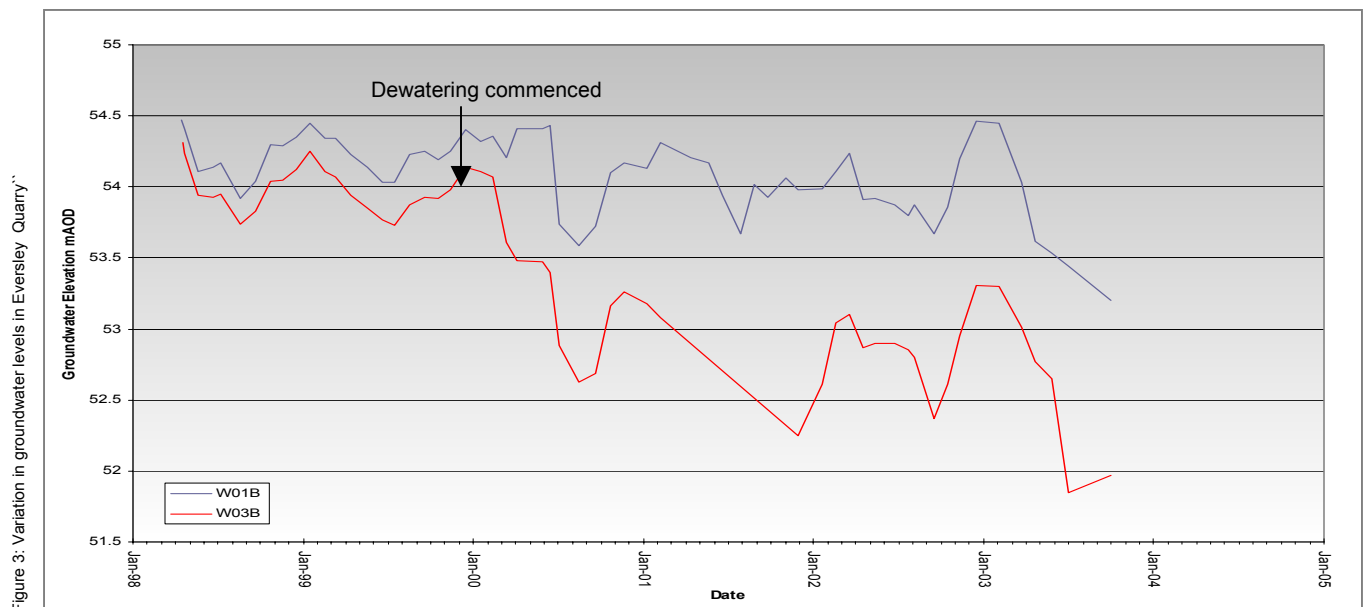
Monitoring well W01 is located furthest to the west and W03 is closest to the proposed point of installation of the well point injection system. A programme of monthly monitoring of groundwater levels was proposed, to be initiated before dewatering commenced to establish background groundwater levels and seasonal fluctuations and to record any effect dewatering may have and the degree to which this can be mitigated after the installation of the recharge wells.

The Reality

Background groundwater levels exhibited seasonal fluctuations with similar frequency and amplitude in all monitoring wells. Dewatering commenced in spring 2000 occurred continuously at a variable rate of between 35 l/sec and 50 l/sec. The dewatering pump is located at the southern edge of Phases 1-3, which are now completely worked out. Water to be extracted is transferred to the pump via internal ditches constructed in the base of the site.

W01 has been least affected following commencement of dewatering with little or no change in W01A and a slight lowering of groundwater levels as well as an increase in the amplitude of natural seasonal fluctuations is exhibited in all three monitoring pipes. Groundwater levels in both W02 and W03 have been affected to a greater extent and clearly exhibit a decrease in groundwater levels since dewatering commenced.

The general trend over time show a decrease in groundwater levels with W02 and W03 exhibiting a slightly higher rate than that of W01, which is situated furthest from the point of dewatering.



Current Status

Mineral excavation currently takes place from Phases 4 and 5, with progression to Phases 6 to 10 in due course. Dewatering for the purposes of dry working of the aggregate continues, with groundwater levels lowered by approximately 4m at the point of groundwater abstraction. Trial of the proposed well point injection system is due to take place during April / May 2004.

Ongoing and continued restoration of the Eversley site is carefully managed by RMC. Final restoration of the site will be to a sympathetically managed nature reserve (Figure 2) comprising woodland, lakes and reed beds.

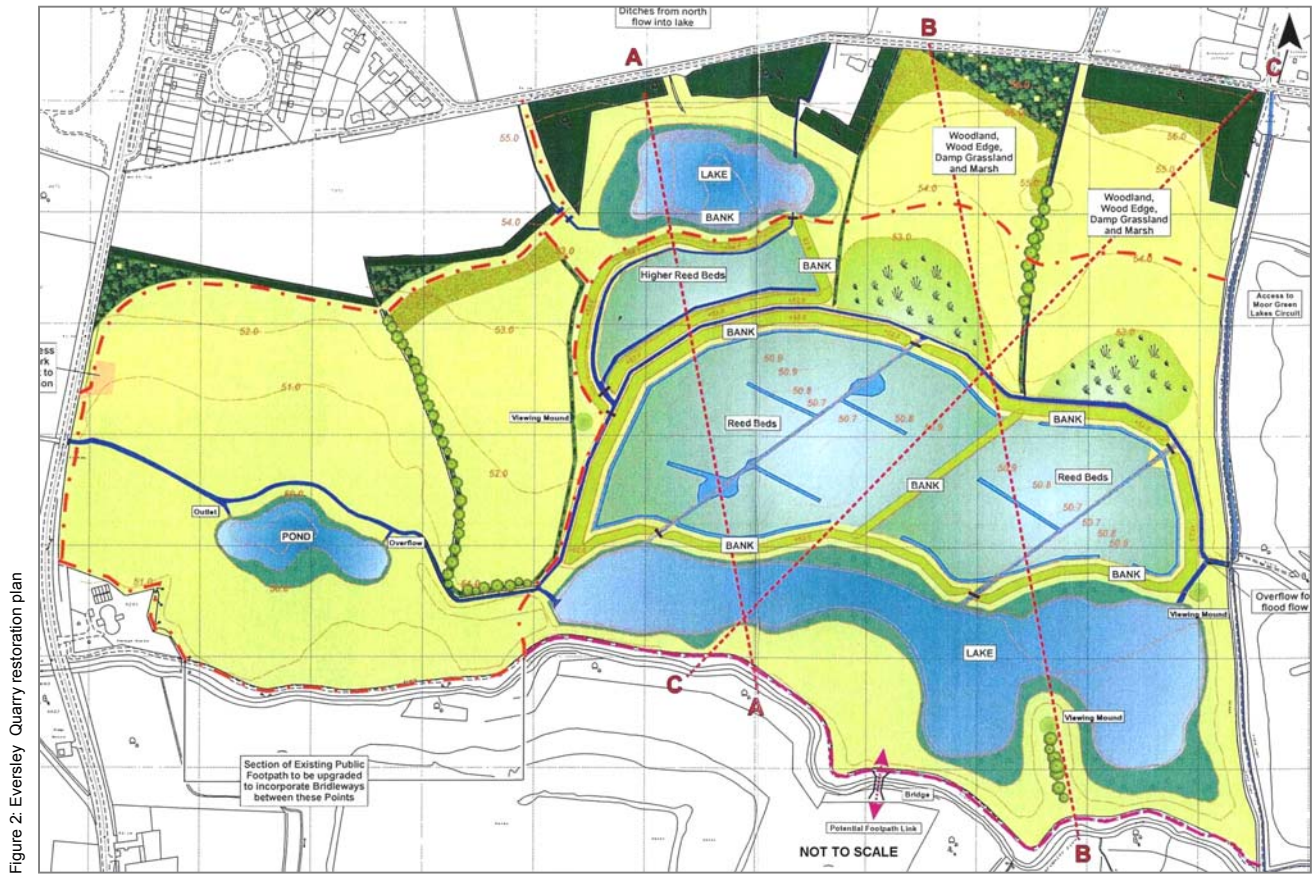


Figure 2: Eversley Quarry restoration plan

Conclusions

Groundwater level monitoring has indicated that the cone of depression due to dewatering has extended to the north-west area of the site. This indicates the necessity for mitigation measures to reduce the effects on groundwater levels in this area and hence any potential for settlement beneath property.

Recharge trench failure occurred as a result of geochemical conditions resulting in iron precipitating out of solution and accumulating in the base of the trench. Trial of the well point injection system during 2004 will indicate whether this alternative measure is likely to work.

Further information

All figures and photographs are reproduced with the approval of RMC Aggregates.

Further queries on Eversley Quarry should be directed to:

Sue Cullum
RMC Aggregates (South East) Ltd
RMC House
Coldharbour Lane
Thorpe
Surrey
TW20 8RA

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UJ. Tel: 01342 327161.



Recharge Features Case Studies

Case Study No. 8 – Norton Disney, Nottinghamshire

Protected Feature: Ancient Woodland & Wetland

Mitigation Method: Buried French Drain



Plate 1: Norton Big Wood Ancient Woodland

Statistics:

Grid reference	488000, 360000
Total quarry area	8.5 ha
Groundwater depth	2m – 4m bgl or 15 – 18 m AOD
Drawdown depth	6m bgl
Dewatering rate	~2500m ³ /day
Consent to Discharge	2500 m ³ /d

Geological Setting:

Overburden	~0.40m
Older river Sand and gravel	~ 4-6m
Lower Lias Clay	

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

This leaflet is one of a series produced as part of the MIRO research project; *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering*, which aim to illustrate the application of recharge features either exclusively or in combination with other mitigation measures in a range of different environmental and geological situations.

Recharge features are often proposed for the mitigation of lowering groundwater levels below sensitive ecological habitats as a result of dewatering. This case study focuses on sand and gravel workings where recharge trenches have been actively used for this purpose.

Background

Norton Disney Quarry, wholly owned by RMC, is surrounded by low lying topography that is widely worked for sand and gravel river deposits. Situated on a former River Trent floodplain, and to the east of the present, these deposits are a major source of aggregate for the construction industry.

The quarry site is situated approximately 15km north east of Newark, and has been operating since the early 1990's. Phases 1-18 of excavation, begun in January 1997, are completely worked out. A secondary stage of excavation is currently being undertaken approximately 250m east of the original site.

Geology

The stratigraphy of the deposits at Norton Disney is fairly uniform laterally, with thin soil cover that varies from 0.2 to 0.7m across the site. Very little overburden, (ranging in thickness from approximately 0.20m to 2.60m), overlies fluvial sand and gravels, which vary in thickness from 3.35m to 8.9m. The mineral has an average composition of 57% gravel, 41% sand and 2% silt. The gravel fraction is predominantly medium to fine grained and the sand fraction is coarse-medium to fine grained.

Within the mineral deposit lenses of clay approximately 3m wide and 0.50m in depth were observed in the working face, although the lenses are not believed to be widespread or laterally extensive. Beneath the sand and gravel lie mudstones and clays of the Lower Lias Clay.

