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Abstract

The hydrogeological effect of limestone extraction from open pits (quarries) depends on the location of the site in the landscape, the vertical and horizontal extent of the excavation, the methods used to excavate the stone, and the extent of karstification. Groundwater quality is commonly affected by quarrying through increased fine sediment concentrations and accidental spillages. Removal of any soil cover allows direct access for pollutants into the aquifer, a problem which may be exacerbated by licensed or illegal tipping of waste following cessation of stone extraction. Quarrying also removes the entire subcutaneous (epikarstic) zone which is an important groundwater store, together with part or all of the unsaturated zone. Pumping of water from the excavation will change the groundwater balance and can alter the direction and amounts of conduit flow, particularly if the quarry extends beneath the water table. Prediction of such impacts is difficult, especially when the limestone is karstified, such that there will always be a degree of uncertainty associated with the impact of the workings. Hence, it is essential that for new quarries monitoring is undertaken prior to, throughout, and following mineral working, with options for mitigation if mineral working causes an unacceptable impact. When a quarry ceases to be worked, the direct impacts on groundwater quality may rapidly decrease but there are important implications for after-use of the site. Impacts on groundwater quantity are likely to be more long-term.

Keywords: environmental impact, limestone, quarries, water quality, water resources

Introduction

Limestone is an important resource in most industrial countries and its extraction from open-pits represents the most visually obvious and the most dramatic anthropogenic impact on karst terrains affecting both landforms and geomorphological and hydrogeological processes. The latter include impacts on groundwater quality and quantity which may be manifest some distance from the actual extraction site. Surprisingly little attention has previously been given to these impacts although there is a more substantial literature on the impacts of underground mining both for carbonate-hosted ores and for minerals such as coal and iron ore which are interbedded with limestones. Two main themes emerge from this literature: the impacts of inrushes of groundwater to excavated galleries (Yuan 1992; Adamczyk *et al.* 1988) and the impacts of dewatering operations designed to reduce these inrushes. The latter include derogation as a consequence of dewatering and the resultant loss of springs and water supplies (Bocker & Hegyi-Hovanyi 1983; Alfoldi 1984), together with the impact of widespread ground subsidence and sinkhole formation as a result of dewatering operations (Kleywegt & Pike 1982; Vegter & Foster 1992). Such problems have relevance to sub-water table limestone quarrying.

The destruction of both relict and active caves by quarrying has been recorded in many countries (e.g. Gillieson 1989; Stanton 1990), and the wider geomorphological impacts of limestone quarrying and possible techniques for their amelioration have been described by Gagen & Gunn (1987) and Gunn & Bailey (1993). Although the focus is primarily geomorphological, there are hydrogeological implications, particularly as both Gunn & Gagen (1987) and Kiernan (1989) note accelerated growth of dolines as a result of quarrying activities. Other authors who have considered the hydrogeological aspects of limestone quarrying include Michel (1988), who examined the conflict between groundwater exploitation and limestone extraction in Germany, and Ekmekci (1993) who briefly outlined some impacts of extraction on karst groundwater systems, with particular reference to quarries near Ankara, Turkey. In Britain, the main focus of research into the hydrogeological impacts of quarrying has been in the Mendip Hills (Stanton 1966; Atkinson *et al.* 1973; Stanton 1977; Harrison *et al.* 1992; Raymond 1994). Here, the planning authority proposed a ‘sacrifice’ area in order to save more aesthetically pleasing and geomorphologically distinct areas. It was suggested by Stanton (1966) that stone reserves be maximized by deep sub-water table working. More recently however, Stanton (1989, 1990) has argued that limestone is more valuable *in situ* as a water resource and for its amenity value. Much investigation on sub-water table quarrying in limestone is

being undertaken by environmental consultants working both for quarrying companies and regulatory authorities. Given the confidential nature of this work little is published; thus it is not possible to cite many case studies. Therefore the remainder of this paper considers in more general terms the impacts of quarrying on karstified aquifers, concentrating particularly on the Carboniferous Limestone. The problems for prediction of impacts and the options for mitigation are both considered.

Hydrogeological importance of stone extraction technique

The extraction of limestone has accelerated markedly in recent years as a result of a world-wide increase both in the demand for limestone and in the technical ability to excavate, transport and process large tonnages of rock. For example, in Britain production of limestone (including chalk and dolomite) in 1993 was 130 million tonnes (British Geological Survey 1994), more than for any other mineral except North Sea oil/gas. Stanton (1977) suggested that annual removal of limestone from the Mendip Hills by quarrying first exceeded that removed naturally in solution at some stage in the 1700s or early 1800s. Similarly, Gunn & Gagen (1989) estimated that quarrying will have removed more limestone from the Peak District by the end of this century than natural processes over the whole of the Holocene. The increased production has been paralleled by a decrease in the number of quarries but a substantial increase in their size, resulting in a greater potential impact. The increased output of limestone has only been made possible by technological advances in extraction techniques, particularly the use of explosives.

In order to excavate large tonnages of limestone efficiently, blasting is necessary to fragment the rock for further handling and processing. Both the type of explosive used and the blast design influence the amount of blast-induced fracturing of the remaining unexcavated rock, and hence its permeability, porosity and hydraulic conductivity. For example, Smart *et al.* (1991) suggest that in sub-water table quarries the blast zone beneath the quarry floor may be considered as a separate aquifer characterized by high fracture density, low primary porosity, and negligible conduit development. Eckmeci (1993) further suggests that this may lead to changes in the direction of underground drainage such that more water may move in one direction and less in another. Explosive type and blast design also influence the form, and future development, of the blasted rock face (Gagen & Gunn 1987; Gunn & Bailey 1993). Increased permeability as a result of blast-induced fracturing may accelerate drainage towards the quarry face, and enhance the development of both subsidence and solutional dolines (Gunn & Gagen 1987).

