Aquifer Reinjection Scheme for Excess Mine Water: Design Methodology and Outcomes

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Abstract Groundwater reinjection systems represent a potential technique in mine water management to: (1) reduce the need for surface discharge or other management processes for excess mine water; and (2) reduce stress on local groundwater resources caused by net abstraction of groundwater. Reinjection systems, through managed aquifer recharge, can help achieve a more sustainable development whereby clean water is returned to the local catchment.
This case study illustrates a method for quantifying requirements for reinjection arrays as part of a mine water management system, where aquifer characteristics including groundwater depth, permeability and lateral extent will vary.

Key words Mine Water, Reinjection, groundwater, sustainability, managed aquifer recharge

Introduction

The controlled reinjection (RI) of water to an aquifer, or managed aquifer recharge, can provide an opportunity for improvements to sustainability in mine operations by reducing the discharge to surface of groundwater arising from dewatering, thus minimising the wastage of finite water resources. Such schemes are not without their challenges, however. The choice of land available for RI at mine properties is often limited, with uncertain and variable characteristics and properties related to topography, groundwater depth, expected RI well performance, and receiving aquifer permeability.

Such RI schemes commonly make use of multiple RI well arrays within the mine property. A successful scheme will require site-specific data to inform the design to achieve the water management objectives. Site-specific challenges must be addressed in the design of the RI testing programme which will feed into the design calculations. This paper presents a case study based on a mine in Europe to demonstrate the challenges associated with the design, testing and assessment of a RI scheme.

Reinjection Scheme Concept

The objective of a groundwater RI scheme is to route excess clean water sourced from mine water sources to a RI wellfield so that it can be injected and returned to the local aquifer system. Appropriate mine water sources are typically clean groundwater sourced from dewatering activities. Dirty mine water, or “contact water”, would be managed by a separate system and is not considered in this discussion.

RI Test Design Considerations

Key factors in the design of a hydrogeologic test programme for a RI system include:

1. A hydrogeology test methodology tailored and adapted to site conditions;
2. Availability of adequate monitoring locations (water levels and climate records);
3. Careful control of the water delivery system to ensure consistent inflow rates;
4. Avoidance of air intrusion within injected water; and
5. Sufficiently long RI test duration.

1. Hydrogeology Test Methodology Tailored and Adapted to Site Conditions

Factors to consider when designing an appropriate hydrogeology test programme include:
(a) Using all testor monitoring locations to characterise heterogeneous aquifers;
(b) Considering use of conventional testing techniques (e.g. packer or pumping tests), which may be more practical to undertake than injection testing to supplement the aquifer test dataset;
(c) Allowing for site topography and access in the layout of the test array; and
(d) Allowing for access to a water supply to feed the test array during RI testing. This includes routing of supply piping, sourcing water from pumping wells distant enough not to affect the RI test results, and sourcing water of similar quality to that to be used in the permanent RI system.

2. Availability of Adequate Monitoring Locations (Water Levels and Climate Records)

Installation of monitoring wells is a cost to the project and may not be considered of high value to an operator trying to minimise drilling costs. However, monitoring at the RI wells alone may not be sufficient to determine aquifer performance, particularly in space-limited or bounded environments. Monitoring locations separate to the RI wells can be incorporated into the permanent performance monitoring system of the RI wellfield, thereby limiting project cost. Adequate pre- and post-test monitoring data should also be collected along with seasonal and test-specific rainfall records to understand both the unsaturated depth to groundwater and the effect of rain events on the natural and induced groundwater table.

3. Careful Control of Water Delivery System to Ensure Consistent Inflow Rates

Feeding the RI wells by gravity may present challenges in maintaining a constant and controlled flow rate during the test period, particularly in locations of varying topography. Upstream control of hydraulic head on the feed pipeline may be required. In the current case study, this challenge was addressed by using a header tank placed near to the RI test wells. This acted as a buffer to short-term changes in flow rates from the water source, as well as mechanism for more discrete control of the driving heads.