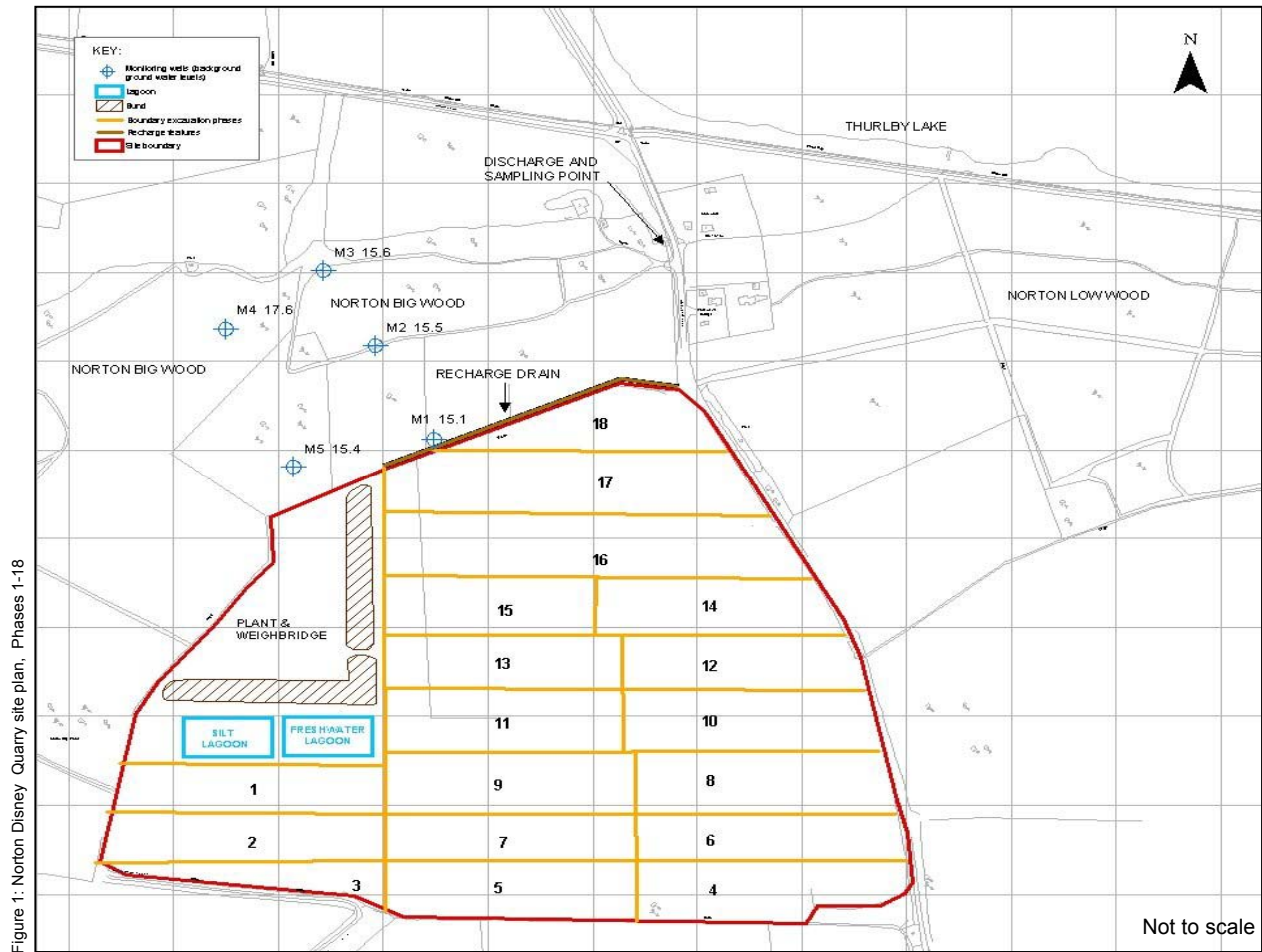


Figure 1: Norton Disney Quarry site plan, Phases 1-18

Hydrology and Hydrogeology

Groundwater flows, on a gentle gradient, from west to east from 17.56m AOD to 15.16m AOD. Surface water flows towards Thurlby lake to the north of the site.

The depth to the base of the sand and gravel increases to the east at a steeper gradient than the water table, and as a result the thickness of saturated mineral requiring dewatering increases from 3m to 6m.

The water table lies at the boundary between the overburden clay, where present, and the sand and gravel. However, where there is little or no clay deposit overlying the sand and gravels, a near surface water table occurs indicated by poor drainage and surface water features as well as vegetation of a more wetland nature as is the case towards the centre of Norton Big Wood.

The Challenge

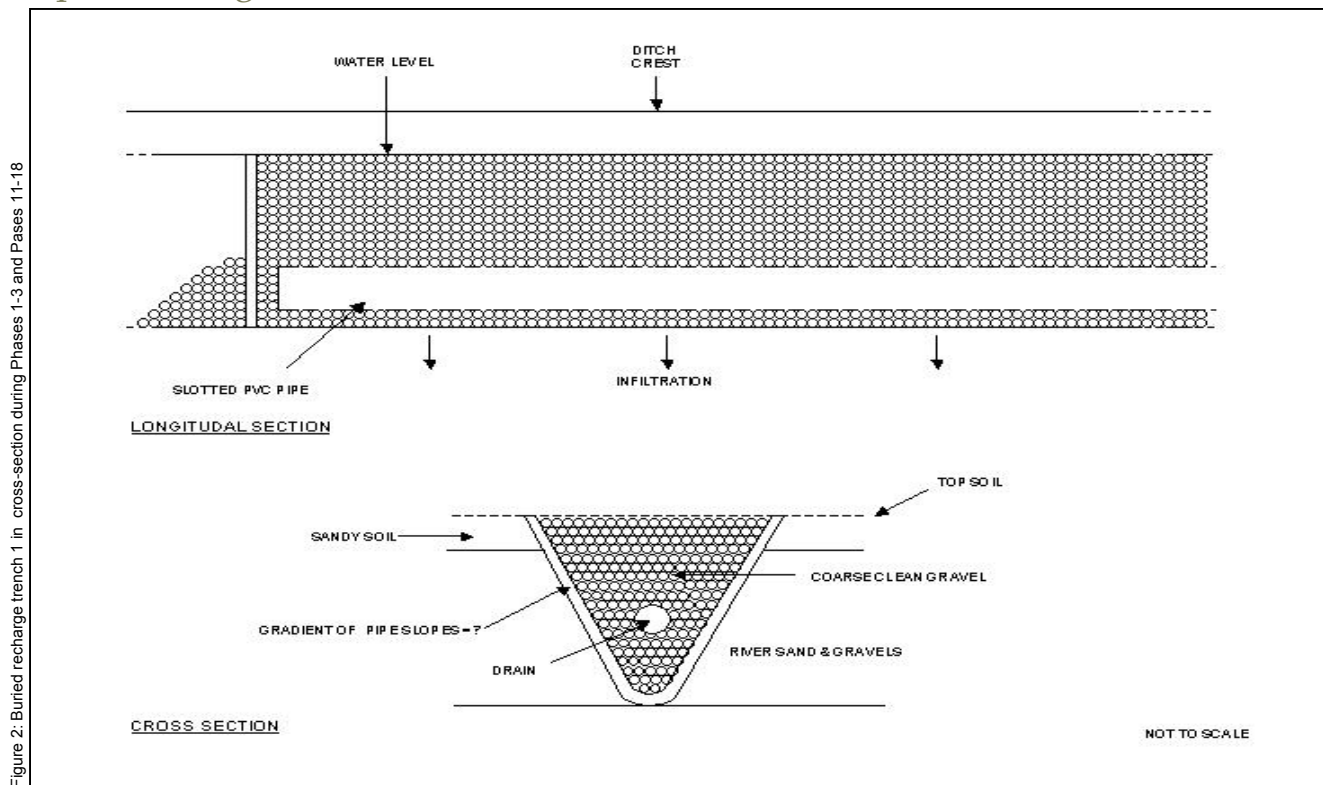
Norton Big Wood (NBW) is an area of ancient woodland located adjacent to the northern site boundary.

Although the woodland is not statutorily designated, there were concerns that the cone of depression from dewatering in the working area may extend into this sensitive habitat potentially lowering the groundwater levels with associated adverse effects.

An assessment of the hydrogeology of NBW and the likely impact of dewatering, undertaken in 1996, concluded that the dewatering and resultant lowering of groundwater levels would, in fact, benefit the woodland trees due to the increase in unsaturated zone allowing water percolation and facilitating the uptake of oxygen by tree roots.

In addition, there is an area of wetland situated towards the centre of the wood which may have been adversely affected if groundwater levels were lowered below what were considered to be minimum acceptable levels to be agreed between RMC / Butterly Aggregates and Lincolnshire County Council. As a result the local authority, Lincolnshire County Council, required the design and installation of a recharge trench, between the excavation and the wood (Figure 1), as a condition of the planning permission in the form of a Section 106 agreement.

Proposed Mitigation Measures



The recharge trench was constructed in 1996 prior to any excavation or dewatering taking place. The trench was constructed as a buried french drain using an old drainage ditch that ran parallel to the northern site boundary and the southern edge of Norton Big Wood. The design comprised a perforated pipe surrounded by coarse aggregate fill. This structure was selected in order to prevent flooding of the haul road following heavy rainfall events and for safety due to the close proximity with the main access and haul road to the site.

Monitoring wells (M1-M5) were installed and it was agreed that the recharge trench would be put into action should groundwater levels fall below the agreed acceptable minimum levels. An additional mitigation measure would be the pumping of water via a hose running along the floor of the wood directly into the stream at the centre of Norton Big Wood. However, it was anticipated that the mitigation measures would only become necessary during the final two phases of excavation which were at closest proximity to the sensitive habitat.

In an effort to reduce the impacts of dewatering and to minimise pumping costs a working strategy was implemented whereby each phase of excavation was dewatered as an individual cell thereby reducing the extent of radius of influence.

All water from dewatering was to be discharged to the worked out area, aside from that required to maintain a sufficient head gradient in the recharge trench. The water for recharge would pass through a settlement lagoon in order to reduce the silt content prior to being discharged to groundwater through the recharge trench. Any overflow from the recharge trench would be transferred via a ditch to the surface water discharge point. Weir boxes with removable lids were installed at either end, to facilitate maintenance of the recharge trench.

The Reality

Excavation and dewatering began in 1997. The excavation area was sub-divided and dewatered as individual cells. Extraction began in the southern part of the site and progressed northward towards Norton Big Wood. The recharge trench was first used in August / September 2002 during the final stages of excavation (Phases 17 and 18) which were closest to Norton Big Wood.

Monitoring of background groundwater levels began in 1996 through monitoring boreholes M1-M5. Water levels were recorded at variable intervals from June 1996 to June 2003.

Water levels recorded during dewatering were below minimum water levels recorded during the background monitoring. This suggests that the recharge trench was ineffective in limiting the extent of the cone of drawdown. A possible explanation is clogging of the slotted pipe and the surrounding aggregate fill as a result of silt deposition.