Potential impacts upon the unsaturated zone

It has generally been considered that the unsaturated zone only contains a small percentage of the total volume of storage in a karst aquifer. For example, Atkinson (1977) calculated that only 12% of water in the Cheddar Spring Catchment, England, is stored within the unsaturated zone. However, Smart & Friederich (1986), working in the same area, suggested that storage in the unsaturated zone is comparable to that in the saturated zone due to a well developed subcutaneous zone (detailed below). In the Causse Comtal, France, over 60% of storage is in the unsaturated zone (Dodge 1984), and the unsaturated zone accounts for almost all storage in two catchments near Waitomo, New Zealand (Gunn 1986). The differences may be accounted for by lithology, hydrogeology and drainage basin size.

Where present, high storage in the unsaturated zone is largely due to a well developed subcutaneous (epikarstic) zone. Here solutionally enlarged voids are present immediately beneath the soil, overlying limestone which has undergone only limited weathering (Fig. 1). The ability of this zone to store significant quantities of water is due to the presence of these voids and only a small number of vertical migration routes (subcutaneous drains). Following rainfall, water accumulates in the subcutaneous zone until the available storage is full, at which time lateral flow towards the subcutaneous drains will occur allowing rapid vertical transmission of water. This storage represents an epikarstic aquifer which, when not draining via subcutaneous drains, leaks slowly via fractures and fissures in the transmission zone (Fig. 1).

Where the unsaturated zone is thin or has a poorly-developed subcutaneous zone and/or fracture/fissure network, storage will usually be low and the impact of quarrying on groundwater quantity will be minimal. However, where a thick, well developed unsaturated zone is present then storage, and hence potential impacts, may be much greater. In both cases quarrying will substantially modify the routing of recharge through the unsaturated zone, and deterioration of groundwater quality may occur.

Although some limestone areas have little or no soil cover, in most there is sufficient to support at least grass/shrub vegetation. In these areas, the first impact of quarrying is the removal of soil and vegetation, thereby reducing evapotranspiration losses and increasing effective rainfall. In England, a change from grass to bare ground is likely to increase annual effective rainfall by about 8% in the north and by up to 40% in the Mendip Hills (Harrison *et al.* 1992); in warmer countries the

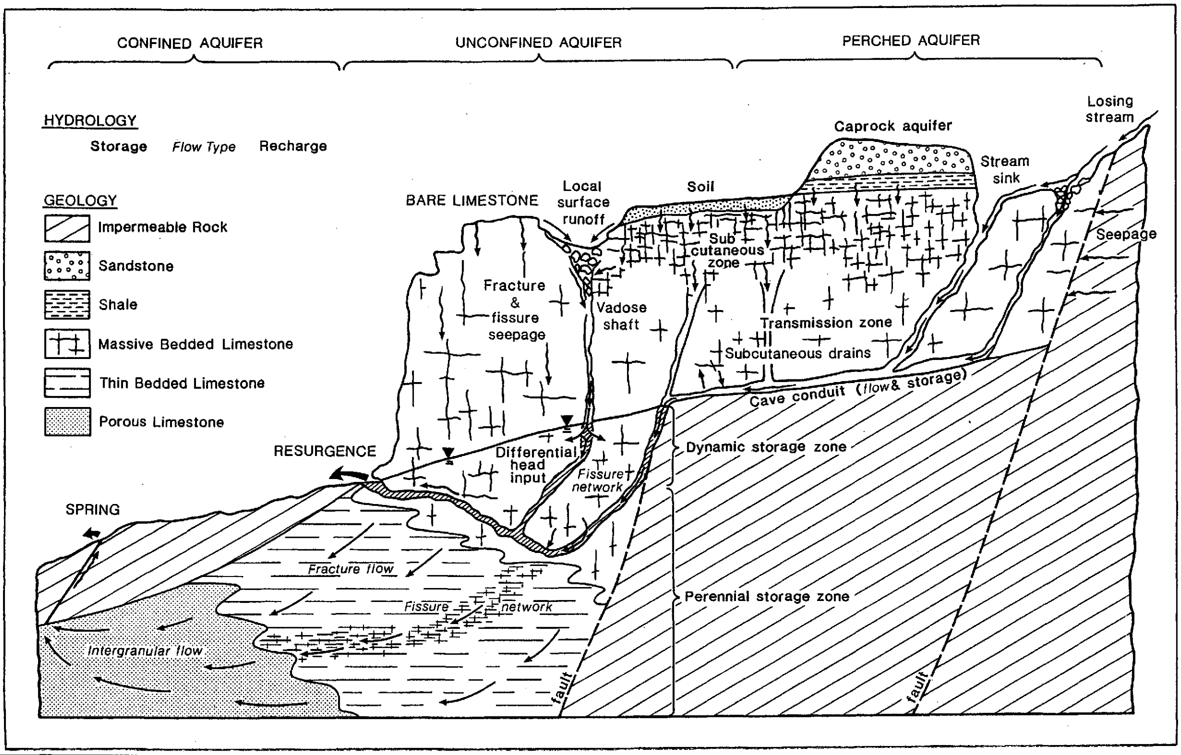

Fig. 1. Schematic representation of recharge, flow and storage types present in carbonate aquifers (from Hobbs 1988).

increase will be higher. This additional water generally forms 'run-in' to the quarry, mostly as surface flow since the quarry floor becomes partly sealed due to packing of fractures, fissures and joints with dust and rock chippings compacted by vehicle movements. Runoff is often turbid and may be channelled to some form of pond or soakaway. From these some water is lost by evaporation, partly negating the results of vegetation removal whilst the remainder may directly infiltrate into the quarry floor or be locally utilized. Unless great care is taken to settle out the majority of the fine material, deterioration of water quality is likely to occur, either in the groundwater system or in the receiving stream. For example, in the Derbyshire Peak District, water was discharged from Eldon Hill Quarry into a closed depression for many years. This in turn feeds a cave where there has been a significant accumulation of fines which have partially blocked a water-filled conduit.

