CONCEPTUAL AND NUMERICAL MODELLING OF MINE WATER REBOUND IN THE TEAM VALLEY, GATESHEAD

Submitted in partial fulfilment of the requirements for the degree of Master of Science in Degree Programme in the Faculty of Science Agriculture and Engineering.

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Declaration

I hereby certify that this work is my own, except where otherwise acknowledged, and that it has not been submitted previously for a degree at this, or any other university.

Eileen Briana Villasenor

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I am deeply grateful to my partner David for his immense support and understanding throughout the summer. Most importantly, I am deeply appreciative for my mom Nancy, whose love and guidance is with me in whatever I pursue.

Mine water rebound in the Team Valley, Gateshead

Conceptual and numerical modelling

Eileen Villasenor

Due to the legacy of coal mining in the northeast, Gateshead has a complicated set of mine water and groundwater issues. A conceptual model was developed to understand the geological and hydrogeological influences on mine water rebound and of the underground mine workings. A numerical model was then constructed to simulate the rate of water level rise under various climatic and pumping regime scenarios using the concept of a multi-pond system. The model outputs suggest the importance of artificially pumping mine water at Kibblesworth to prevent rebound and groundwater flooding.

Background

Great Britain has a long history of coal mining dating back to the Roman times. Historically, groundwater was pumped to artificially lower the water table and allow for coal mining activities. The abandonment of coal mines and cessation of pumping has allowed for groundwater levels to recover. This causes rebound at the surface and results in groundwater flooding. Currently, mine water is pumped at Kibblesworth, but the Coal Authority is exploring cost-effective and sustainable alternatives to the pumping regime. Modelling mine water rebound in the Team Valley, Gateshead is of interest due to the impacts of a changed pumping regime on the economy, current and new development, and the water environment.

Building the conceptual model

Prior to the construction of a numerical model, a conceptual model must be developed to gain a robust understanding of the geological and hydrogeological influences on mine water rebound and of the underground mine workings.

Geology and hydrogeology

The bedrock geology of the northeast is made up of sedimentary rocks from the Carboniferous period. The Pennine Coal Measures are the most prevalent and comprise coal seams that were once mined. The drift deposits are primarily composed of boulder clay and laminated clay and silt. The hydrogeology of the Tyne and Wear is complex and poorly understood because the legacy of coal mining has drastically altered the natural behaviour of groundwater. The mine workings have created fractured-like aquifers where groundwater can flow through more easily.

Defining a pond system and interconnections

The numerical model is based on the concept of a multi-pond system that is based on the collieries, coal seams, and interconnections in the mine system so that the water level in any one pond is consistent throughout that pond. Figure 1 shows the spatial distribution of the Brockwell coal seam within the pond system. Defining the pond system provided the areal extents of the workings and pond recharge areas, which are two major inputs into the model.

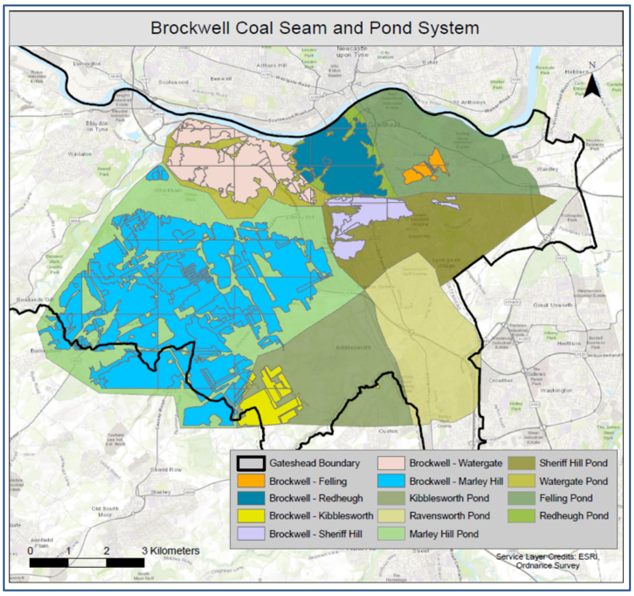

Figure 1 – Example of how areal extents and pond recharge areas were calculated using ArcMap.