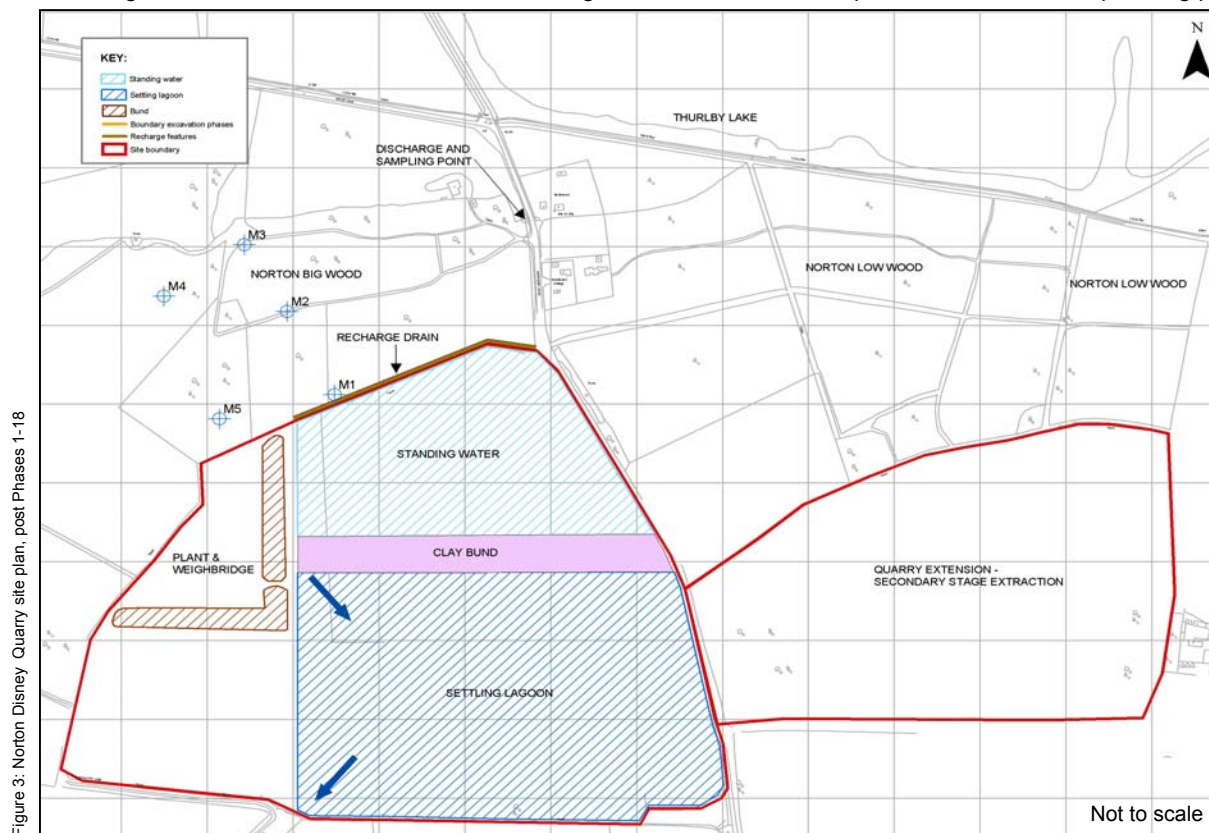
Seepage of groundwater through the exposed face in the final two working cells suggests that a large amount of the water discharged from the trench flowed down gradient into the void created by the excavation. It was found that increasing the flow through the trench resulted in flooding of the haul road towards the eastern end of the trench.

Current Status

The worked out area is now a settlement lagoon recycling water from the plant. As part of the restoration programme and in order to limit the extent of drawdown from the settlement lagoon a clay bund was constructed in the northern end of the worked out area (Figure 3). As a result water is only circulated through the water body south of this low permeability barrier.

Although this has proved to be partially effective in maintaining groundwater levels higher than those within the settling lagoon, groundwater seepage is apparent on the exposed northern face due to the limited dewatering carried out to facilitate the restoration.

Excavation is now taking place in an extension area to the east. Although adjacent to Norton Low Wood, the area is not sensitive to groundwater fluctuations and hence no mitigation measures were required as a condition of planning permission



Conclusions

The lowering of groundwater levels below Norton Big Wood, suggests that the efficacy of the recharge feature was limited.

The unsatisfactory performance of the recharge trench is attributed to possible siltation prior to and/or during its operation and to recirculation of water to the excavation rather than recharge of the aquifer to the north.

Rolling restoration of the working areas would have prevented the formation of a large void and may have led to a less extensive drawdown cone. The use of a low permeability bund between the working area and the recharge feature would have reduced groundwater flow to the void increasing the potential efficiency of the recharge feature and limiting the lateral extent of the cone of depression.

Further information

All figures and photographs are reproduced with the approval of RMC.

Further queries on Norton Disney Quarry should be directed to:

Chris Pointer, RMC (UK) Ltd, RMC House, Church Lane, Bromsgrove, Worcestershire, B61 8RA

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson, Symonds Group Ltd, Symonds House, Wood Street, East Grinstead, West Sussex, RH19 1UU. Tel: 01342 327161.



Recharge Features Case Studies

Case Study No. 9 – Tattershall Thorpe, Lincolnshire

Protected Feature: Myers Plantation SSSI

Mitigation Method: Recharge Trench



Plate 1: Myers Plantation SSSI

Statistics:

Grid reference 521500, 361500
Total quarry area 225 ha
Dewatered area 72.8 ha
Groundwater depth 0.1m – 1.7m bgl
Drawdown depth ~5m bgl
Dewatering rate ~900 m³/day

Geological Setting:

Clay overburden (~ 1.1m)
Fluvio-glacial sand and gravel (~ 2.6m)
Glacial till

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

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This case study focuses on the life cycle of a recharge feature and its effect in mitigating the lowering of groundwater beneath a protected habitat as a result of dewatering.

Background

Tattershall Thorpe Quarry, wholly owned by RMC, (formerly Butterly Aggregates), occupies most of the former RAF Woodhall Spa airfield in the region of Lincolnshire which has long been quarried for sand and gravel. Planning permission for the site was granted in May 1986 and Phases 1-14 are now completely worked out.

Myers Plantation, a designated Site of Special Scientific Interest (SSSI), situated immediately east of the site, sits at a lower topography than the northern area with a further reduction down gradient to the south west.

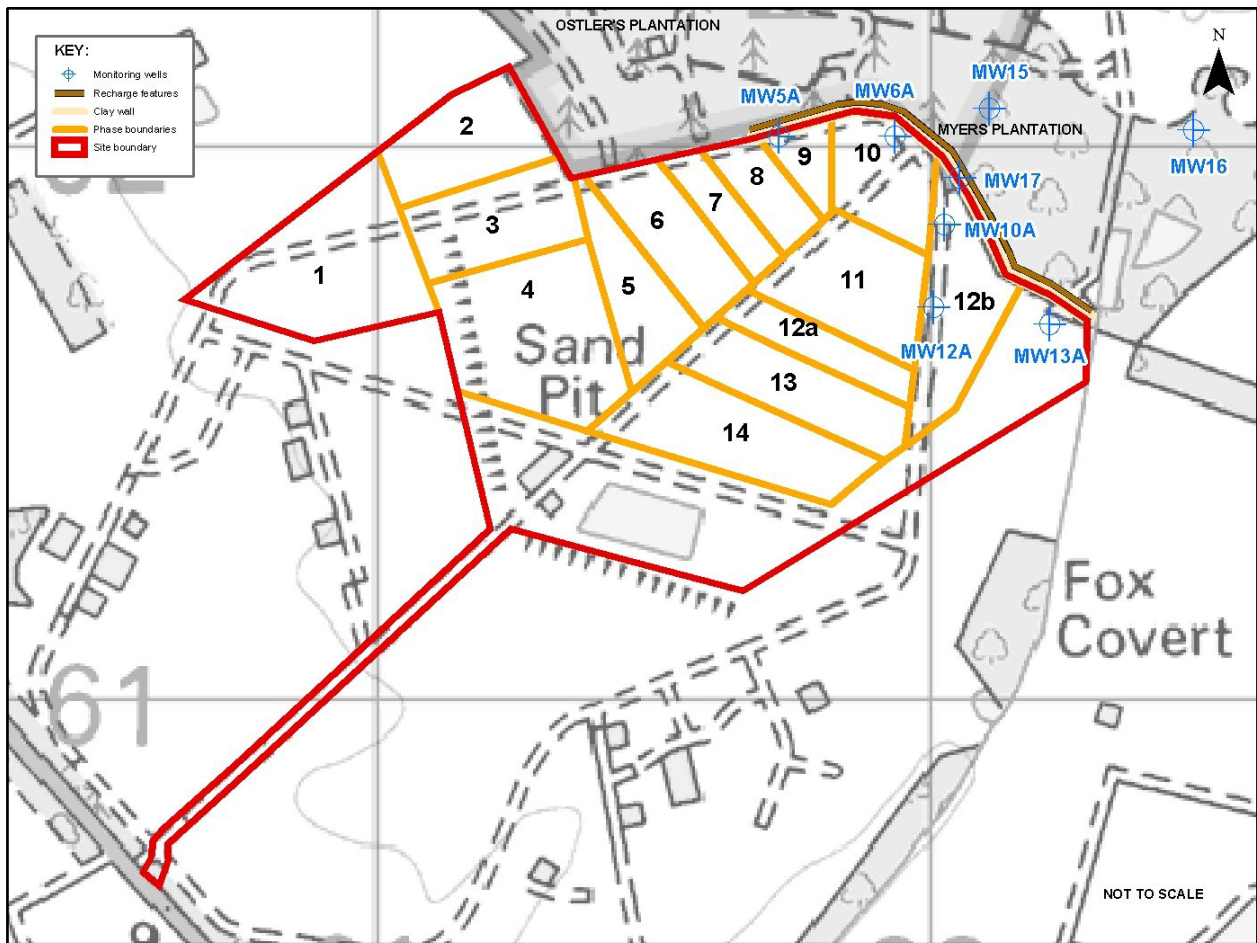
Geology

The mineral is worked from an extensive, laterally discontinuous, fluvio-glacial sand and gravel deposit.

Overburden consisting of thin pebbly soil overlying clays, silty sand and clayey sand, is on average 1.10m thick. The sand and gravel deposits range in thickness from 0.7m to 7.8m and underlie Myers Plantation. On average, the deposits are 2.6m thick comprising predominantly fine grained, gravelly sand. The mineral is thinner and more clayey in the south east where it unconformably overlies the chalky till.

Below the drift undifferentiated Upper Jurassic deposits extend to an undetermined depth.

Figure 1: Tattershall Thorpe Quarry site plan



Hydrology and Hydrogeology

Groundwater levels decrease sharply from 15.47mAOD to 11.2mAOD in a south west direction. Groundwater flows down gradient from Ostler's Plantation in the north and Myers Plantation in the north east.

A near surface water table occurs beneath Myers Plantation with maximum groundwater levels of approximately 0.1m below ground level and seasonal fluctuations of approximately 1m. The geometry and permeability play an important role in controlling groundwater flow whereby the non-conformable boundary between the sand and gravel and the low permeability glacial till prevents groundwater from flowing eastwards.

The Myers Plantation SSSI is drained by a number of open channels which discharge into the drain adjacent to the quarry boundary.

Due to historic land use as an airfield, the quarry site is underlain by an extensive system of tile and pipe drains which act to maintain a below surface groundwater level. In order to facilitate dry working of the mineral, dewatering to the base of the sand and gravel deposits was required.

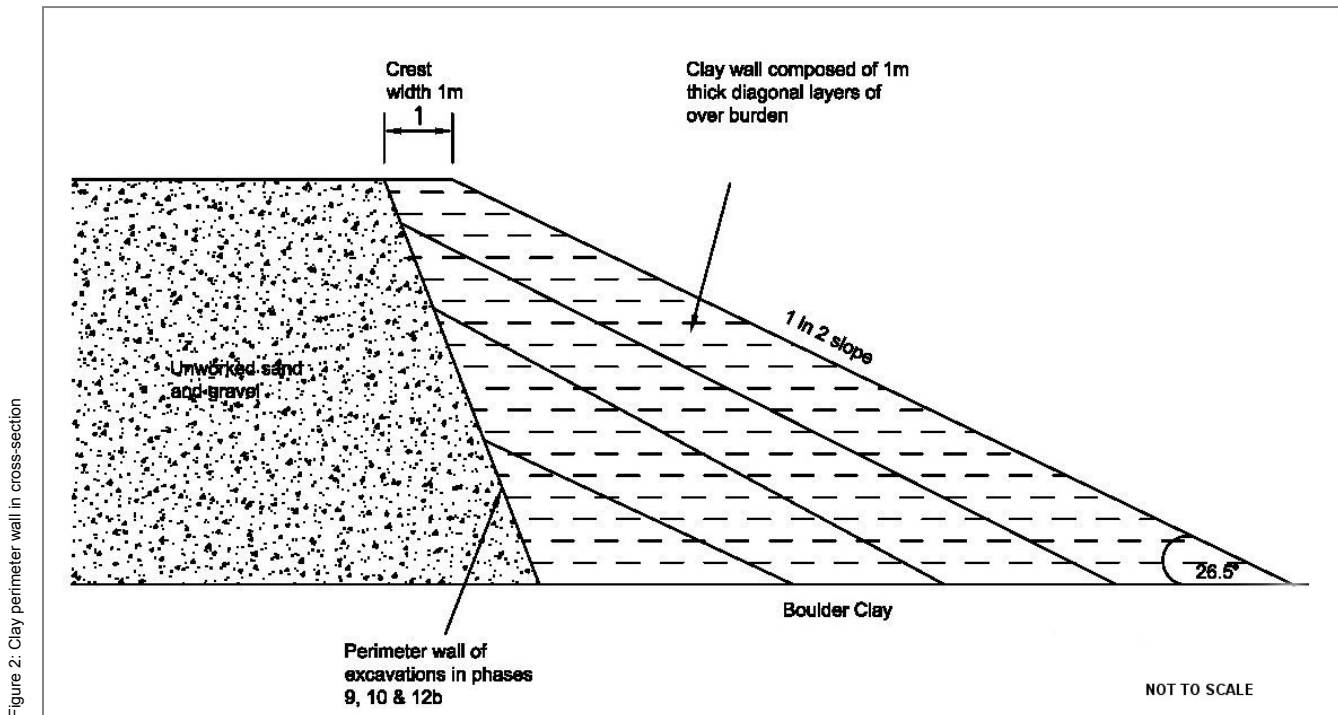
The Challenge

Myers Plantation is a designated SSSI due to its wetland – heathland habitat, bordering Phases 9, 10 and 12b (Figure 1). These habitats with their characteristic near surface water table are sensitive to changes in ground water level and the sand and gravel within the excavation area is laterally continuous with those deposits beneath the Myers Plantation.