In addition to point-source pollution, the removal of soil will alter the potential for diffuse contaminant inputs. In agricultural areas devoted to intensive crop growth, inputs from non-point agricultural sources such as fertilizers and insecticides will be reduced. However, other inputs may increase as the soil, which is normally an important zone of filtration and water purification, is removed. In the longer term, there will be changes in the amount and locus of solutional erosion, as in most karsts the soil is the major source of carbon dioxide, and the majority of solution takes place in the subcutaneous zone which not only represents a major store in the unsaturated zone, but also controls water movement therein (Williams 1983). During periods of heavy rainfall the subcutaneous zone becomes saturated and water flows laterally towards zones with enhanced vertical permeability, subcutaneous shafts, which transmit water rapidly to the saturated zone (Gunn 1981; Friederich & Smart 1982). Thus, if the subcutaneous zone is removed during quarrying the hydraulic function of the unsaturated zone is partly destroyed. The net result of these near surface changes is likely to be an increase in annual and peak discharges but a decrease in base flows. For example, Stanton (1990) has recorded increased winter and decreased summer discharges from springs draining quarried areas in the Mendip Hills. However, quarrying through the unsaturated zone may also intersect vadose cave streams, resulting in increased surface runoff in the quarry and loss of water from the natural groundwater regime with the potential to reduce spring discharges.

Overall, it may be concluded that quarrying in the unsaturated zone is likely to result in relatively local impacts, such as increased runoff, reduced water quality, re-routing of recharge water through the aquifer, and localized reduction in groundwater storage. These may be considered largely as water management issues which do not impinge on the large scale groundwater resource.

This not withstanding, in some areas attempts have been made to mitigate the effect of reduced unsaturated zone storage (for quarries remaining above the water table) by creating a 'compensation' pond in the zone of water table fluctuation. Such a pond, which is sized to represent the estimated loss of unsaturated zone storage due to quarrying, is allowed to fill during winter, then naturally declines during the summer to support spring discharge and borehole abstractions.

Potential impacts upon the saturated zone

Once a quarry has reached the lateral limits of its planning boundary and extracted all the stone possible from the unsaturated zone it has to work beneath the water table to win more reserves (although it is recognized that many operators proceed with sub-water table workings prior to exhaustion of dry stone for reasons such as stone quality, provision of a water supply and for operational purposes). Where the aquifer in question has a large seasonal fluctuation in water level then it is possible to work stone during dry periods and allow the quarry to flood through the wet season. This is the 'minima' impact method of sub-water table working, although as will be discussed below, the creation of flooded workings can significantly modify groundwater behaviour in their vicinity. More commonly, where stone is won from beneath the water table it is by dewatering the aquifer. Water is pumped out from a central low sump in the quarry floor, from abstraction boreholes around or within the quarry, from galleries, or from trenches.

Pumping from a quarry will reduce the hydraulic head and thus lower water levels in the rock draining to the quarry. In those limestones which are relatively homogenous something approaching a classic cone of depression may develop. However, the anisotropic nature of most limestones means that an uneven 'zone' of depression is more likely, with preferential development along the areas of highest permeability. The form of the zone will also be affected by any permeability barriers, such as clay or fractures filled by vein minerals. Water pumped out of the aquifer is usually discharged into a surface water course, and hence is likely to be lost from the local groundwater system thereby reducing spring flow(s), drying up water supplies and possibly changing the overall direction of underground flow (Fig. 2; modified from Harrison *et al.* 1992).

In addition to seepage by diffuse flow into sub-water table workings, phreatic conduits may be directly intersected potentially causing severe problems in terms of both inflow of water to the quarry and loss of resource by conduit drainage and by severing a flow route. The area at risk will be a function of conduit geometry and the transmissivity of inter-conduit blocks. For example, in the Mendip Hills, where conduits are developed down dip, they tend to have the form of a loop in long section, the gradient of their rising and falling limbs being determined by the local dip. The height difference between the peak of one limb, and trough of the next may be considered as the amplitude of the conduit. Where conduits have a high amplitude, with peaks at the water table, then the area at risk is reduced to that between the quarry and the first section of the conduit which reaches the water table. If the limestone is of a high transmissivity then leakage can take place from one section of a conduit to another, thereby increasing the area at risk of derogation. The risk of derogation may also be increased if old choked passages are flushed and become operational again due to changes in the hydrogeological regime induced by sub-water table operations. If the conduit flows along the strike of the limestone, then conduit development may be more regular in long section, showing no distinct rising and falling limbs. In this case the conduit gradient would be shallow, and the area at risk to derogation would depend on the level at which the conduit was intersected. Water loss from conduits can occur even where they are not directly intersected. For example, Edwards *et al.* (1991) demonstrated that quarry dewatering near to phreatic conduits can induce groundwater flow out of such systems and into the surrounding diffuse flow zone. In this case, repeat dye traces from a series of sinking streams which were undertaken at various stages of sub-water table working indicated an increase in loss of water from phreatic conduits as the zone of depression increased around the quarry sump.

Other hydrological and hydrogeological impacts

Sub-water table quarrying may also impact upon surface water courses fed by karst springs. Firstly, there is the potential for contamination from increased suspended sediment loads and from pollutants such as fuel oils. Although regulatory authorities may specify limits on the amount of sediment that discharge water can contain, these limits may be exceeded during periods of heavy rainfall. Such exceedance may result in a breach of consent conditions and the possibility of prosecution. A second possible impact is flooding downstream of the dewatering discharge point. As the requirements for dewatering are often greater in winter when surface watercourses also tend to have a greater discharge, the potential for flooding increases. The increases in flood flows will be accompanied by decreases in base flows and some streams may cease to flow during drier parts of the year.