Defining the pond interconnections provided the details of the connections including the elevation and discharge coefficients, which defines the ease at which water can move through the connection. These were used as inputs into the numerical model. The pond system and interconnections were defined in ArcMap using spatial GIS data provided by the Coal Authority and Gateshead Council. Although seven total ponds were defined, only three were used in the numerical model analysis.

Construction of the numerical model

Modelling of predictive mine water rebound useful for determining the hydrological and environmental risks and time scales associated with mine water rebound as a basis for making decisions about continued artificial pumping (Younger *et al.,* 2002). The numerical model was based on the concept of a multi-pond system and a groundwater water balance. The inputs and outputs into the water balance system are summarised in figure 2.

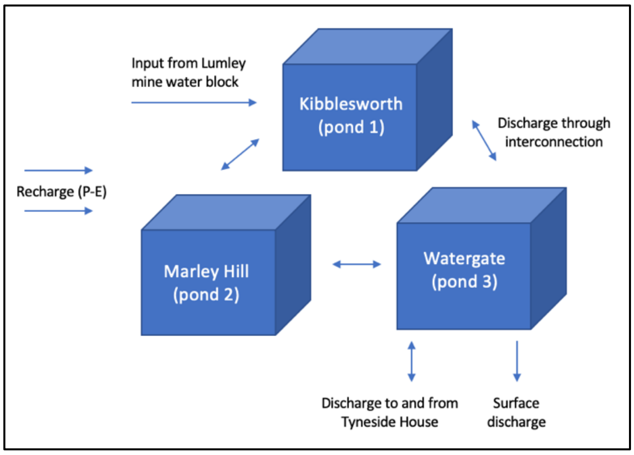

Figure 2 – Summary of inputs and outputs into the 3-pond system.

The numerical model was calibrated against the observed water levels at Kibblesworth (figure 3). It should be noted that as with any numerical model, the outputs are subject to several assumptions and limitations. The resulting calibrated parameters were then used to make predictions of mine water rebound under various recharge and discharge conditions.

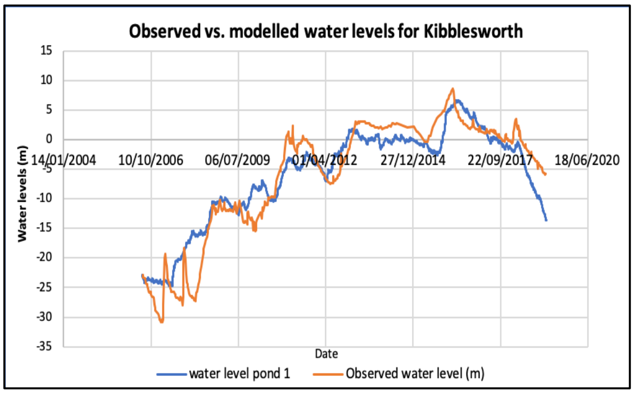

Figure 3 – calibrated model against the observed water levels at Kibblesworth.

Predicting mine water rebound

Four scenarios were modelled to predict the rate of water level rise under various recharge and pumping regimes. Table 1 summarises the four scenarios.

Table 1 – summary of four scenarios modelled.

Scenario	Precipitation (mm)	Abstraction (m^3/d)
1	Observed rainfall values as previous four years (2015-2019)	Abstraction reduced by half of observed values from 2015-2019
2	Rainfall increased by 20% of observed values for previous four years (2015-2019)	Observed values as previous four years from 2015-2019
3	Rainfall increased by 20% of observed values for previous four years (2015-2019)	Abstraction reduced by half of observed values from 2015-2019
4	Observed rainfall values as previous four years (2015-2019)	Abstraction reduced by a quarter of observed values in the first year (19-20), then by half in the second year (20-21), then to zero in the last two years of the prediction period

Overall, the model outputs suggested that the abstraction at Kibblesworth has a major impact on the rate of water level rise in the Kibblesworth pond and immediate surrounding areas. The rate of pumping also had an impact on the direction of discharge to and from ponds. However, recharge had a greater impact on the ponds furthest away from the abstraction. This suggests that there may be additional interconnections with ponds to the north and south of the study area. Additionally, the results suggest that there may be additional inputs/outputs that are not accounted for in the model.