Due to concern that the zone of influence resulting from dewatering of the excavation area, particularly for Phases 9, 10 and 12b would extend into the SSSI, causing considerable lowering of groundwater levels with potential adverse effects, Lincolnshire County Council granted planning permission with the following condition:

'No mineral extraction whatsoever shall take place in the working phases 9, 10 and 12b identified on Plan (P1/1236/3/1 until such time as the County Planning Authority is satisfied that agreement has been reached between the Mineral Operators (Butterly Aggregates Limited) and the Nature Conservancy Council (now known as English Nature), on acceptable working methods and safeguards for nature conservancy within the SSSI and Nature Reserve adjoining the site.'

Proposed Mitigation Measures



A stepped action plan was proposed for the excavation of phases 9, 10 and 12b which were worked progressively along the boundary from north west to south east.

From the outset of excavation of Phase 9, a low permeability clay perimeter wall (Figure 2) would be progressively constructed using overburden or glacial till exposed by previous phases. At any given time only 15m of the working face would be exposed in order to minimise the potential for groundwater to flow into the excavation.

It was agreed that weekly monitoring would continue of boreholes 15, 16, and 17, (amongst others sited in the SSSI) and twice daily of borehole 10a which is sited on the boundary between the excavation area and Myers Plantation. Based on the background monitoring a set of three annual trigger levels was proposed for each of the boreholes 15, 16 and 17 and agreed with the Local Authority. A rain gauge was also installed on site in order to facilitate the interpretation of the hydrographs.

Should groundwater levels fall below the agreed trigger levels (e.g. 13.93m AOD for MW17 for August to October); Butterfly aggregates were obliged to notify English Nature and the Lincolnshire Trust for Nature Conservation.

Furthermore, if groundwater levels remained below trigger levels in any of the three boreholes for two consecutive weeks or more, as a direct result of dewatering, a recharge feature would be constructed. This would consist of deepening an existing drainage channel between the SSSI and the excavation and damming one end in order to reverse the flow to recharge the aquifer. The excavation-side wall of the channel would also be lined with clay in order to minimise groundwater flow in the direction of the excavation.

Discharge rates would be controlled according to observed groundwater levels and only water entering the working area would be pumped to the recharge channel, therefore it would be considered to be a closed circuit system. Maintenance would be periodically undertaken to prevent the channel from silting up, which would reduce its infiltration capacity and hence efficiency.

The Reality

Dewatering of Phase 9 began in May 1992. Upon commencement of dewatering the groundwater levels in monitoring wells 15, 16 and 17 fell below the agreed trigger level values for that period (Figure 3). The low permeability bund was constructed as proposed.

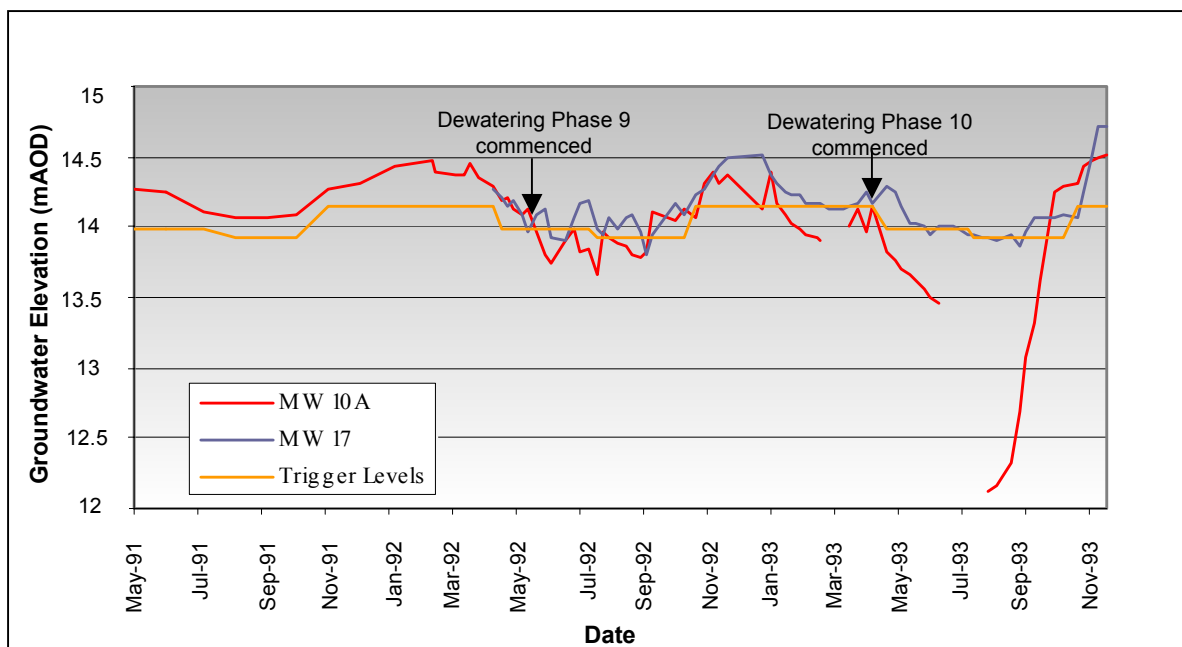
Groundwater levels recovered to above trigger levels and remained so until September 1992 when levels recorded in monitoring wells 15 and 17 fell below the pre agreed minimum values again. Meteorological evidence suggested that the reduction in water table level coincided with a period of low precipitation and high evaporation.

However it was decided to put into use the recharge trench to try to raise the groundwater levels to their natural wetland state.

Water abstracted from the excavation site, was continuously discharged into the recharge trench at a variable rate. The hydrograph (Figure 3) indicates that groundwater levels did recover although this also coincided with increased precipitation.

The Reality (continued)

Figure 3: Variation in groundwater levels in Tattershall Thorpe Quarry and Myers Plantation



During dewatering of Phase 10, which commenced in June 1993 in closest proximity to Myers Plantation SSSI, the hydrograph illustrates a marked difference between groundwater levels measured in MW 10A, (within the working area) and 60m away at MW 17, (outside the excavation area sited just within the SSSI).

Groundwater levels in the SSSI were observed to be 1.80m higher than in the excavation area. Between these two points the clay bund ran along the boundary of the excavation area and the recharge trench lay between the clay bund and the SSSI. This suggests that the mitigation measures were effective in minimising the impact of dewatering and artificially maintaining groundwater levels in the SSSI.

Conclusions

The low permeability bund was effective in maintaining groundwater levels in the early stages of dewatering. It is evident from the difference in groundwater levels between MW 10A and MW17, located either side of both the perimeter low permeability bund and the recharge trench, that the combination of mitigation measures was successful.

Further information

All figures and photographs are reproduced with the approval of RMC.

Further queries on Tattershall Thorpe Quarry should be directed to:

Chris Pointer
RMC (UK) Ltd
RMC House
Church Lane
Bromsgrove
Worcestershire
B61 8RA

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU.

Tel: 01342 327161.



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Appendix B

Recharge Trench Experiments

Recharge Features Experimental Sites

Experiment No. 1 – Chamberhouse Farm, Berkshire

Protected Feature: Bowdown & Chamberhouse Woods SSSI

Mitigation Method: Recharge Trench

Plate 1: Recharge Trench, Chamberhouse Farm



Statistics:

Grid reference	451600 165900
Total quarry area	Greenfield Site
Dewatered area	-
Groundwater depth	~1.1 m b.g.l
Drawdown depth	~ 1 m
Dewatering rate	3,024 m ³ /day

Geological Setting:

Overburden	(0.9 – 1.8 m)
Terraced Sands and Gravel	(2.8 – 5.1 m)
London Clay	
Reading Beds	

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

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The experimental sites were set up where a functioning recharge trench can be monitored in a controlled manner under a variety of management scenarios, to investigate the optimum construction and the operation and management of a recharge trench.

The aim of the Chamberhouse Farm experiment was to explore some of the practical factors which might contribute to the effectiveness of a recharge feature in meeting its purpose, the maintenance or reversal of lowering of groundwater levels below a nearby sensitive feature.

Background

The Chamberhouse Farm site is located approximately 5 km east of Newbury, Berkshire, within the floodplain of the River Kennet and within an area of ecological importance (in close proximity to the Bowdown & Chamberhouse Woods SSSI, and the Thatcham Reedbeds SSSI and cSAC). To the west, south and east the site is bounded by the River Kennet, and to the north by the Kennet and Avon Canal. The recharge features experiment was situated in the western end of the site.

River Terrace and Valley sands and gravels form the economic mineral of the Chamberhouse Farm site. The site itself is identified as a Preferred Area within the Local Mineral Plan and constitutes a satellite resource block for Tarmac's existing Lower Farm Quarry processing plant, which is located on the opposite side of the River Kennet, to the west.

Geology

The River Terrace and Valley sands and gravels are present within a broad two kilometre wide belt oriented from west to east within the valley bottom of the River Kennet. Dipping gently to the east, the solid geology of the surrounding area consists of Upper Chalk, overlain by Reading Beds, in turn overlain by London Clay.

Within the experimental area overburden comprising topsoil, alluvium and occasional peat, varying in thickness between 0.9 m and 1.8 m, were found to overlie the sand and gravel mineral deposit. The sand and gravel deposits were described as poorly sorted grey flint gravel with 10% - 20% white to light grey coarse grained clean sand, with little silt evident.

Thicknesses of 2.8 m to 5.1 m were recorded in the vicinity of the experimental area (an average of 3.9 m recorded within the monitoring wells). Underlying the sands and gravels, within the experimental area, drilling revealed a blue grey stiff to firm silty clay, interpreted to be the London Clay.

Hydrogeology

The River Valley and Terrace and Valley sands and gravels are classified by the Environment Agency as a Minor Aquifer with soils of a high leaching potential. The underlying London Clay is classified as a Non Aquifer.

Within the experimental site area historic groundwater levels recorded range from 65.87 m AOD to 66.78 m AOD (approximately 0.63 m to 1.54 m below ground level). Within the installed monitoring wells, water levels were observed to generally coincide with the boundary of the overburden and the sand and gravel.

Background groundwater levels recorded in the experimental area were found to be approximately 1.1 m below ground level (bgl), varying from 65.96 m AOD to 66.37 m AOD across the site.

Groundwater levels recorded within the Bowdown and Chamberhouse Woods (and located approximately 85 m north of the proposed experimental area), between 1990 and 1993, varied from 65.57 m AOD (recorded in Dec 1990) to 66.92 m AOD (recorded in Jan 1993) with an average of 66.6 m AOD.

Generally groundwater flow across the Chamberhouse Farm site is from west to east.