Quarrying of adjacent non-limestones may also impact on the hydrogeology of a karstified aquifer, and where a spring has a large component of allogenic

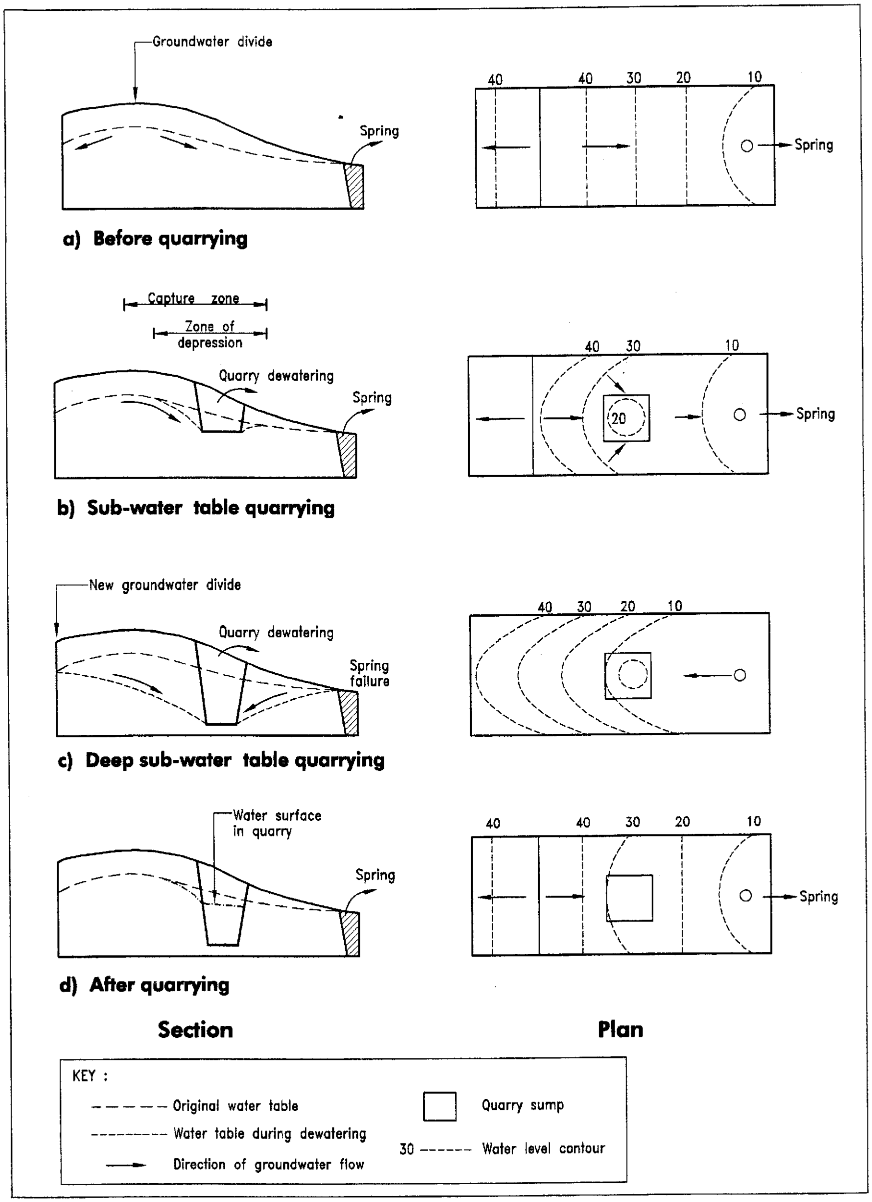

Fig. 2. Schematic diagram showing the potential effects of sub-water table quarrying on the water table (modified from Harrison *et al.* 1992).

recharge any deterioration in the quality of this water can be significant. For example, a sinking stream, which supplies up to 26% of the discharge from St Dunstans Well, a spring in the Mendip Hills, was contaminated by run-off from a quarry extracting rock from Silurian volcanics, and as a result the spring could no longer be used for potable supply (Stanton 1977).

In addition to direct hydrogeological impacts, it was noted in the introduction that large scale dewatering of limestone aquifers to permit mining operations has resulted in extensive surface lowering and sinkhole collapse. The dewatering of open pits for stone extraction is a more recent phenomenon and has involved individual sites rather than large regions. Nevertheless, it will be interesting to see if similar effects occur.

Predicting the impacts of sub-water table quarrying

In contrast to the relatively local impacts of quarrying in the unsaturated zone, sub-water table quarrying may

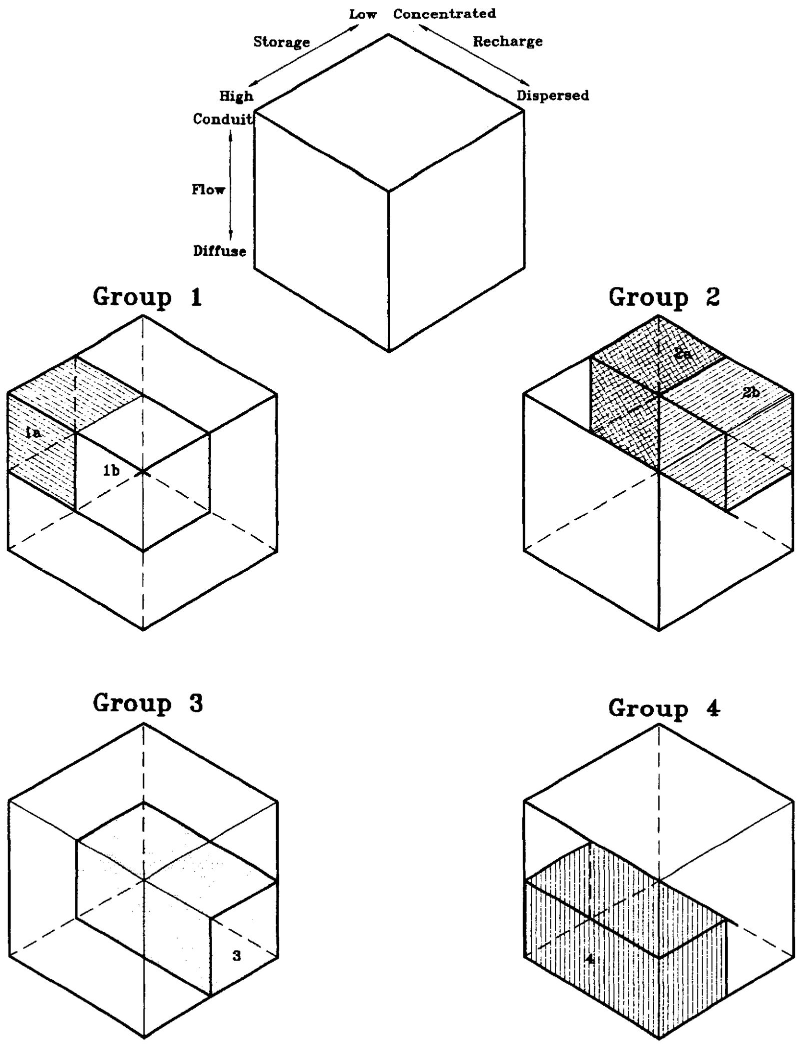

Fig. 3. Carbonate aquifer classification: assessment of the potential impacts from sub-water table quarrying (modified after Smart & Hobbs 1986).