Future work and uses

Incorporating mine water rebound into future groundwater flood mapping may be useful for determining areas at risk and susceptible to flooding from mine water rebound. Future work surrounding mine water rebound should incorporate the other four ponds and interconnections to the north and south of the study area. Additionally, it may be useful to look at Gateshead as a whole when modelling predictive mine water rebound. The outputs of this study may be useful for evaluating the effects of a changed pumping regime on water levels in the mine system. Overall, this report can be used to gain a conceptual understanding of mine water rebound in Gateshead and of the impacts of abandoned coal mine systems on the hydrogeology.

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1.0 Introduction

Due to the legacy of coal mining in the North East, Gateshead has a complicated set of mine water and groundwater issues. The cessation of mine water pumping has caused mine water and groundwater rebound resulting in localised flooding in areas of development. Flooding can have major impacts on communities, infrastructure, the economy, and on the environment. Cessation of pumping can also contaminate groundwater and threaten drinking water supply; in addition, the mine structures can permanently change groundwater flow (Environment Agency, 2006). Current groundwater levels in Gateshead in the North East of England are the highest ever recorded and primarily result from abandoned mine workings (Keeble, 2019).

Groundwater provides clean, fresh water for many homes, industries, agriculture, and the environment, and in the northeast of England, provides about 14% of public water supply (Environment Agency, 2006). It is also an integral part of the water cycle linking rainfall with surface water bodies and in some cases, rivers may be completely fed by groundwater, known as having good hydraulic connection (Younger, 2007).

However, rising groundwater levels are of great concern in Gateshead because of the impact of surface flooding on existing and future property development. In addition, 6% of groundwater bodies in England are at risk of failing to meet the Water Framework Directive objectives due to pollution from abandoned mine workings; thus, finding solutions for managing ground surface flooding and contamination from groundwater and mine water rebound is essential (Environment Agency, 2006).

The Coal Authority does not have statutory responsibility to maintain artificially lower groundwater levels through mine water abstraction but does have responsibilities for managing safety issues dealing with mine water pollution; thus, Gateshead Council is the lead local flood authority (LLFA) for helping to manage the risk from surface water, groundwater, and ordinary watercourses (Keeble, 2019). Currently, the Coal Authority pumps mine water at the Kibblesworth and Chester South Moor shafts within the

Central Durham coalfield block to prevent mine water outbreaks to the surface; however, pumping of the mine water can be costly (Keeble, 2019).

The Coal Authority will be exploring possible cost-effective and sustainable alternatives to the Kibblesworth pumping regime in the coming years to manage water and flooding within the coalfield, such as cessation of artificial pumping, continuing the existing pumping strategy, and controlled engineered gravity discharges (Keeble, 2019). The main concerns with changing the pumping regime at the Kibblesworth station deal with the risks in raising the water level, especially for current and new developments.

Modelling of predictive mine water rebound is useful for determining the hydrological and environmental risks and time scales associated with mine water rebound as a basis for making decisions about continued artificial pumping (Younger *et al.,* 2002). Prior to the implementation of a numerical model, a conceptual model must be developed to understand the geological and hydrogeological influences on mine water rebound. A Groundwater Rebound in Abandoned Mine-workings (GRAM) model will be used in this report to simulate mine water rebound under different pumping and climatic conditions. Understanding mine water rebound is essential in Gateshead as urban development continues to thrive.