4. Avoidance of Air Intrusion Within Injected Water

Entrained air within the RI well feed water can promote well clogging by leading to air entrainment in the RI well pack or precipitation of dissolved minerals causing well clogging

(Pyne, 1994). Both have the effect of reducing well efficiency. This can be mitigated by fitting valves and outlets that allow flushing of the feed lines and headworks of air prior to introduction of the water to the RI test well. Sealed headworks, if used, require additional care to control air within the system. Drop tubes should be installed within the RI wells to minimise turbulent flow causing air entrainment when the water is injected.

5. Sufficiently Long RI Test Duration

Test duration should ideally be sufficient to (a) observe the effects of any hydraulic boundaries, (b) observe superposition effects from adjacent RI wells, and (c) assess changes in well performance over time. Often it is not possible to run long term tests during preliminary design phases, however, they should be planned to run for a long as practicable. Access to water supply to feed the injection wells may factor into the test duration planning. Longer term assessment can continue during commissioning of the RI arrays which can lead to design revisions during construction.

Case Study – Reinjection System Testing and Design for Mine Water Management

This paper examines the process of developing a clean water RI scheme on a mine site in Europe. The practical challenges associated with the RI test site included the following:

- The aquifer to be dewatered and reinjected into is a fractured rock aquifer which had not previously been characterised in detail;
- Expected aquifer anisotropy and heterogeneity;
- Space-limiting topography within mine property, causing challenges for well placement and limited access to test locations;
- Placement of wells is limited laterally necessitating linear array layouts;
- Limited thickness of unsaturated zone at some locations, resulting in constraints on water level rise during reinjection; and
- Challenging logistics for water delivery to the RI test sites requiring a complex network of piping.

The testing programme was designed to address these challenges as discussed below.

RI Test Array Construction and Hydrogeology Testing

A series of RI wells were constructed to test the RI area. These wells were expected to be utilised for both testing and as part of the site permanent RI system. Wells were drilled at 300 mm diameter to a depth of either 150 to 300 m below ground level, dependant on geology, and completed with filter packs and 200 mm diameter well screens. To observe groundwater level response, monitoring wells were constructed near to the RI wells to equivalent depths. Where possible, the RI wells were located in pairs to form array locations. Typically the test arrays were constructed along a valley side road as indicated in Figure 1.

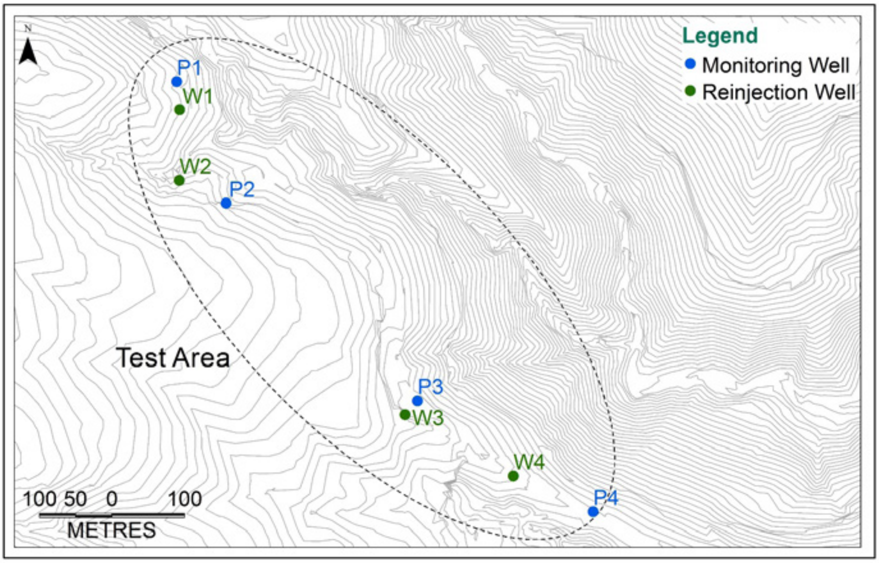

Figure 1: *Plan view of typical layout of reinjection test arrays.*

As the area had not yet been hydrogeologically characterised, a series of hydrogeologic tests were undertaken in both the RI wells and monitoring wells. A summary of the testing performed is presented in Table 1. Water for the testing activities was sourced from groundwater abstraction wells distant to the test array transmitted by 100 mm diameter pipe.