have large scale, long-term impacts which must be predicted when quarry workings are proposed. Prior to assessing these impacts it is necessary to characterize the aquifer, especially to determine the degree of karstification. This is important as prediction of impacts is more problematic the more karstified an aquifer is. Karst aquifers can be defined in terms of their three end member attributes of recharge, flow, and storage (Smart & Hobbs 1986). Recharge is ranged between concentrated and dispersed end members, the former being characterized by large inputs at discrete points (e.g. sinking streams), the latter by smaller inflows at a much larger number of points (e.g. rainwater infiltration through the soil). Flow varies between conduit and diffuse end members. Conduit flow occurs in open channels with relatively high velocities giving rise to turbulent flow. Diffuse flow is confined to tight fractures and pores with small openings; velocities are low and flow is laminar, obeying Darcy's law. Storage varies between high and low end members and includes water stored in the soil, subcutaneous zone, conduits, and the saturated zone and is expressed in terms of the storage volume and annual recharge. The end members of the recharge, flow, and storage types can be plotted on three orthogonal axes to form a cube, the position of an aquifer within which can aid selection of the most suitable methods for predicting impacts. Four groups (and two sub-groups) have been defined based on the type of recharge, flow and storage present (Fig. 3) as follows.

Group 1: represents aquifers with high storage, conduit flow and variable recharge. The prediction of the

impact of quarry dewatering is most difficult in these aquifers as it is highly dependent upon the likelihood of the workings intersecting an active conduit. As storage in these aquifers is significant they can present a substantial water resource; hence the potential impact can also be significant. The group can be split into two subgroups: 1a with concentrated recharge, 1b with dispersed recharge, although there will be a continuum between these extremes. Examples of aquifers with conduit flow and a high proportion of concentrated recharge include the catchments of St Dunstans Well in the Mendip Hills, and Russet Well in the Peak District. Examples of aquifers with conduit flow and only limited concentrated recharge include Banwell Spring in the Mendips and the Holme Grove Risings/Bubble Springs in the Peak District which form the source of the River Lathkill.

Where concentrated recharge is dominant the potential impact is much greater and more difficult to predict. Although the resurgence(s) for such concentrated inputs can often be determined, the exact course or depth of the conduit is not normally known along its full length. Intersecting one of these conduits may dewater a large area down the hydraulic gradient from the quarry and could present significant problems for disposal of the discharge, especially if, as is sometimes the case, the water becomes turbid after heavy rain. Such impacts are also possible in aquifers with dispersed recharge although the conduits are usually (but not always) less well developed in the upper reaches of spring catchments.

Group 2: represents aquifers with low storage, conduit flow and variable recharge. Prediction of impacts within this group is no simpler than for group 1, but with low storage the number of water supplies and size of springs supported by the aquifer is likely to be much smaller. As with group 1, this group can be sub-divided according to recharge type, the potential impact due to the possibility of the intersection of conduits fed by sinking streams being higher where concentrated recharge is present. An example of a low storage aquifer with concentrated flow and moderate amount of concentrated recharge is Ogof Fynnon Ddu in South Wales.

Group 3: represents systems with dispersed recharge, diffuse flow and low storage. They may be typified by thin limestones with seasonal springs. However, they may also occur where thicker rock sequences are present such as the Carboniferous Limestone beneath the Ribble Valley. In this instance the storage is reduced by the presence of shale and mudstone bands such that the utilisable storage is low, the flow is diffuse and recharge is dispersed via leakage through overlying boulder clay.

The group 3 systems are 'minor or non-aquifers' and present no problem from a hydrogeological viewpoint for sub-water table quarrying. They are not a significant water resource, but if the potential impact must be determined (for planning permission for example) then, formulae applicable to homogeneous aquifers can be used to give a best estimate. In such cases, the limitations of these formulae to fissure flow systems must be emphasized when quoting predicted impacts. The importance of local geology and topography should always be considered.

Group 4: represents aquifers which have diffuse flow, high storage and variable recharge, an example of which is the Pwllwy Spring to the north of Cowbridge, South Wales. Diffuse flow at this location has allowed a borehole to be drilled adjacent to the springs, which is now used for public water supply. Because these aquifers have high storage they provide a useful resource which may be derogated by sub-water table working. They may also support moderately large springs, which in turn may provide stream/river base flow. As with group 3 the potential impact can be assessed using standard formulae providing that their limitations are understood.

Within the central area of the cube an aquifer may not fall into a distinct group. One such example is a series of springs in the Peak District along the Wye from Cowdale to Cheedale/Millers Dale. These drain a large block of limestone to the north whose characteristics could place them in either group 1b, or group 4. In such cases a judgement will have to be made as to which are the most suitable methods to determine the potential impact of subwater table quarrying. There are a number of methods of determining where an aquifer falls in the proposed classification (Fig. 3). The first is by field observation and/or desk study utilizing geological and topographic maps, borehole information and abstraction data, as well as caving reports, dye trace studies, etc. Spring hydrographs can also be examined to determine if discharge is flashy or not. Examples of the effect of varying recharge, flow, and storage on the spring hydrograph are given in Smart & Hobbs (1986). A third method is to continuously monitor the electrical conductivity of spring discharge water, the coefficient of variation of which (for a representative time period) can indicate the degree of karstification. In a similar manner, turbidity pulses may also be used (Hobbs 1988). Finally, direct measurements of aquifer permeability in a statistically significant number of, and suitably located, boreholes can be used (Smart *et al.* 1991). In most cases, only limited information will be available and a subjective estimate of the position of the aquifer within the classification will have to be made.