The Priors Moor Ditch is a man made ditch constructed for the purposes of land drainage, which acts as a groundwater sink locally, resulting in north easterly and south easterly components of groundwater flow in the vicinity.

Results of field and laboratory testing undertaken by Tarmac during earlier hydrogeological investigation indicate that theoretical permeability values (based on the Hazen formula) may potentially range over two orders of magnitude.

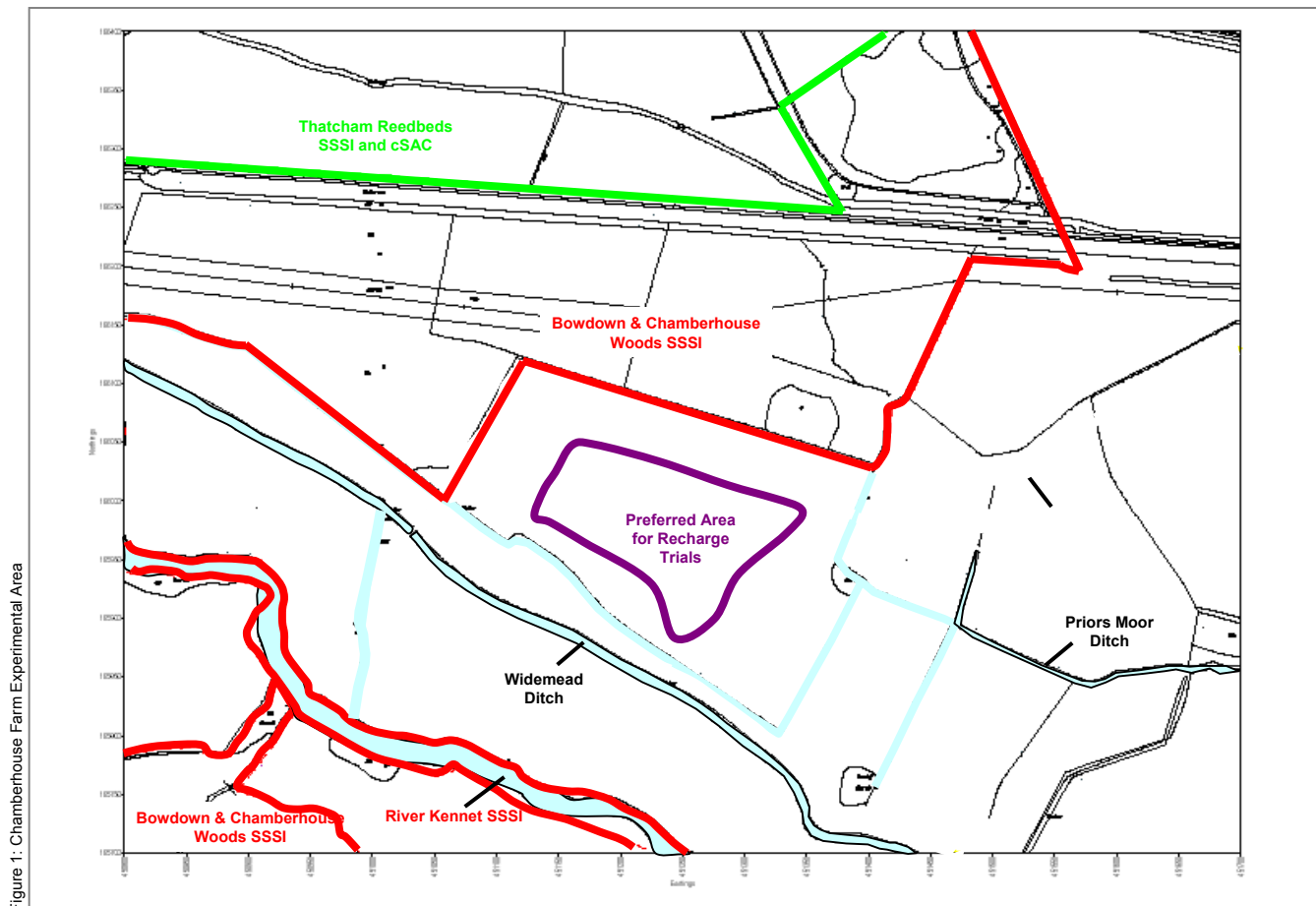


Figure 1: Chamberhouse Farm Experimental Area

The Challenge

Chamberhouse Farm, in contrast to the other experimental site of Methley Quarry, is a greenfield site and as such groundwater levels have not been significantly impacted by human intervention (with the exception of the influence of the Priors Moor Ditch).

The aim of this experiment was to create a temporary cone of depression, and then to monitor the response of the drawdown cone to artificial recharge using the nearby recharge trenches.

The purpose of the experiment was to explore some the practical factors which might contribute to the effectiveness of a recharge feature in meeting it's purpose, the maintenance or reversal of lowering of groundwater levels below a nearby sensitive feature, the Thatcham Reedbeds, which constitute a Site of Special Scientific Interest (SSSI) and a candidate Special Area of Conservation (cSAC) site, and are located approximately 270 m north of the proposed experimental area.

The Experiment

The overall principle of the experiment was firstly to generate a cone of depression in groundwater levels below the experimental area of Chamberhouse Farm.

At the point where one metre drawdown would be predicted, it was proposed to install two recharge trenches (on opposite sides of the cone of depression and differing dimensions) and discharge abstracted water to each of them (in roughly equal volumes) for an extended period whilst continually monitoring to observe changes which may be attributable to recharging.

Trench 1 (north of the abstraction well) was designed to be approximately 10 m long, 1 m wide and 1 m deep (a maximum internal surface area of 32 m²), such that it's base would be placed in the top of the sand and gravel deposits and the thickness of (dewatered) unsaturated zone below would be approximately 1 m when groundwater levels were depressed during pumping.

With a thinner unsaturated zone of 0.5 m, Trench 2 (south of the abstraction well) was designed to be approximately 1.5 m deep, by 5 m long and 2 m wide (maintaining the same basal area as Trench 1, with a maximum internal surface area of 31 m²).

Groundwater monitoring wells, with data loggers, together with a network of manually dipped piezometers were installed to continually record and monitor groundwater levels underlying both the experimental site and nearby SSSI both prior to, during and following abstraction.

During Week 1 of the experiment, monitoring of background groundwater levels was undertaken. Week 2 saw the carrying out of an initial pumping trial in order to gather further information on the hydraulic properties of the underlying aquifer; and to monitor the cone of depression created.

The final siting of the recharge trenches, where approximately 1 m of groundwater drawdown was interpolated, was determined during this initial pumping trial.

At the start of the constant discharge test, groundwater was abstracted at a rate of 22 l/s. However it was observed that drawdown within both the well, and in the surrounding area was lower than predicted (indicating a potentially higher permeability). Drawdown of groundwater levels within the immediate surrounding area of the abstraction well was not reaching the 1 m needed for the recharge features experiment.

In order to generate a greater drawdown, the submersible pump was changed for a surface suction pump and the constant discharge test continued with an abstraction rate of 35 l/s. The increase in abstraction rate to 3,024 m³/day was agreed with the Environment Agency prior to the change in pump.

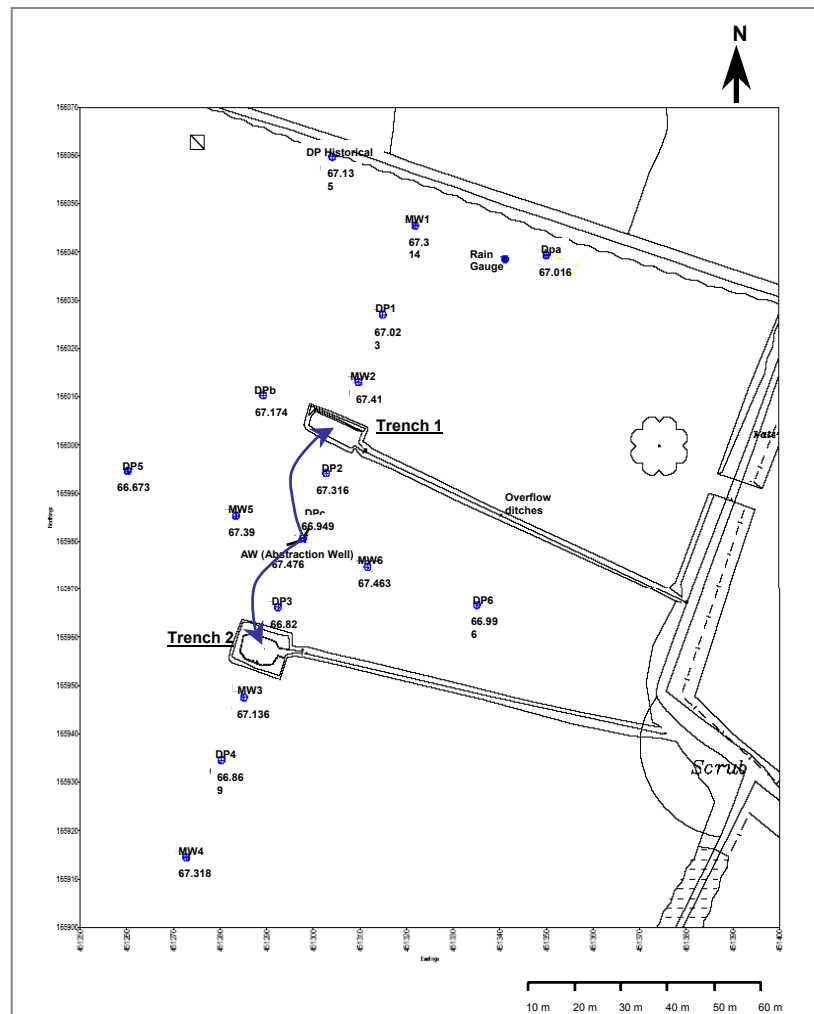


Figure 2: Chamberhouse Farm Experiment Layout

The Reality

One overall observation was the significant impact that rainfall had on groundwater levels within a short space of time after the start of a rainfall event, and the impact this has had in terms of masking some of the results of the constant discharge test and during periods of discharging to the recharge trenches.

After an initial pumping trial a constant discharge test was performed to ascertain the in-situ hydraulic properties of the sand and gravel aquifer, and to monitor the development of a cone of depression in order to determine the distance from the abstraction well at which approximately 1 m of drawdown might be predicted.

The initial pumping observations indicated that the sand and gravel aquifer was behaving in a manner closely resembling that of an unconfined aquifer. Analysis of constant discharge test results indicated potential transmissivity values ranging from 741 m²/d to 867 m²/d. Assuming an average sand and gravel aquifer thickness of approximately 4 m, this corresponds to permeability range of approximately 185 m/d to 217 m/d.