Typical results from the RI testing are presented in the Analysis and Evaluation Section below.

Analysis and Evaluation

A summary of results from all tests conducted is as follows:

- Packer Tests: estimated bulk K of 10^{-6} m/s to 10^{-8} m/s;
- Well performance: specific capacity of up to 7.5 m^3/hr/m for abstraction and 4.5 m^3/hr/m for injection; and
- Aquifer analyses: estimated T of up to 400 m^2/d.

Typical results from the RI testing are presented in Figure 2 and Figure 3.

In several of the tests the results suggested the presence of hydraulic barrier boundary conditions. Some tests also showed incomplete recovery of groundwater levels with recovery to levels significantly higher than pre-test conditions, suggesting the filling of storage in a bounded aquifer. Both of these observations are potentially problematic for an RI system as groundwater levels could rise more quickly than anticipated or the volume of water which can be injected could be limited by the filling of bounded aquifer storage. RI well performance could also be impacted by weather conditions. Heavy rainfall events during the test period were shown to influence shallow groundwater levels. Higher groundwater levels reduce both the available injection head and the thickness of the unsaturated zone, which can make injection wells less effective.

***Table 1** Hydrogeologic Test Phases Conducted*

Hydrogeology Test Type	Test Description	Analysis and Evaluation
Monitoring Well Testing		
In-situ packer tests	Falling head and constant rate tests during construction	Analysed to obtain aquifer parameters – Transmissivity (T) & Hydraulic Conductivity (K)
Reinjection Well Testing		
Step Tests	To assess capacities and sustainable pumping rates for subsequent tests	Analysed to obtain aquifer parameters – T & K Well performance assessment
Constant Rate Pumping Tests with Recovery	Minimum of 24 hours pumping from RI wells.	Analysed to obtain aquifer parameters – T & K, to assess boundary conditions, and well performance
Injection Step Tests	To assess capacities and sustainable injection rates for subsequent tests	Analysed to obtain aquifer parameters – T & K Well performance assessment
Constant Rate Injection Test with Recovery	Continuous and constant gravity-fed injection of pumped groundwater into RI wells for minimum of 48 hours	Analysed to obtain aquifer parameters – T & K, to assess boundary conditions, and well performance

