Observations on the East End Mine groundwater impact.

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I was invited by Alec and Heather Lucke, in their role as leading members of the East End Mine Action Group (EEMAG), to attend a two day meeting at Mt Larcom on 1st and 2nd August 2007. The first day, effectively only the afternoon, was spent in site visits including an inspection of the mine. On the second day, Bruce Pearce, a hydrogeologist with the Department of Natural Resources and Water, presented the results of his review of the data that have been assembled over the past 30 years on the impact of the mine pumping on the groundwater in this district.

It is not my intention to attempt a critical review of these data nor to present a detailed critique of the work presented by Bruce Pearce. Indeed, it would not be possible for me to do this without undertaking a detailed study of the site and the data, and that would take months. What I intend to do is to discuss the assumptions and the logic that underlie the long running debates on this issue. What I have to say here is not intended to be, and should not be interpreted as, criticism of the work of Bruce Pearce as reported by him on 2nd August. I was impressed by the detailed analysis he has carried out using a difficult data set. However, I do question some of the assumptions on which his analysis is based and I am concerned that the data available to him is probably not the best kind to use in analysing a karst aquifer.

I first visited this area about 5 years ago when I was shown around by Alec and Heather Lucke at the instigation of Dingle Smith, a karst expert from the Australian National University. I was accompanied on that visit by Dr Mark Ellaway, an expert on karst hydrology and geochemistry from the University of Melbourne. What registered with me on that visit was that here was an area with abundant surface expressions of karst development but it appeared that the investigations being undertaken into the groundwater hydrology were those that would normally be used on an unconfined Darcian aquifer. Shortly after that visit I was invited by the publishers of *Geo Date* to write a piece on karst and the management of karst landscapes (Finlayson, 2002). I used the situation I had observed at Mt Larcom as the basis for a discussion about how karst landscapes differ in terms of groundwater behaviour from non-karst areas.

It is interesting (for me, at least) to speculate on what kind of understanding we would now have of the behaviour of groundwater in the Mt Holly Beds surrounding the East End Mine if the investigations and monitoring had been carried out using techniques appropriate to a karst aquifer. The first step in such an investigation would be to identify and map the surface expressions of karst development – sinkholes, springs etc. To the best of my knowledge this has never been done in any systematic way in this area so we really don't know just what is the extent of karst development here. It is the case that there are a number of very well developed sinkholes and reports of their behaviour by knowledgeable local residents indicate that they must be connected to significant conduits in the limestone. A detailed discussion of methods of groundwater investigation in karst areas is provided by Drew and Goldscheider (2007, included here as an Appendix).

The second step in such an investigation would be to set up a monitoring program on the water chemistry of springs and boreholes in the area. Initially at least, this would need to be done with frequent monitoring and could lead to an understanding of the nature of the groundwater body and the likely pathways of water movement. So, for example, if the springs produced water with high carbonate concentrations most of the time but with markedly lower concentrations during wet periods this would indicate that they were draining water stored in tight fissures but were also connected to fast conduit flows during rainfall events. Ideally, selected sites would be continuously monitored to detect this kind of behaviour.

The third step would be to attempt to establish, using tracing techniques, where the water entering sinkholes is going. This would only be attempted after steps one and two were completed and the information gained from those steps would inform the choice of tracing pathways.

At this late stage in the analysis of the groundwater impacts of the East End Mine, it is probably not reasonable to suggest a return to first principles and to undertake this kind of investigation, desirable though that might be. However, if it could be confirmed that there are conduit flows through these beds, and that they are not all along the strike, then the concerns of the Bracewell residents, that their groundwater is being adversely impacted by mine pumping, would need to be viewed in a different light to that suggested by Bruce Pearce's analysis.

There are specific items of information available that suggest there may be conduits connecting Bracewell to the East End area closer to the mine. Some time ago, and I am not sure of the date, effluent from a piggery was accidentally discharged into a karst sinkhole on the farm of the Lucke Brothers at Bracewell (GR 872582)[1]. Odours identified as being like pig effluent were apparently reported from a bore at Armstrong's property (GR 891604) and from the East End Mine (GR 921578). These reports are unsubstantiated and there is no evidence that they were investigated by hydrogeologists working on this case.