Once the nature of a karst aquifer has been defined, the most suitable method of prediction can be assessed and the risk to the aquifer of quarrying determined. Methods range from the use of numerical formulae (Geoffrey Walton Co. and Nottingham Univ. 1988) and computer models for more homogeneous aquifers, to plotting the position of sinking streams, cave passages and springs in karstified aquifers, in addition to more general field based hydrogeological techniques. Given the technological advances in computer systems, it is now possible to model successfully very complex

Table 1. *Hydrological and hydrogeological features potentially at risk from sub-water table limestone mineral operations, and options for mitigation*

Feature at risk	Potential impact	Mitigation measure
1. Water quantity		
Groundwater resource	Reduction or loss of resource	Artificial recharge
Physical loss of aquifer	Reduction or loss of resource	None
Groundwater abstractions	Loss of supply	Alternative source (e.g. mains/augmentation by recharge)
Spring flow	Reduction or loss of flow	Augmentation
Surface water flow—too low	Ecology/fisheries/amenity	Augmentation
Surface water flow—flooding	Structural/ecological damage	Water management
Surface water abstractions	Loss of supply	Alternative source (e.g. mains/augmentation)
2. Water quality		
Groundwater	Poor quality limits range of use of resource	Water treatment prior to use
Surface watercourses	Ecological impact, loss of resource	Clean-up, re-stock flora and fauna, treatment prior to use

aquifers, even those with a moderate degree of heterogeneity. There will always remain a degree of uncertainty associated with predictions of the potential impacts of mineral workings in karstified limestone aquifers. Thus, following prediction of potential impacts a risk assessment, including an analysis of the associated uncertainties, should be undertaken to determine if the risks outweigh the need for the stone reserves. In most instances such decisions will not be clear cut, and a pragmatic approach may be required. This may entail specification of a comprehensive monitoring regime such that any impacts can be identified at an early stage. Proposals for mitigation should also be outlined so that these can be implemented if monitoring identifies an impact.

Options for monitoring and mitigation

Sub-water table workings may impact upon both the quantity of water present in an aquifer and its quality. The main features of concern, the potential impact upon these, and the options for mitigation are outlined in Table 1.

Of the features at risk, it is the groundwater resource per se that is the most obvious. This may be reduced by mineral workings due to loss of both unsaturated and saturated storage capacity and due to dewatering. However, recharge to the aquifer may also be increased due to a reduction in evapotranspiration when vegetation is removed, although it may later decrease if restoration to a lake or wetland takes place. Such an increase will also be negated once workings proceed to sub-water table levels and groundwater is abstracted. The importance of such a loss will depend upon the potential utilization of an aquifer. For instance, where recharge is low, then sustainable aquifer use will be small, and the resource may be classed as limited. The options for mitigation are few, the most obvious being the artificial recharge back to the aquifer of any pumped water. However, this relies on the presence of suitable recharge sites sufficiently removed from the abstraction point to avoid re-circulation and the sites also have to be well integrated with the aquifer to accept the sometimes large volumes of water pumped. The use of boreholes for artificial recharge is often impracticable as there is a large degree of uncertainty as to whether sufficient voids, which are well integrated with the aquifer, will be intersected. Although some improvement in water acceptance may be possible via acidization/explosives this may not improve local rock permeability sufficiently. In some instances it may be possible to utilize recharge trenches or sumps.

Historically in Britain, mitigation of derogation has been carried out in preference to more technical solutions which replenish the lost resource. For example, supplies lost or reduced by dewatering may be compensated, or replaced, by water from another source such as the mains supply. Streams fed by springs which have dried up can be augmented by water discharged from the quarry, provided that pipes can be laid from the sump to the spring. If this water is stored, either in a suitably sized surface reservoir, or by constructing a sump in the base of the quarry, then it may be possible to maintain surface water courses during the summer months. However, both options are problematical: surface reservoirs are expensive and rely on suitable nearby sites, and quarry sumps limit lateral development and become inoperable as the quarry penetrates the saturated zone to greater depths. On occasions it is necessary to ensure a similarity in quality between augmentation water and the 'original' groundwater discharge in order to preserve any site specific flora/fauna or depositional features such as tufa. In some countries, e.g. Germany, legal regulations are such that water abstraction takes priority over limestone quarrying, and workings must remain at

least 2 m above the known water level in the vicinity of the quarry (Michel 1988).

Where surface flows are reduced due to increased leakage rates through the stream bed it may be possible to reduce these by sealing leaky section(s) with a suitable clay or membrane. Such operations must be undertaken in conjunction with habitat re-construction in the areas affected.

Flooding caused by discharging groundwater, pumped to dewater workings during periods of high natural flow in surface water courses can affect upon structures adjacent to the stream, and stream bank flora and fauna. Such flooding can be avoided in many instances by good water management practices and by adequate assessment of likely surface water flows and quarry discharge requirements. In extreme cases flooding will occur irrespective of quarry discharges. However, at such times dewatering should cease so as not to exacerbate problems. Often a large sump in the quarry floor can be used as a 'buffer' to temporarily accommodate high rainfall totals, although such buffering is limited by sump volume.

Impacts upon water quality are generally associated with suspended sediment, or accidental spillages of fuel and oil etc. The latter can be minimized by good practice, such as bunding around storage tanks and re-fuelling areas, and limiting vehicle maintenance to specific areas with controlled runoff/oil interceptors etc. In addition, the use of underground pipes and storage tanks should be avoided, unless the tanks are double skinned, with leak detectors, and pipes are contained within secondary channels, also with leak detectors. High loading of suspended sediment in surface water courses can be prevented by good water management practices such as separating surface water and groundwater, utilizing settlement lagoons, and installing continuous turbidity monitors on discharge outfalls, with automatic shutdown if trigger levels are exceeded.