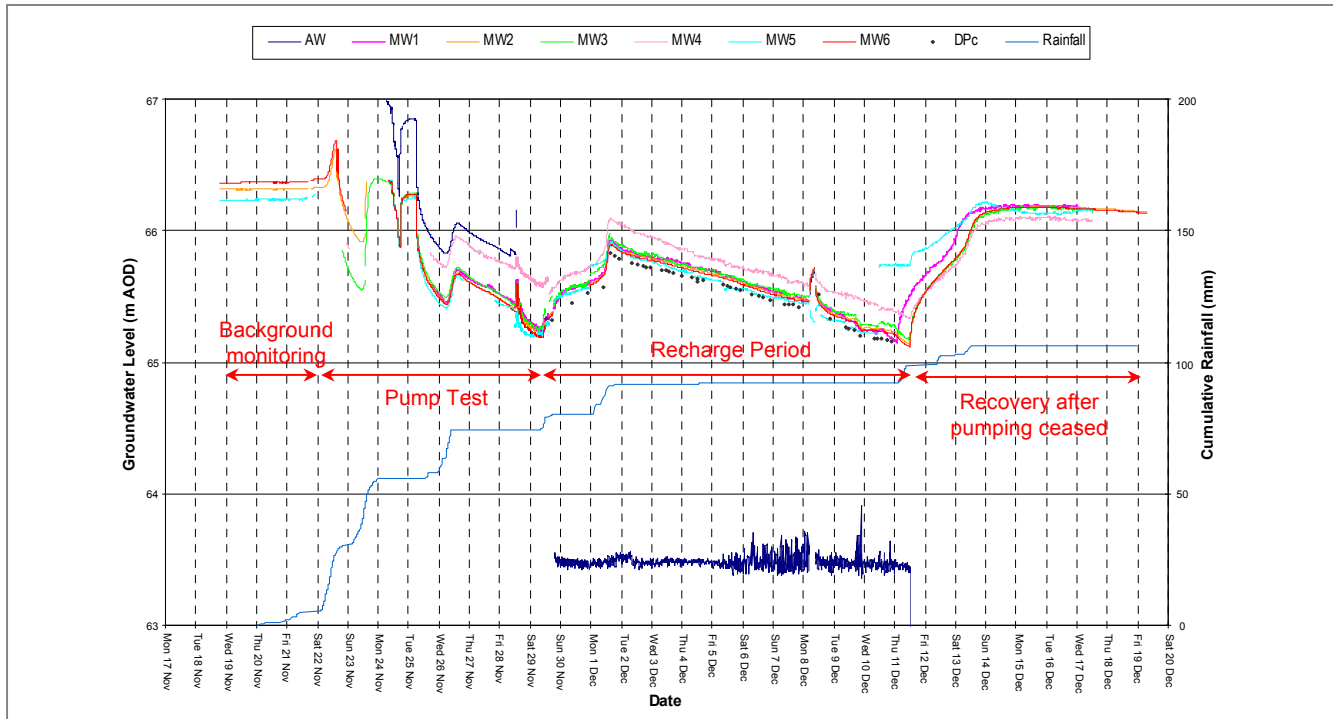


Figure 3: Experimental Results

During the recharging phase, abstraction of groundwater continued at a rate of approximately 33 l/s to 35 l/s.

Ignoring the rainfall event, the rate of drawdown from 26 November to 29 November (prior to recharging) was observed to be approximately 0.003 m per hour. Discharging to the two recharge trenches commenced on 29 November 2003, with approximately 21 l/s to Trench 1 and 15 l/s to Trench 2 until 8 December.

An initial period of groundwater level recovery immediately after recharging commenced may be observed. Although some of this may be attributable to the rainfall event of 29 November, it may be seen that previous rainfall events have been reflected as spikes in groundwater levels that decline as sharply as their initial rise. This was not the case during the 29 – 30 November period, and hence it may be assumed that the rise in groundwater levels during this time may be attributable to the commencement of recharging.

The groundwater levels in monitoring wells near to Trench 1 were observed to increase at a rate of approximately 0.005 m/hr (0.5 cm/hr) during this period. Levels near to Trench 2 were calculated to rise at a mean rate of approximately 0.006 m/hr in MW3, and 0.005 m/hr in MW4. Groundwater levels had risen by approximately 0.53 m to 0.59 m prior to the rainfall event of 1 December when groundwater levels were observed to jump by a further 0.2 m.

Following the rainfall event, groundwater levels were observed to decline, by 8 December they had reached approximately the same levels as just before the rainfall event of 1 December. However it was found that mean drawdown rates had decreased from 0.003 m/hr to 0.0006 m/hr which may be attributed to the impact of discharging abstracted water to the recharge trenches.

However, given that the recharge rate was calculated to be up between 0.4 cm/hr and 0.6 cm/hr, and the original drawdown rate was found to be approximately 0.3 cm/hr, it would be expected that there would be a net gain to groundwater levels of around 0.1 – 0.3 cm/hr, yet levels still continue to decline during recharging. This potentially suggests that the cone of depression was still developing.

The Reality (continued)

After the cessation of pumping the groundwater levels were observed to rise quickly, reaching a level 0.10 to 0.19 m below the original level within 4 to 7 days.

During recharging, in Trench 1 (receiving a constant discharge of approximately 22 l/s), losses to overflow ditches were initially high at 60%, but within 24 hours had dropped to around 30% and then after a further five days declining to around 20% to 28% loss. In contrast, it was observed that discharge rates to the overflow ditches were proportionally higher for Trench 2, which was in receipt of a lower groundwater discharge (15 l/s). From commencement of recharging, losses to the overflow ditches were approximately 50% to 60% of the total volume inputted. This high loss remained relatively consistent during the following six days.

Plate 2: Chamberhouse Farm Experimental Site



Theory

In order to begin to understand the response of groundwater levels during recharging, it is useful to consider the water balance of the experiment (Figure 4). When a groundwater system is in **steady state**, flow is independent of time and water levels will no longer change. Prior to reaching a steady state situation, groundwater flow is said to be in **unsteady state**.

Groundwater flow is based upon the principles of the conservation of fluid mass which seeks to balance system inputs and outputs, through changes in water mass held in storage within the porous media ($Q_{in} = Q_{out} - \Delta\text{mass held in storage}$)

In a steady state situation, $Q_{in} = Q_{out}$, and therefore there is no change in the volume of water being either released or taken into storage.

In an unsteady state situation, where inputs and outputs are not equal, the groundwater system will seek to re-establish equilibrium by releasing water for storage (seen as a fall in groundwater levels) or taking into storage (seen as a rise in water levels).

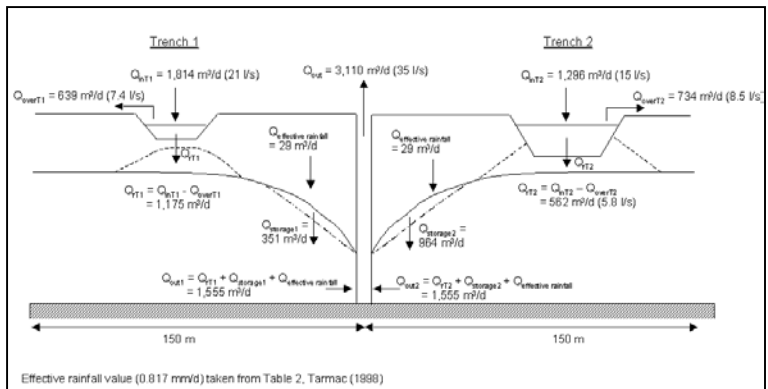


Figure 4: Chamberhouse Farm Experimental Water Balance

As can be seen from the water balance in Figure 4, in the case of Chamberhouse Farm inputs and outputs were not equal, and hence water levels were observed to fall as water was released from storage to compensate.

The drop in groundwater levels (and hence cross sectional flow area with respect to Darcy's Law, $Q = KiA$) will also lead to an increase in hydraulic gradient (i) between water levels within the trench and within the underlying ground in order to maintain the discharge rate (Q).

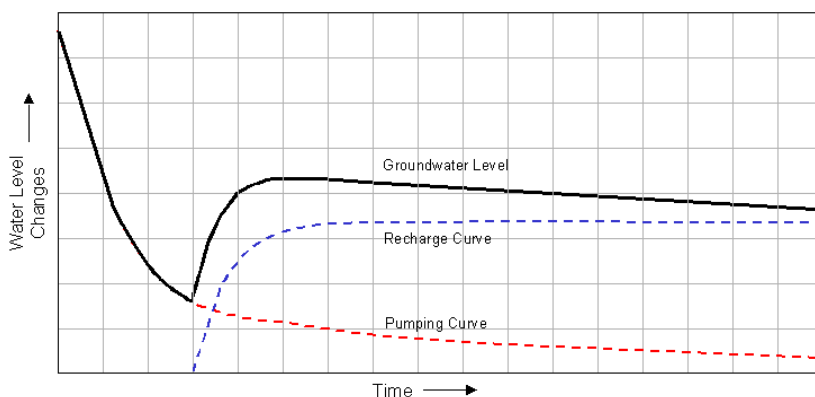


Figure 5: Schematic Diagram Showing the Theoretical Response of Groundwater Levels to Recharging at Chamberhouse Farm

Following the principles of conservation and superposition (Figure 5), it may be seen that when recharging starts inputs exceed outputs, and hence water is taken into storage with an associated rise in groundwater levels.

Over time, water levels which may be associated with recharging alone are likely to reach a steady state. However in the case of the pumping curve, continued drawdown in an unsteady state aquifer will mean outputs exceeding inputs once again, and a subsequent drawdown of water levels again.

However, it may be seen that groundwater levels are not as low as they would have been if no recharging had taken place.

Conclusions & Limitations

Experimental results showed that the permeability of the sand and gravel aquifer was higher than originally predicted, leading to a greater potential radius of influence, and hence a greater predicted drawdown in MW1 (the monitoring well closest to the Bowdown and Chamberhouse Woods SSSI).

Even though some rise in groundwater levels was apparent as a result of recharging, the total rise in groundwater levels of 0.5 m was not enough to lead to groundwater levels recovering to background in the vicinity of the SSSI.

However, if the recharge trench had been located in closer proximity to the SSSI, or had been a larger internal surface area (in order to enable a larger recharge volume to enter the ground in accordance with Darcy's Law), this may have made a difference.

What can be seen from the Chamberhouse Farm experiment is that during recharging, drawdown rates were significantly lower than prior to recharging. Where ecosystem (or man made structures) are potentially sensitive to even small changes in groundwater levels this may be important.

Groundwater level responses to recharging from Trenches 1 and 2 appear to occur at the same time and have the same magnitude of impact. This may suggest that the difference in basal trench dimensions did not make a significant difference. This may be due to the fact that the overall internal surface area for each trench was approximately the same.

What is not known, and cannot be judged from the data collected during this experiment, is whether if recharging to the aquifer had been started at the same time as groundwater abstraction, whether the extent of the zone of dewatering influence could have been minimised, or it's rate of expansion slowed down.

Further information

Further information may be found in a separate report, available from Symonds Group, entitled '*Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering: Chamberhouse Farm, Newbury – Experiment: Overview and Findings*'.

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Further queries on Chamberhouse Farm should be directed to:

Eddie Bailey
Tarmac Southern Ltd
Stancombe Quarry
Stancombe Lane
Flax Bourton
Bristol
BS48 3QD

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU. Tel: 01342 327161.



Recharge Features Experimental Sites

Experiment No. 2 – Methley Quarry, West Yorkshire

Protected Feature: Mickletown Ings SSSI

Mitigation Method: Recharge Trench

Plate 1: Recharge Trench 2, Methley Quarry



Statistics:

Grid reference	441000, 426500
Total quarry area	~13 ha
Dewatered area	~ 1.2 ha
Groundwater depth	~10 m AOD
Drawdown depth	~ 3 m
Dewatering rate	Variable, maximum of ~3000 m ³ /day

Geological Setting:

Silt and clay alluvial deposits (1-2 m)
Terraced sand and gravel (~10 m)
Carboniferous Coal Measures

Dry working of mineral deposits is often preferred by mineral operators, since it enables more efficient and safe excavation of aggregate. This involves lowering the water table to approximately the base of the mineral by dewatering the working area. Dewatering can have a considerable impact on groundwater levels in the surrounding area, creating a 'cone of depression' upon the water table. The radius of influence of lowered groundwater may often extend beyond the boundaries of the working area.

The significance of any environmental impact of dewatering depends upon the sensitivity to lowering of groundwater levels of structures, habitats, and land uses within the surrounding area. With increasing environmental awareness, operators are often required as a condition of planning consent to install/propose mitigation measures to minimise such a reduction in groundwater level. Recharging of abstracted water to the ground/groundwater is an example of one possible mitigation measure.

This leaflet is one of a series produced as part of the MIRO research project; *Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering*, which aim to illustrate the application of recharge features either exclusively or in combination with other mitigation measures in a range of different environmental and geological situations.

The experimental sites were set up where a functioning recharge trench can be monitored in a controlled manner under a variety of management scenarios, to investigate the optimum construction operation and management of a recharge trench.