1.1 Aims

This report aims to develop a conceptual and numerical model for mine water rebound in the Team Valley, Gateshead. The aim of the conceptual model is to describe the geology, hydrogeology, and other influences on mine water rebound due to the history of coal mining. The conceptual model will provide a better understanding of the behaviour of groundwater in the mine workings underlying the study area. The aim of the numerical model is to model the water levels and mine water rebound under various recharge and pumping rates. The outputs of the numerical model will be used to assess the potential impacts of various scenarios on groundwater flooding in the Team Valley.

1.2 Objectives

The objectives of this project are to:

- Develop a conceptual model of the geology, hydrogeology and interconnection of mine workings using information from the literature and data provided by the Coal Authority and Gateshead Council.
- Develop a conceptual understanding of the geometry, boundary conditions, and hydrological parameters needed to develop a numerical model.
- Construct and implement a numerical model to model the hydrogeological behaviour of the mine system.
- Predict groundwater rebound under various recharge and pumping rates.

1.3 Scope of project

The purpose of this project is to develop a conceptual model that represents the interaction between mine water/groundwater rebound and the coal workings in the Team Valley, Gateshead and to implement a numerical model. The purpose of the numerical model is to assess the impacts of various recharge and pumping rates on rebound. Data was provided by the Coal Authority. The supervisor for this project was Dr. Geoff Parkin. The hydrogeology of the region is poorly understood due to the long history of coal mining and the alteration of groundwater systems. Therefore, the goal of this project is to provide a foundation for understanding minewater and groundwater rebound in Gateshead and the associated implications and to suggest further research.

1.4 Background and project area

The Team Valley lies on the south bank of the Tyne within Gateshead between the rivers Derwent and Don; Gateshead is a town in the northeast of England situated roughly 13.7 km inland from the North Sea and contains approximately 200,000 residents and 90,600 households (Keeble, 2019). The city has an important history of coal mining and is currently growing in development.

The River Team is one of the four major rivers within Gateshead and runs through the Team Valley Trading Estate, which is home to over 700 businesses and is of significant economic importance within Gateshead and the North East (Keeble, 2019; Davies *et al.,* 2014). Extensive coal mining has taken place across much of the catchment in the past while artificial pumping still takes place at Kibblesworth (Keeble, 2019).

The project study area comprises the Kibblesworth mine water pump and the Team Valley Trading Estate located in the Central Durham North region (figure 1).