Potential impacts upon cessation of mineral working

Once mineral working has ceased at a site it may either be left dormant, or be re-developed. If a sub-water table working is left dormant then it will fill with water at a rate depending upon local rainfall, evaporation, and groundwater flow. During the early part of this period any derogated springs will be unlikely to re-commence flowing as water will be flowing into storage in the quarry void. Given that this will have a storativity of 100% as opposed to 1 to 3% for karstified limestone, groundwater levels may take some time to recover. Furthermore, because the void will have an infinite transmissivity the quarry will have a flat water surface. Thus, groundwater levels close to the quarry, especially up the hydraulic gradient, will never recover to their previous levels and some springs may never return, depending upon their proximity to the quarry.

Like all man-made holes in the ground, disused limestone quarries may be used as formally constituted waste disposal sites, and unless considerable care is taken there may be rapid migration of contaminants and minimal dilution of leachate prior to arriving at a spring. Edwards & Smart (1989) quote one instance in the UK of landfilling in a disused Carboniferous Limestone quarry in South Wales where no liner system was employed. Leachate from the landfill moved rapidly to a spring over 2 km away resulting in gross contamination. Subsequently the landfill was capped with a low permeability layer to reduce leachate generation. Similarly, Bodhankar & Chatterjee (1994) document waterborne disease and serious illness resulting from the contamination of public water supplies by pollutants from an unlined limestone quarry used as a disposal site for urban waste. For this reason the development of disused quarries in karstified limestone as landfill sites is not generally recommended although with care and use of appropriate liners it may be possible to reduce the risk of pollution to an acceptably low level. In assessing the suitability of a limestone quarry as a potential landfill site its location is of some importance (Sendlein & Palmquist 1977) as are points at which to monitor for potential leachate migration (Quinlan *et al.* 1986). It has been suggested that deeper quarries may be more suitable for landfill because fissure size and frequency tends to decrease with depth. However, it is important not to assume that this is always the case since water tracing and related studies carried out independently by the authors have revealed high groundwater flow velocities (>100 m/day) at depths of up to 50 m beneath the floors of already deep quarries in areas with no known conduit development. If disused quarries are used as landfills then composite engineered liners should be installed with leak detection systems where appropriate.

Not only do landfills present a problem directly from leachate generation, but also from contaminants introduced from fires. In the English Peak District several fires have occurred in limestone quarries which have been used to dispose of vehicle tyres. Such fires can result in contamination of groundwater with phenolic compounds, zinc, cyanide, and polyaromatic hydrocarbons. Even though no pollution at springs was detected, this may have been due to an inadequate monitoring programme, monthly sampling being adopted, rather than a sampling regime tied to spring discharge response to rainfall.

Although the main focus of the use of worked out quarries for landfills is associated with licensed landfilling, illegal 'fly' tipping can also be a problem, especially in small isolated workings. At such locations there is no regulation of waste disposal, and with no liner present to limit any leachate migration, the potential for impact

upon local springs/groundwater abstractions may be significant. In recent years, planning authorities in the UK have placed much greater emphasis on the end use of worked out quarries. Consequently, many planning applications now propose schemes for the restoration of mineral workings to include nature walks around flooded workings which can also be used for sport fishing, sub-aqua diving and boating. In such instances, the prediction and maintenance of the final rest water level is of importance if a safe and sustainable environment is to be created.

Conclusions

The need for stone reserves is often such that quarries are developed in karstified limestone aquifers. The impact of this can be a reduction in, or loss of, groundwater resources, reduced flow from springs and in surface water courses, and potentially an impact upon the quality of these features. The prediction of impacts may be very uncertain. In such cases, development should only proceed where a comprehensive monitoring regime is implemented, and where measures are proposed for mitigation, should the aquifer be affected.

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References

ADAMCZYK, A. F., MOTYKA, J., WILK, Z. & WITCZAK, S. 1988. Mining drainage of a karstic aquifer and the related problems. *In*: *Karst Hydrogeology and Karst Environment Protection. Proceedings of the 21st International Association of Hydrologists Congress Guilin*, 1097–1104.

ALFOLDI, L. 1984. Connection between thermal springs in Budapest and mining activity. *In*: BURGER, A. & DUBERTRET, L. (eds) *Hydrogeology of Karstic Terrains*. Heise, 222–224.

ATKINSON, T. C. 1977. Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *Journal of Hydrology*, **35**, 93–110.

——, BRADSHAW, R. & SMITH, D. I. 1973. *Quarrying in Somerset. Suppl. 1, Hydrology and Rock Stability. Mendip Hills. A review of existing knowledge*, Somerset County Council.

BOCKER, T. & HEGYI-HOVANYI, K. 1983. Multi-scale mathematical modelling of carbonate type aquifers for the planning of dewatering systems in bauxite mining. *In*: *Proceedings of the 5th International Congress of the International Committee for the Study of Bauxites & Aluminium, Zagreb*, 233–241.

BODHANKAR, N. & CHATTERJEE, B. 1994. Pollution of limestone aquifer due to urban waste disposal around Raipur, Madhya Pradesh, India. *Environmental Geology*, **23**, 209–213.

BRITISH GEOLOGICAL SURVEY 1994. *United Kingdom Minerals Yearbook 1993*, British Geological Survey, Keyworth.

DODGE, E. D. 1984. Les characteristiques hydrogeologiques des aquiferes karstiques du Causse Comtal (Aveyron, France). *Hydrogeologie—Geologie de l'ingenier*, **3**, 241–252.

EDWARDS, A. J. & SMART, P. L. 1989. Waste disposal on karstified Carboniferous Limestone aquifers of England and Wales. *In*: BECK, B. F. (ed.) *Engineering and Environmental Impacts of Sinkholes and Karst*. Balkema, Rotterdam, 165–182.

——, HOBBS, S. L. & SMART, P. L. 1991. Effects of quarry dewatering on a karstified limestone aquifer: A case study from the Mendip Hills, England. *In*: *Proceedings of the Third Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes*, National Water Well Association, 77–92.

EKMEKCI, M. 1993. Impact of quarries on karst groundwater systems. *In*: GUNAY, G. (ed.) *Hydrogeological Processes in Karst Terrains*, International Association of Hydrological Sciences Publication no. **207**, 3–6.