The Methley Quarry experiment aims to examine how quickly an existing cone of depression reacts to the commencement of recharging, the influences of siltation and the growth of vegetation and to examine how well the response can be predicted using a groundwater model.

Background

Methley Quarry is located approximately 2 km north-west of Castleford, West Yorkshire, near to the town of Mickletown. The site is operated by Lafarge Aggregates Ltd, and owned by Methley Estates. The quarry is situated on Second Terrace Sands and Gravels and Alluvium, bound to the north and east by the River Aire and to the south by the River Calder.

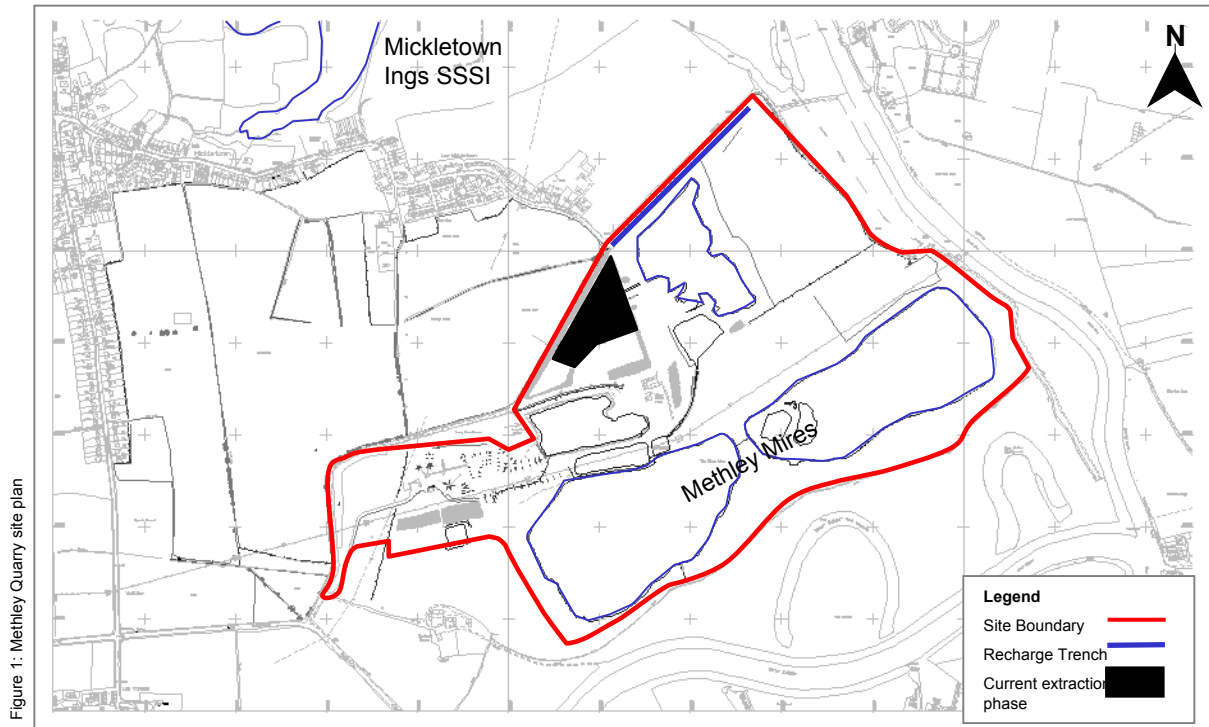
The extraction of sands and gravels from the existing quarry site has almost been completed with the eastern part of the site restored, having been backfilled with the overburden, sub-soil and topsoil. The remaining completed open extraction phases are used as part of the water circulation system for the abstracted water.

A planning application has been accepted to extend the mineral workings to the north of the existing site and extending to the west towards Mickletown Ings SSSI.

Geology

The Second Terrace Sands and Gravels and Alluvium are present on the valley floors of the Rivers Aire and Calder. The Terraced Gravels are found to underlie the whole of the floodplain and with a thickness ranging between 6 and 12 metres at the quarry site, with the Alluvial deposits up to 4 metres thick

The underlying geology is made up of the Carboniferous Middle Coal Measures, consisting of a complex cyclic sequence of mudstones, siltstones, sandstones, seat earths and coal. As a result of folding and extensive faulting individual beds are commonly discontinuous and restricted to the area in which they are found. Borehole logs show the Terraced Sands and Gravels at the quarry site to sit directly on top of a mudstone horizon of the Coal Measures.



Hydrogeology

The Terraced Sands and Gravels and the Alluvium are water bearing and form a minor unconfined aquifer. The groundwater level in the sand and gravel lies between 5 and 7 metres below the ground surface (7 to 9 m AOD).

The Middle Coal Measures are classified as a Minor Aquifer due to the sandstone horizons within the coal measures acting as locally important supplies of water. However the mudstones that underlie the quarry area are considered to provide a lower permeability layer that will restrict the movement of groundwater between the sands and gravels and the Middle Coal Measures creating a perched groundwater system in the sands and gravels.

Dewatering operations provided the major influence on the direction of groundwater flow, with the flow of water encouraged towards the excavation from the surrounding area. The water was retained and circulated in the surface water lagoons at the site before being pumped to the Methley Mires lagoons to the south of the site.

During periods when mineral was being extracted the dewatering operation proceeded permanently through the winter months and intermittently during summer months.

The result of this dewatering was the lowering of the groundwater level by approximately 2 metres in the excavation phase and a cone of depression could be identified.

The Challenge

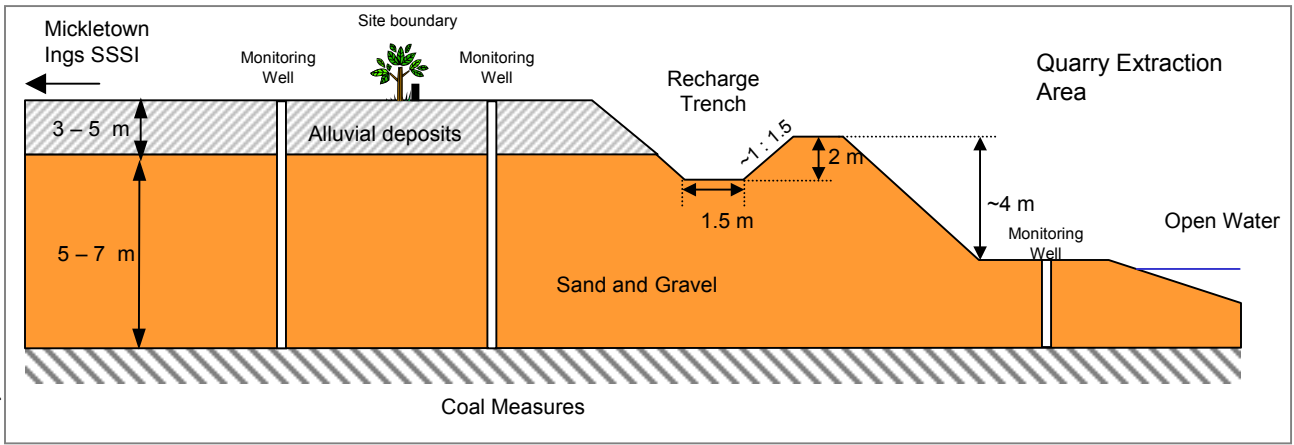
The Mickleton Ings SSSI are located approximately 500 metres to the north of the quarry site. The Ings are a wetland comprising shallow areas of open water fringed by marshland and support a diverse habitat for aquatic flora and associated invertebrate fauna. The Ings are considered to have formed as a result of mining subsidence that has progressively inundated the low-lying fields in the floodplain of the River Aire.

Concerns relating to the potential impact of dewatering at Methley quarry on the Mickleton Ings SSSI were expressed during the planning application for the current quarry site.

This led to a monthly groundwater monitoring program and the installation of a recharge trench along the northern boundary of the extraction phases as part of a layered mitigation strategy were the dewatering operations found to have an impact on the Mickleton Ings SSSI.

Mitigation Measure

Figure 2: Cross section design of recharge trench, Methley Quarry



The recharge trench at Methley quarry has not been required to mitigate any effects of the site dewatering. Monthly groundwater monitoring in the land surrounding the site has been undertaken during the extraction of material in the existing area. Trigger levels were set as to the water level in the nearest of the ponds of the Ings and in a monitoring well between the Ings and the quarry site.

In the event that the water levels fall below the trigger levels the recharge trench was to be put into operation. Although the water levels in the Ings, for a period in 2000, were found to have fallen below the trigger levels the Environment Agency established no link between the Mickletown Ings and Methley quarry, with opencast coal excavations to the north of the site found responsible for the falling water levels.

The Experiment and Model

The Methley Quarry experiment aimed to examine how quickly an existing cone of depression reacted to the commencement of recharging and how well this could be predicted.

A Groundwater Vistas model was created to represent the existing situation at the site, to predict the response of the groundwater to recharging and the effectiveness of the experimental recharge trench.

In order to establish the accuracy of the model predictions the on site experiment had water pumped to the trench for a two week period and the groundwater levels in the surrounding area monitored.

The recharge trench at Methley was constructed over 10 years ago. The trench was excavated through the alluvium and into the sands and gravels but has since become silted up and vegetated.

The extraction of material has been completed right up to the trench leaving only a sand bank separating the trench from open excavated area.

The experiment separated the trench into two sections, each 50 metres in length, which were blocked off by clay bunds at either end.

One of the long term influences into the efficiency of recharge trenches is thought to be siltation and growth of vegetation.

In order to try and quantify the scale of this impact, one of the trenches was kept in it's existing state (Trench 1).

The other one (Trench 2) was cleared of all vegetation and silt such that it's base was once again within the underlying sands and gravels.

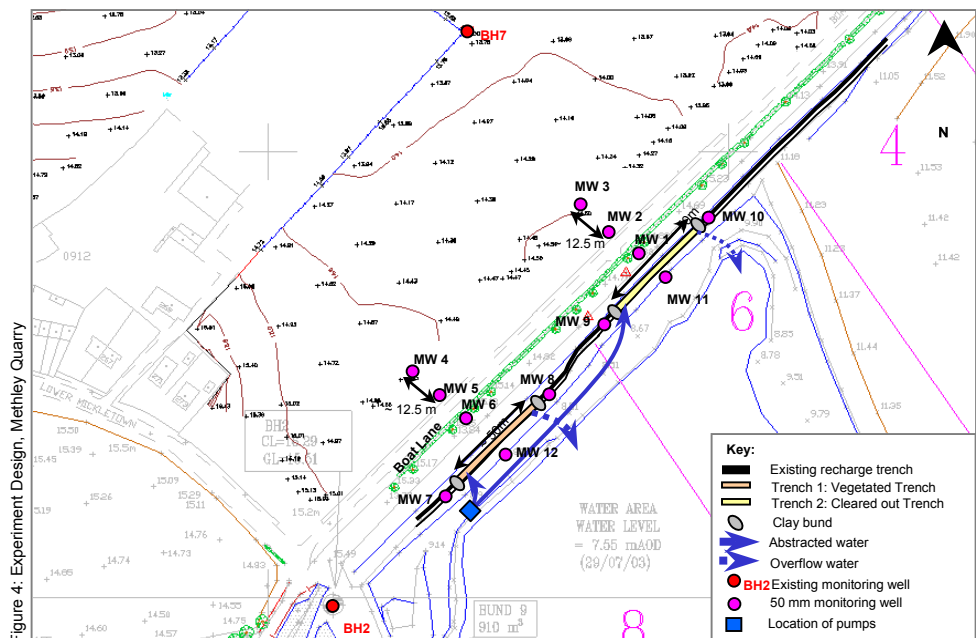


Figure 4: Experiment Design, Methley Quarry

The Experiment and Model (cont.d)

The groundwater model was created to represent the existing state of the quarry at the time of the experiment, taking into account all surface water influences in the area surrounding the quarry site.