In May and June 2002 a dye trace was attempted from the sinkhole at GR 872582 by Dingle Smith, using an artificial pulse of water and the dye Rhodamine WT. Details of the procedure can be found in his report to EEMAG (Smith, 2002) and I will not repeat them here. It should be noted however that Smith has considerable experience in dye tracing and is an acknowledged expert in the field. While this does not guarantee that his results are correct, it does indicate that his work cannot be lightly dismissed. He reports a positive trace from the sinkhole to the East End Mine and states *"The conclusion of the dye experiment is that it is indicative of a direct groundwater link between the input point in the disputed Bracewell area and the mine pump out. Certainly the result is such that the experiment should be repeated"* (p3).

A basic assumption in Bruce Pearce's work is that any conduits in this material are aligned along the strike and therefore could not provide a link between Bracewell and

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[1] All grid references refer to the Bajool 1:100,000 sheet 9050.

the mine. Both the pieces of evidence outlined above contradict this notion. This does not mean that Pearce is wrong in his assumption. What it does mean is that there is a very strong case to suggest that the assumption may not be valid and that this issue needs to be investigated in more detail. It would be entirely unreasonable to expect the residents of Bracewell to ignore the evidence that points to a conduit link to the mine given the current state of knowledge. They have far more reason to believe that such a link exists than Bruce Pearce has to deny its existence.

Bruce Dudgeon, in his BAppSci field project report (Dudgeon, 1988) clearly identifies karst conduits in the East End aquifer and it is reasonable to assume that similar conduits would also be present in the Bracewell aquifer. The presence of sinkholes and springs in that area are strong indicators of this. While Dudgeon recognises the karst properties of the East End Aquifer, an important assumption in his work is that this aquifer is bounded by volcaniclastics that carry "zero flow" (p101). This is also an important part of Bruce Pearce's analysis as he assumes that the Bracewell limestones are separated from the East End limestones by these impermeable volcaniclastics. This may so but I have not been able to find objective proof that this is the case.

The curiously structured report by Freelance and Spate (2003) arrives at the conclusion that there are effects other than climate on the present condition of the Bracewell aquifer with the obvious implication that this is mine pumping. This work was done with incomplete data but it would be foolhardy to dismiss out-of-hand work conducted under the supervision of such an eminent scientist as Tony Jakeman. His eminence does not make these results correct but it should cause us to consider them carefully.

Interpretation of the impacts of the mine pumping on the groundwater of this district is complicated by the long run of years with below average rainfall. The argument being presented to the residents of Bracewell is that the changes to their local groundwater system are caused by the climatic conditions and not by the mine, despite the arguments in the Freelance and Spate report. While this must be acknowledged as a possibility, the evidence presented to support the case that climate alone is responsible for the present condition of the Bracewell aquifer is not convincing. The notion that the decline in groundwater levels at Bracewell is solely climate driven is a testable hypothesis and not an established fact.

In the information presented on 2nd August about drawdown around the mine, it was shown that there is more drawdown at East End than at Bracewell. The conclusion drawn was that in the East End case there was the combined effect of climate and mine while the lesser drawdown at Bracewell indicates a climate effect only[2]. If this logic is correct, then other locations in the Mt Holly Beds that are sufficiently far from the mine not to be affected, should show similar drawdown patterns to Bracewell. To the best of my knowledge, there has been no attempt to look at other

[2] An equally defensible conclusion from the drawdown data shown on August 2nd is that the combined climate and mine drawdown at Bracewell is less than the combined climate and mine drawdown at East End, close to the mine. If this was, in fact, an unconfined Darcian aquifer, the Dupuit-Forchheimer approximation would suggest exactly that.

sites in this way. Of course, they would also have to be sites where there is no significant irrigation pumping.

In summary, it is my view is that it is bizarre that the investigation of the groundwater impacts of a *limestone* mine has been carried on for around 30 years without any significant attention being given to the particular hydrogeological properties of limestone.

Recommendations

1. There should be a repeat of the dye trace carried out by Dingle Smith in 2002. His advice should be sought on the best way to conduct this in order to capitalise most effectively on the knowledge he gained in the 2002 trace.

2. Borehole records for a wider area of the Mt Holly Beds should be interrogated to compare with drawdown currently observed at East End and Bracewell.

3. The activities in Recommendations 1 and 2 should be carried out with the full involvement of the local community. Standards of proof that are going to be acceptable to the community, the mine and the Department need to be clearly set out in advance, and in writing.

4. There is obviously a great deal of accumulated knowledge within the local community about the groundwater in this area. I have not seen any evidence that this knowledge source is being tapped either to assist in framing the research questions that should be asked or to help provide answers to questions. Detailed discussions should be held with the local community within a framework designed to use their knowledge to best advantage.