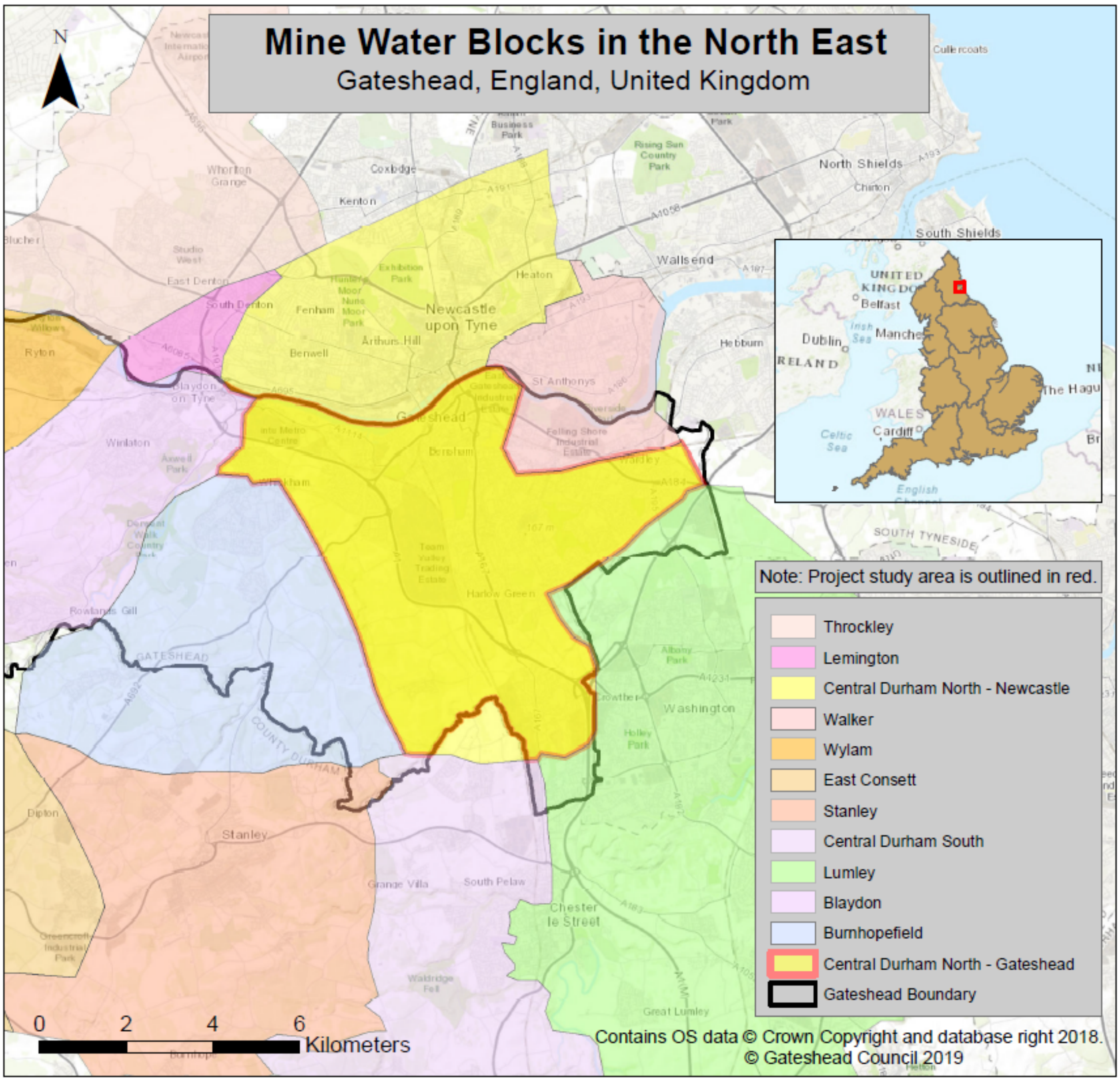

Figure 1 - project study area covering the Central Durham North mining block over the Team Valley, Gateshead.

2.0 Literature review

2.1 Review of mechanisms for groundwater rebound

Groundwater rebound, also known as groundwater flooding, is defined as the emergence of groundwater at the surface away from perennial river channels where the otherwise normal ranges of groundwater level and flow are exceeded (Macdonald *et al*., 2008). Groundwater flooding presents risks for public health, infrastructure and housing, ecology, and agricultural land (Keeble, 2019). The Department for the Environment and Food and Rural Affairs (Defra) recognised the significant effects and risks of groundwater flooding across the United Kingdom and the need for groundwater flood management. There are several mechanisms for groundwater flooding and the occurrence of them depend on several factors, spatially and temporally.

In general, prolonged and extreme rainfall enable the water table in an unconfined aquifer to rise above the land surface and is one of the most common mechanisms of groundwater flooding; this mechanism is often referred to as clearwater flooding (Macdonald *et al*., 2008). Another mechanism for groundwater flooding is associated with shallow unconsolidated sedimentary aquifers because of their limited storage capacity (Macdonald *et al*., 2008). The storage capacity of an aquifer is restricted by its geological properties and may result in flooding depending on the intensity of rainfall.

Groundwater naturally flows to low-lying areas; thus, high groundwater levels can cause inflow to sub-surface structures and may lead to semi-active springs that are often incorporated into development; Other mechanisms of groundwater flooding include: surcharging water from culverted watercourses resulting from insufficient flow capacity combined with blockages, leaking drains, barriers to flow in the subsurface such as constructed walls or other built infrastructure, and shallow seepage (Parkin *et al.,* 2015).

Groundwater flooding resulting from groundwater rebound is a prevalent mechanism in the northeast. The mining industry have artificially lowered water tables in the past, but the cessation of mine workings has allowed depressed groundwater levels to recover and rise to previous natural levels (Environment Agency, 2006). The rising groundwater levels may cause groundwater flooding problems in areas where development occurred in the interim (Keeble, 2019).