FRIEDERICH, H. & SMART, P. L. 1982. The classification of autogenic percolation waters in karst aquifers : A study in GB Cave, Mendip Hills, England. *Proceedings of the University of Bristol Spelaeological Society*, **16**, 143–159.

GAGEN, P. J. & GUNN, J. 1987. Restoration blasting in limestone quarries. *Explosives Engineering*, **1**, 14–15.

GEOFFREY WALTON CO. AND NOTTINGHAM UNIV. 1988. *Technical Review of the Stability and Hydrogeology of Mineral Workings*, for The Department of the Environment, HMSO, London.

GILLIESON, D. S. 1989. Effects of land use on karst areas in Australia. *In*: GILLIESON, D. & SMITH, D. I. (eds) *Resource Management in Limestone Landscapes: International Perspectives, Special Publication 2*, Department of Geography & Oceanography, University Coll., Australian Defence Force Academy, Canberra, 43–60.

GUNN, J. 1981. Hydrological processes in karst depressions. *Zeit Geomorph.*, **25**, 313–331.

—— 1986. A conceptual model for conduit flow dominated karst aquifers. *In*: GUNAY, G. & JOHNSON, A. I. (eds) *Karst Water Resources*. International Association of Hydrological Sciences Publication no. **161**, 587–596.

—— & BAILEY, D. 1993. Limestone quarrying and quarry reclamation in Britain. *Environmental Geology*, **21**, 167–172.

—— & GAGEN, P. J. 1987. Limestone quarrying and sinkhole development in the English Peak District. *In*: BECK, B. F. & WILSON, W. L. (eds) *Karst Hydrogeology: Engineering and Environmental Applications*. Balkema, Rotterdam, 121–126.

—— & —— 1989. Limestone quarrying as an agency of landform change. *In*: GILLIESON, D. & SMITH, D. I. (eds) *Resource Management in Limestone Landscapes: International Perspectives, Special Publication 2*, Department of Geography & Oceanography, University Coll., Australian Defence Force Academy, Canberra, 173–181.

HARRISON, D. J., BUCKLEY, D. & MARKS, R. J. 1992. *Limestone Resources and Hydrogeology of the Mendip Hills*. British Geological Survey Tech. Report SA/92/19, Keyworth, Nottingham.

HOBBS, S. 1988. *Recharge, Flow and Storage in the Saturated Zone of the Mendip Limestone Aquifer*. PhD thesis, University of Bristol.

KIERNAN, K. 1989. Sinkhole hazards in Tasmania. *In*: BECK, B. F. (ed.) *Engineering and Environmental Impacts of Sinkholes and Karst*. Balkema, Rotterdam, 123–128.

KLEYWEGT, R. J. & PIKE, D. R. 1982. Surface subsidence and sinkholes caused by lowering of the dolomitic water table on the Far West Rand gold field of South Africa. *Annals of the Geological Survey of South Africa*, **16,** 77–108.

MICHEL, G. 1988. Conflict between groundwater exploitation and limestone quarrying in the karst region of Warstein (Federal Republic of Germany). *Proceedings Karst Hydrogeology and Environment Protection Conference, Guilin, China*, 178–182.

QUINLAN, J. F., EWERS, R. O. & FIELD, M. S. 1986. How to use groundwater tracing to 'prove' that leakage of harmful materials from a site in a Karst Terrane will not occur. *In*: *Proceedings Environmental Problems in Karst Terranes and their Solutions Conference, National Water Well Association, Dublin, Ohio*, 289–301.

RAYMOND, F. (ed.) 1994. *Mendip Limestone Quarrying: A Conflict of Interest*. Somerset Books, Tiverton, 1–70.

SENDLEIN, L. V. A. & PALMQUIST, R. C. 1977. Strategic placement of waste disposal sites in karst regions. *In*: TOLSON J. S. & DOYLE, F. L. (eds) *Karst Hydrogeology*, 323–336.

SMART, P. L., EDWARDS, A. J. & HOBBS, S. L. 1991. Heterogeneity in carbonate aquifers: Effects of scale, fissuration, lithology and karstification. *In*: *Proceedings of the Third Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes, National Water Well Association, Dublin, Ohio*, 373–388.

—— & FRIEDERICH, H. 1986. Water movement and storage in the unsaturated zone of a maturely karstified carbonate aquifer, Mendip Hills, England. *In*: *Proceedings Environmental Problems in Karst Terranes and their Solutions Conference, National Water Well Association, Dublin, Ohio*, 59–87.

—— & HOBBS, S. L. 1986. Characterisation of carbonate aquifer : A conceptual base. *In*: *Proceedings Environmental Problems in Karst Terranes and their Solutions Conference, National Water Well Association, Dublin, Ohio*, 1–14.

STANTON, W. 1966. The impact of limestone quarrying on the Mendip Hills, Somerset. *Proceedings of the University of Bristol Spelaeological Society*, **11,** 54–62.

—— 1977. A view of the hills. *In*: BARRINGTON, N. & STANTON, W. *Mendip—The Complete Caves and a View of the Hills*. Cheddar Valley Press, Somerset, 193–234.

—— 1989. Bleak prospects for limestone. *New Scientist*, **13 May 1989,** 56–60.

—— 1990. Hard limestone: Too valuable to quarry. *Mineral Planning*, **43,** 3–9.

VEGTER, J. R. & FOSTER, M. B. J. 1992. The hydrogeology of dolomitic formations in the Southern and Western Transvaal. *In*: BACK, W., HERMAN, J. S. & PALOC, H. (eds) *Hydrogeology of Selected Karst Regions*. Heise, 355–376.

WILLIAMS, P. W. 1983. The role of the subcutaneous zone in karst hydrology. *Journal of Hydrology*, **61,** 45–67.

YUAN, D. 1992. Karst and karst water in China. *In*: BACK, W., HERMAN, J. S. & PALOC, H. (eds) *Hydrogeology of Selected Karst Regions*. Heise, 315–338.

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