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APPENDIX

Methods in Karst Hydrogeology

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CHAPTER 11

Combined use of methods

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11.1 INTRODUCTION AND SUMMARY OF METHODS

Any full and rigorous groundwater investigations, whether in karstic or non-karstic conditions, requires the application of more than one investigative method. However, the mix of methods used in karst areas may differ significantly from those commonly used where flow is laminar and diffuse and hence where Darcy's law is applicable; in particular the combination of orthodox methods with those appropriate only to karst (speleological investigations for example). This chapter provides a summary of the methods described in this book together with a brief overview of the conjunctive use of methods to address particular karst groundwater problems.

One approach to the use of several techniques in an investigation is to use complementary methods in which data from one technique is used to supplement the inadequacies of data derived from another method. For example, using water tracing to give more accurate information concerning flow paths than can be obtained from piezometric maps. Or using natural tracers (e.g. isotopes, hydrochemistry) to obtain general information regarding all or a part of a groundwater system and then obtaining precise data for a particular locale by using artificial tracers in which the input function is controlled. The methods may also be used to validate results obtained by other means (for example confirming data obtained by indirect means such as geophysics by direct exploration of the aquifer via cave conduits).

Methods may also be use in combination to allow conceptual models of varying degrees of sophistication to be developed. The results of water tracing, groundwater level observations and karst hydrogeomorphological mapping may be combined to build a picture of a karst groundwater system. Spring and swallow hole flow data may be analysed together with hydrochemical data to help to understand the dynamics of flow systems. Finally, some mathematical modelling approaches, as described in this book, may require large amounts of high quality data derived in a variety of ways to produce a holistic view of a groundwater system. However, other analytical modelling approaches, with more limited aims, such as spring hydrograph, chemograph or tracer concentration analysis from springs require comparatively modest data inputs. Some modelling approaches require no real-world input data at all, but are primarily intended to better understand specific processes.

In standard groundwater textbooks such as Fetter (2001) and Brassington (2006) the suite of methods most usually advocated are geological, including lithological interpretation of rocks cores; geophysical, (rock-water properties) and pumping tests allied, if appropriate with water budget computations and modelling. Such a combination may not be the most relevant to a karst groundwater study where an appropriate investigative strategy might be:

- understanding the geological framework
- hydrological mapping (recharge and discharge locations)
- tracer tests to establish hydrological linkages

If practicable and relevant these investigations might be followed by speleological surveys, geophysical studies (either of large areas of the aquifer or to locate particular subsurface features). Depending on the purpose of the study, natural tracer information may be relevant, particularly hydrochemical data if water quality is a concern Hydraulic methods may be employed, but their importance is greatest where access to the aquifer using the other methods listed above is limited.

Table 11.1 summarises the groups of methods described in this book. The methods are grouped according to the chapters of the book and for each the main types of data obtained are listed together with the limitations or drawbacks of the methods.

11.2 COMBINED METHODS FOR SPECIFIC INVESTIGATIONS

In hydrogeological investigations the methods used will be strongly influenced by the questions that need to be answered but also by the available resources. In the case of karst, the type of karst involved will also influence the methods used. For example, borehole based investigations are often of very limited value in upland karsts whilst speleological investigations are often not possible in lowland karsts. Examples of aspects of hydrogeology that are often of particular importance in karst groundwater systems are discussed below.

11.2.1 Determining the catchment areas for springs

Because karst groundwater systems often drain to springs it is often essential to define the area contributing water to that spring, partly to assess potential yields, partly to assist with protecting water quality. Geological information is indispensable to determine the likely limits of a catchment. Geomorphological observations may also be helpful in some cases. It is important to note that groundwater flow paths in karst aquifers may run across valleys and below mountain ridges. Therefore, topographic limits cannot necessarily be translated into groundwater divides, as can often be done in other groundwater environments.

Water balances, though they are often difficult to determine, help in the estimation of the *minimum* surface area of a spring catchment. Karst aquifers are often drained by several springs with overlapping catchments, and this needs to be considered when establishing a water balance for a particular spring. The possible existence of unknown or inaccessible outlets (e.g. submarine springs) represents another difficulty. Mapping of sinking streams and swallow holes and their topographic catchments makes it possible to delineate the allogenic part of the catchment area.