The model was created in steady state and calibrated to the monitored groundwater level data and the volumes of water being dewatered. The recharge trench sections were modelled using the general head boundary in MODFLOW. The calibrated steady state model was converted to a transient state allowing the response of the groundwater to recharging over time to be predicted. The transient model was also expanded to simulate the influence of the trench in dry and drought conditions and to examine the impact of varying the depth, width, hydraulic conductivity of the trench and the volumes of water that are required.

The Reality

The experiment involved pumping water, at a rate up to 6 l/s, to the two sections of the recharge trench for a two week period, with water levels in the trench sections controlled using overflow pipes discharging any excess water to the nearby open water lagoon.

The south-east boundary of the trench comprised a sand embankment, where the extraction of sand and gravel had been completed to within a couple of metres of the trench location. As water was pumped into the vegetated section trench (Trench 1) the flow of water through the sand embankment caused a failure around the position of the overflow pipe. This resulted in a 3 metre wide section of the embankment collapsing and the trench having to be abandoned.



Plate 2: Operational recharge trench (Trench 2), Methley Quarry



Plate 3: Failure of sand embankment, Trench 1, Methley Quarry

The results from both the groundwater model and the site experiment showed the groundwater levels in the monitoring wells to respond almost immediately to the commencement of recharging.

The data obtained from the vegetated section of the trench is limited due to the collapse of the sand embankment. The data that was obtained showed that the short period of recharging was enough to raise the water level by up to 0.5 metres, although only for a short period.

The results from the second, cleared out, section of trench showed a much more stable response, with water levels rising by up to 0.5 metres and reaching close to a steady state level within three to four days after the commencement of recharging. Apart from natural fluctuations the water level was maintained for the duration of pumping.

The transient groundwater model showed the response of the groundwater levels near to the trench to be fairly immediate. The modelled results for the second, cleared out trench section provided a reasonable prediction of the response to recharging through the trench. The levels in the monitoring well were modelled to rise by up to 0.5 metres within the first few days after recharging commenced. The water levels then began to equilibrate reaching a steady state level after approximately 50 days.

The mass balance from the model showed that only a small portion of the water volume being dewatered would be required to achieve the observed response. But as the groundwater levels reach a steady level a large proportion of the water (up to 80 %) will return directly to the quarry excavation through the sands and gravels.

Both the groundwater model and the experiment showed the response of the groundwater to diminish with distance from the trench.

At 50 metres the model predicted a small and delayed rise in the groundwater level. However no such response in the groundwater was evident from the experimental results in the 2 week period of recharging.

The Model

With the groundwater model found to provide a reasonable prediction of the groundwater response it was expanded to simulate periods experiencing dry and drought conditions. Also the impact of varying the internal surface area of the trenches and the hydraulic conductivity of the trench base and sides and the volumes of water that are required for the trench were examined.

The modelled dry and drought conditions provide a greater response in the groundwater levels to recharging with the steady state water levels only marginally lower than the modelled levels in the normal conditions.

The effect of changing the conductance of the trench has shown that the groundwater is quite sensitive to small changes in the trench. The response of the groundwater changes almost proportionally to changing the internal surface area of the trench and to changing the hydraulic conductivity of the base and the sides of the trench.

The response of the groundwater to different volumes of water was also quite considerable, with the rise in the groundwater level changing proportional to the change in the head level in the boundary. The volumes of water that were required to be pumped to the trench were modelled to be only a small fraction of the volumes of water that can be drawn from the groundwater through the dewatering.

Figure 4: Comparison of model and experimental results for Trench 2, Methley quarry

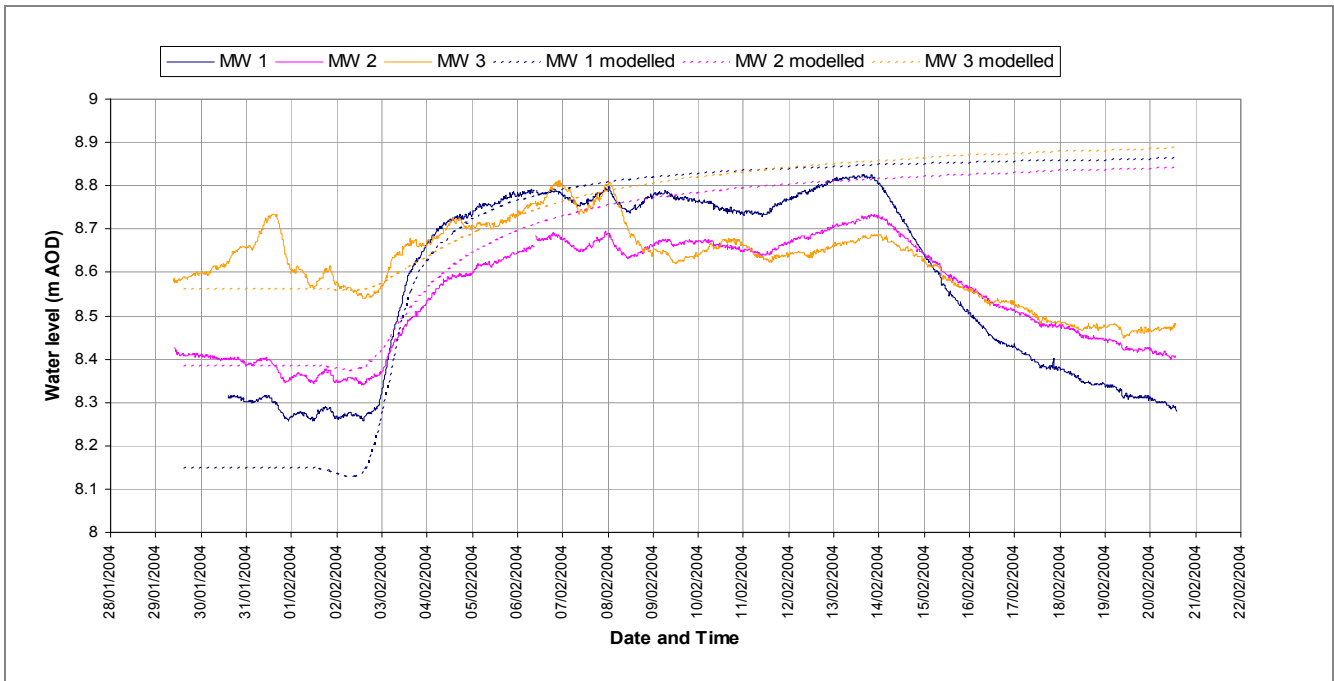
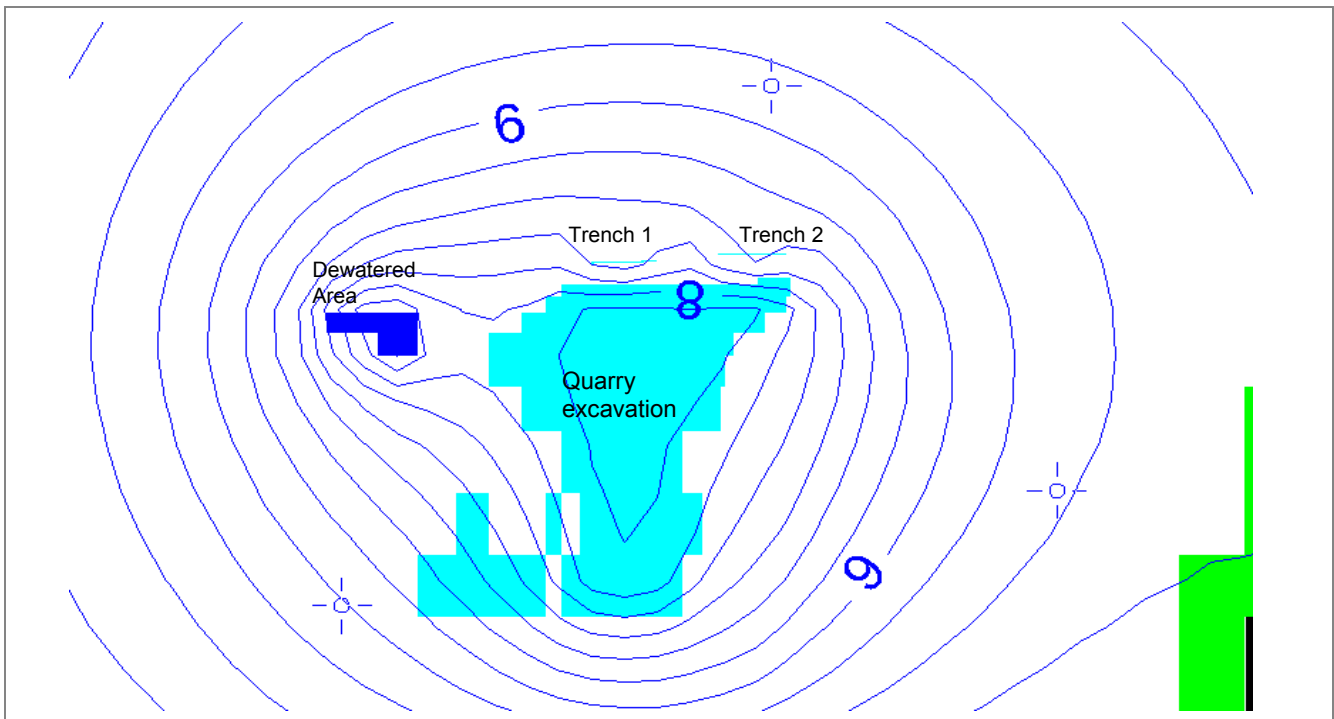


Figure 5: Modelled groundwater contours showing response to recharging



Conclusions & Limitations

The experiment highlighted issues concerning the design and operation of recharge features.

The excavation of material to within a few metres of the trench left the sand embankment unstable and a collapse occurred. The collapse of the sand embankment resulted in that 50 m section of the trench having to be abandoned, while safety issues for any personnel working near to the trench should be considered.

Both the experiment results and the model results showed that groundwater responded almost immediately to the commencement of recharging, with the majority of the rise in groundwater levels occurring within the first few days. The water levels failed to reach the original rest water level before any dewatering at the site had begun, however the trench alone was only intended to limit derogation to the agreed trigger levels.

The model results for the normal conditions did provide a good comparison to the experimental results for Trench 2, predicting a similar rate that the water levels would raise, and was within 15 cm of the steady state water level.

The impact of recharging through the trench was to have a relatively localised effect on the groundwater levels. With quite a large increase in water levels close to the trench, but the response diminished with distance, with only a small response modelled in monitoring wells at a distance of 50 metres.

These results would suggest that, in isolation, the recharge trench, in its current location and of its current size, would not be adequate to mitigate any impact on the Mickletown lngs SSSI if the quarry dewatering were to cause the water levels to fall below the trigger levels.

However, the modelling showed that it is likely that the Methley quarry is at a great enough distance not to impact the water levels in the SSSI. Were the quarry dewatering found to effect the SSSI the trench would not be used as the only mitigation measure but as part of a layered strategy.

The groundwater model has shown that water levels are quite sensitive to small changes in the trench properties. The range of response of the groundwater to different volumes of water was also considerable, with the rise in the groundwater level changing proportionately to the change in the head level at the boundary.

Over the long term recharging the trench acts to maintain the increased water levels in the direction that is required (towards the SSSI) however large amount of water will return to the excavation.

Further information

Further information may be found in a separate report entitled '*Optimising the Efficiency of Recharge Features as a Mechanism for Mitigating the Impacts of Quarry Dewatering: Methley Quarry, Castleford – Experiment and Modelling.*

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Further queries on Stonecastle Quarry should be directed to:

Kirk Blackburn
Lafarge Aggregates Ltd
Northern Service Centre
PO Box 36
Retford Road
Worksop
S81 7YU.

For further information on this research project contact:

Claire Huxley or Dr. Alan Thompson
Symonds Group Ltd
Symonds House
Wood Street
East Grinstead
West Sussex
RH19 1UU.

Tel: 01342 327161.



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