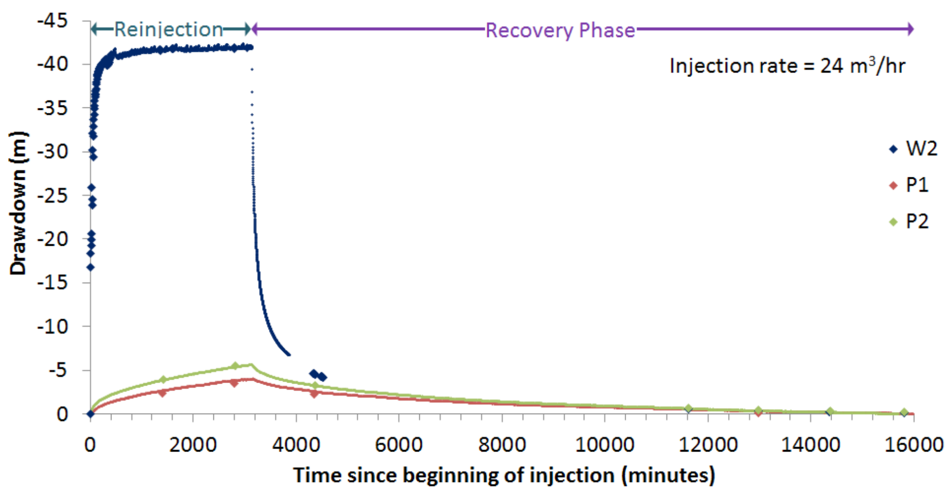

***Figure 2**: Typical Reinjection Test with Recovery Phase – negative drawdown indicates water level rise.*

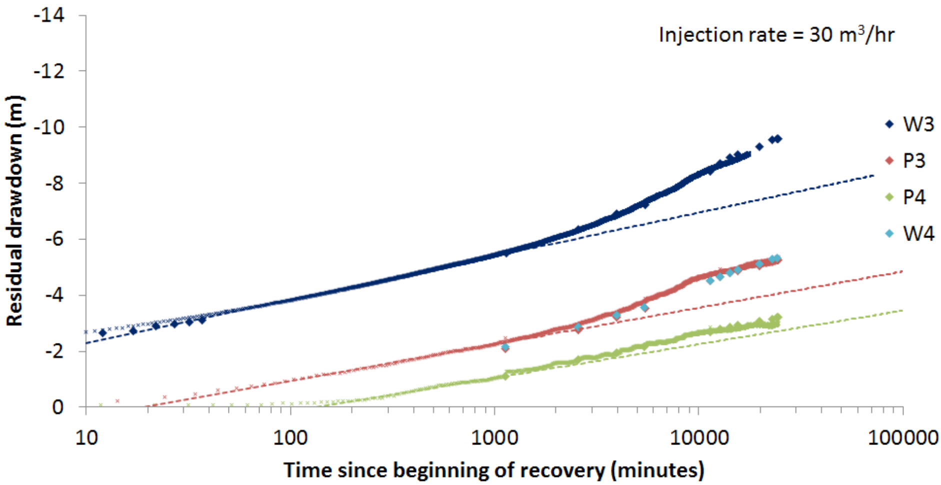

***Figure 3**: Typical Plot of Reinjection Test Recovery Phase as residual drawdown versus time (log scale) – negative drawdown indicates water level rise.*

RI testing suggests that long-term RI may be possible for clean water disposal at the project site. RI into an individual RI well is likely to affect the performance of nearby RI wells in an array of multiple RI wells. Longer duration RI trials were recommended to further investigate the presence of barrier boundary conditions and well performance.

Design Calculations and Key Performance Factors

Design calculations for the array of multiple RI wells proposed for the full scheme were based on the principle of superposition of drawdown (Preene *et al.* 2016), using best-case (where the rise in groundwater levels resulting from a given injection rate was relatively low) and worst-case (where the rise in groundwater levels resulting from the same injection rate was higher) responses to RI extrapolated from field test data from individual wells. Specific drawdown curves from RI data were extrapolated to two years of injection to support the development of these scenarios. Using this method, various RI well array layouts were considered for the short- and long-term phases of mine operation, which had differing water management requirements. A highest permissible groundwater level was applied in the design as a constraint on injection rates and well spacing. The highest permissible groundwater level was typically set to avoid water levels close to the RI wells rising to within 10 m of ground level.

The method identified the likely number of RI wells and well spacing required to enable RI at the desired rate in various phases of the mine operation under best- and worst-case scenarios. In the course of the design an understanding was developed of the optimal balance between RI well numbers and spacing.

Several performance factors proved to be key to the design calculation and should be assessed during the testing phase. These are summarised in Table 2.

***Table 2**: Reinjection Scheme Key Performance Factors*

Aquifer Characteristics	Wellfield Design Criteria
• Pre-injection depth to groundwater table • Hydraulic conductivity and anisotropy • Aquifer lateral extent • Presence and location of hydraulic boundary conditions • Aquifer response to weather events	• Well efficiency and rate of decrease over time • Potential range of suitable well spacing • Potential well interaction/ superposition effects

Ongoing monitoring and assessment on commissioning should be used to refine the system design and for maintenance and operational control.

Conclusions

Reinjection wellfields can be used to limit the amount of groundwater to be managed by other means within the mine water management plan. This paper has discussed design of a testing programme to determine design parameters for a Reinjection array. The case study discussed demonstrates the successful testing and assessment of a reinjection scheme in a complex and anisotropic aquifer dominated by discrete features. Design of the reinjection system based on this test work must consider key performance factors including aquifer characteristics and wellfield performance criteria. System design calculations should consider available land constraints and incorporate best- and worst-case scenarios for well and aquifer conditions.

References

Preene, M. Roberts, T.O.L. and Powrie, W. (2016). Groudwater Control – Design and Practice, 2nd Edition. Construction Industry Research and Information Association, CIRIA Report C750, London.

Pyne, R D G (1994). Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery. Lewis Publishers, Boca Raton.