Natural tracers can sometimes resolve ambiguities concerning contributing areas whilst the use of artificial tracers is an essential tool in providing unambiguous information as to whether or not particular areas (tracer input points) lie within a particular spring catchment (e.g. Goldscheider 2005, Lütscher & Perrin 2005). As the delineation of source protection zones usually implies land-use restrictions, which may require financial compensation, it is crucial to have highly reliable data, which can only be provided by tracer tests.

Table 11.1. Summary of methods available for hydrogeological investigations in karst areas.

Method or group of methods	Data obtained/advantages	Disadvantages/limitations
Geological methods	Aquifer framework and geometry information Karstifiability of the rock Orientation, location, type and frequency of potential flow paths Theoretical hydraulic conductivity and porosity	Data not necessarily directly related to groundwater Often not a predictable and unambiguous relation between lithology and hydrogeology
Geomorphological methods	Degree of karstification Types of recharge Historical hydrogeomorphology	Data mainly from the surface (indirect) Static framework rather than hydrodynamics Limited data from covered karsts
Speleological methods	Locating and mapping conduits in 3D Monitoring water quality and quantity within the aquifer Determining the temporal evolution of conduit systems	Access to cave systems may be limited or non-existent Specialist speleological skills required Only a small and perhaps unrepresentative part of the aquifer is likely to be accessible
Hydrological methods	Water budget compilation Characterisation of flow systems by spring hydrograph analysis	Water budget often incomplete, as catchment boundaries are not always clear, and not all inputs and outputs can be monitored Hydrograph alone gives limited information of the origin of the water (needs to be combined with chemograph)
Hydraulic methods	Determination of transmission and storage characteristics Determination of piezometric level Determination of groundwater velocity and flow direction	Many methods not wholly appropriate under non-Darcian conditions Estimates of flow directions and magnitudes may not be accurate Pumping tests may not give representative results
Hydrochemical methods	Hydrochemical characterisation of groundwater bodies Information on water quality and contamination problems May be used as natural tracers for the origin and movement of the water	Difficulties in developing an adequate sampling strategy (high temporal variability) In karst aquifers, microbial contamination is often of greater importance than chemical

(Continued)

Table 11.1. (Continued)

Method or group of methods	Data obtained/advantages	Disadvantages/limitations
Isotopic methods	May be used as natural tracers for the origin and movement of the water; this includes: Identifying sources of karst waters and mixing processes Determining residence time/age of karst waters	Input function not known precisely Ambiguities possible in interpreting data
Tracer methods	Determination of flow routes and velocities Determining contributing areas for springs Information on contaminant transport Usually very reliable, precise and unambiguous information	Difficulty in recognising "negative" tracings Usually only gives information for selected points and the hydrological conditions during the tracer test Limited applicability for very deep and large systems with very long transit times Visible colouring and toxicity concerns for some tracers
Geophysical methods	Determining geological structures and overburden thickness Locating conduits, fractures and other preferential flow paths Data can be obtained over wide areas Information on the structure and properties of the underground without drilling, i.e. at relatively low cost	Results may be difficult to interpret without ambiguity (non-uniqueness) Resolution vs. depth of investigation (i.e. the greater the depth, the lower the resolution) Some techniques require very precise location control (gravimetry), others have noise problems or require heavy or expensive equipment
Modelling methods	Conceptualising all or a component of karst aquifer systems May give a better understanding of specific processes, such as speleogenesis, conduit flow and conduit-matrix interactions Simulating groundwater flow and contaminant transport Predicting changes in water quality and quantity	Difficulties in applying conventional models for flow and transport (modelling may lead to significantly erroneous results if the nature of karst is not adequately considered) Exacting data requirements for holistic modelling (distributive models ideally require data on the location and geometry of the entire conduit network, which is never available)

11.2.2 Locating water sources

Springs are the obvious and commonly the preferred source of water supply in karst areas but inevitably there are often requirements for water source in areas that are not close to springs and boreholes must be drilled to obtain a supply.

Boreholes are more uncertain sources of reliable water supply in karst than in other aquifers as groundwater flows are highly localised, often in all three dimensions. Finding optimal locations for supply wells is notoriously difficult but may be assisted by thorough geological and geomorphological investigations (locating inception horizons for conduits, relatively impermeable layers and highly soluble layers within the limestone, faults, fracture zones and lineaments for example).

Geophysical methods are useful in identifying water-bearing zones, particularly in karst aquifers covered by thick soils and sediments, where surface expressions of fracturing and karstification are scarce. Some methods, like microgravity, assist in locating conduits (gravity-lows), particularly if they are relatively large and at shallow depth. Other methods, like seismic, resistivity profiling and various electromagnetic techniques, are powerful tools to locate fracture zones (e.g. Bosch & Müller 2005, Sumanovac & Weisser 2001).

Borehole geophysics and a variety of hydraulic tests can be performed in open boreholes and in screened wells. On one hand, such tests can be used to obtain information on the hydraulic properties of the aquifer. On the other hand, they may also help to optimise the construction and pumping rate of the well, e.g. to locate productive zones, to decide where the well should be screened, and to determine sustainable pumping rates (safe yields).

Exploration and mapping of karst conduits (active cave systems) may be a useful way of locating water supplies in some karsts.

11.2.3 Assessing water quality and contamination problems

Water quality and contamination studies always require hydrochemical and/or microbiological investigations. Microbial pathogens are particularly relevant in karst aquifers, where filtration and inactivation processes are of limited effectiveness. The high variability of karst groundwater flow systems requires adapted, event-based sampling strategies. Automatic samplers and continuous monitoring devices are particularly useful to obtain a better temporal resolution. As such devices are not available for bacteriological parameters, a variety of other parameters, such as turbidity and organic carbon, can be used as indicators for the possible presence of bacterial contamination (Pronk et al. 2006).

A variety of other methods described in this book can also be used within the framework of such investigations. Tracer tests allow the propagation of contaminants to be studied, and specific tracers can be used as surrogates for specific groups of contaminants, e.g. microspheres for *Cryptosporidium* cysts (Renken et al. 2005), and bacteriophages for pathogenic viruses (Rossi et al. 1998). Isotope techniques make it possible to distinguish whether a particular water constituent, such as sulphate or nitrate, is of natural origin or results from human activities (Einsiedl & Mayer 2005).

Geophysical methods can sometimes be used to delineate highly concentrated contaminant plumes (Fels 1999), although the heterogeneity of karst limits this approach. Models that simulate transport processes can also predict the impact of contamination on an aquifer or spring. However, transport modelling in karst is even more problematic than flow modelling and requires input data that are generally not available. Therefore, the use of models for that purpose should be restricted to cases where detailed data are available, and the model must always be validated by independent field data, preferably tracer tests (see the example from Walkerton, Canada, in the Introduction of this book).

11.2.4 Conceptualising karst flow systems

Although all karst aquifers have a considerable degree of similarity in terms of the manner in which they function, there are also considerable differences within and between particular karst aquifers; for example in the spatial distribution of conduits and fissures, in the degree of hierarchical organisation of the drainage system and in the amount and type of storage. Difficulties in reconciling these smaller scale differences with a "global" conceptual model of karst hydrogeology mean that a wide variety of data sources may be required to usefully conceptualise karst hydrogeology. These include detailed information on the location and relative importance of flow routes derived from speleological investigations and detailed information concerning the recharge, storage and transmission characteristics of the aquifer. Quantitative data from water tracing (breakthrough curves for example) and analysis of spring hydrographs and chemographs are particularly relevant in this context. Knowledge of the basic geological framework and values for hydraulic conductivity and hydraulic head, which may suffice to model aspects of many non-karstified aquifers are commonly inadequate in karsts.

11.2.5 Assessing groundwater vulnerability in karst areas

Determining the vulnerability of a groundwater body to contamination is of fundamental importance in groundwater management. The European COST Action 620 provided a conceptual framework for vulnerability and risk mapping for the protection of carbonate (karst) aquifers (Zwahlen 2004). Although some aspects of vulnerability mapping are common to all aquifer types and conditions (assessment of protective cover for example), karst regions require more specific data such as the location of points of concentrated recharge and their local catchments.

Geological, geomorphological, pedological and hydrological mapping provide the basic data required for vulnerability assessment. Speleological observations may also be of great use. Geophysical techniques make it possible to assess the thickness and properties of the overlying layers, and may also help to characterise the epikarst, identify fractures, and localise zones of potential or actual infiltration. However, such techniques are more appropriate for detailed, site-specific vulnerability assessment, while simpler (and less precise) techniques are usually used on the scale of large catchments, regions or countries.

A variety of techniques are available to validate a vulnerability assessment. Releasing a tracer at the land surface and monitoring its breakthrough at the spring is the most direct approach but restricted to selected points (Goldscheider et al. 2001). Other methods, including, hydrochemical and isotopic techniques, also provide information on contaminant pathways, transit times and attenuation processes in the system, and can thus be used for validation. The initial vulnerability map may be modified in the light of these data.