Another mechanism for groundwater flooding in the northeast is mine water rebound from historical mine workings. The rate of minewater rebound is rapid at the start of the cessation of dewatering but decreases as the voids fill up with water (Keeble, 2019). Mine systems form new pathways and discharge points that were previously unconnected; thus, discharge of minewater to the surface can occur via adit openings making certain locations more vulnerable to rebound (Keeble, 2019; Parkin *et al*., 2015).

Groundwater flooding from abandoned mine workings may generate risks to subsurface infrastructure, such as tunnels and the basements of buildings, and may even threaten infrastructure before the water levels reach the ground surface where there is inundation of building basements or other assets (Macdonald *et al*., 2008). Areas susceptible to minewater rebound may also be prone to issues such as surface water pollution, localised flooding, overloading of sewers and sewage works, pollution to overlying aquifers, and increased risk of subsidence (Keeble, 2019). Groundwater and minewater rebound from abandoned mine workings are the most relevant mechanisms of groundwater flooding in Gateshead.

2.2 Groundwater and mine water rebound geohazards

Geohazards largely threaten the environment, economy, and social well-being in which geological processes are the principal causative factors (Younger, 2007). Groundwater causes a wide range of geohazards, but for this report, only the most relevant are mentioned. The four main geohazards relevant to the study area that are of high significance in terms of risk and susceptibility are mine water rebound, groundwater contamination, groundwater rebound and ground surface flooding, and subsidence.

The mining of coal generally extends below the water table and results in disruption of natural hydrogeological conditions; thus, the closure of coal mines entails a cessation of mine dewatering and can give rise to significant changes in the local and regional hydrogeological regime (Younger, 2016). Mine water rebound is considered a common geohazard because it alters natural hydrogeological processes that may in turn lead to other geohazards or problems. The abandonment of mine workings results in mine water rebound geohazards, which can be large-scale and very long-term.

Groundwater contamination is another common geohazard associated with the cessation of mine water pumping. Cessation of dewatering can lead to gradual flooding of the mine workings, which causes a rapid dissolution of the efflorescent salts that have developed by the oxidation of pyrite (Younger, 2016). The dissolution process often results in the deterioration of the water quality and may contaminate rising groundwater. Thus, the flood level in the mine workings can reach a point where dramatic pollution of surface watercourses occur, leading to detrimental consequences for ecological status and public water supply (Younger, 2016).

Flooded mine workings can also lead to the reactivation of mining subsidence geohazards triggered by changes in groundwater water levels and weakening of mine supports leading to surface subsidence (Younger, 2016; Younger, 2007). The reactivation of subsidence is due to the physical destabilisation of open mine voids by water through physical/chemical changes that result in weakened floors, walls, or roof strata and through downcutting of floors and undercutting of walls by rapidly flowing groundwaters (Younger, 2007). Subsidence caused by mine water rebound can often lead to surface collapses, destabilisation of buildings and houses, and sinkholes.

Geohazards associated with suspension of groundwater pumping are also common in many urban areas and are of significance in Gateshead due to concerns of potential cessation of pumping at the Kibblesworth station. By discontinuing artificial pumping, groundwater rebound may occur through mine workings and dry springs, creating consequences such as surface and groundwater contamination as it reaches the surface, and flooding due to rising groundwater levels. To avoid this geohazard, it is generally a common practice to artificial pump water so that drawdowns hold the water table below the level at which it becomes problematical (Younger, 2007). However, it should be noted that groundwater rebound is not always the sole cause of rising groundwater levels due to the potential of leakage of water from distribution pipes and/or sewers contributing to the rise of the water table (Younger, 2007).

2.3 History of coal mining in the UK and in Gateshead

Great Britain has a long history of coal mining dating back to the Roman times. In 1825, railways began to open, which enabled the mass transportation of coal and allowed for a further growth of the industry (Leifchild, 1968). Coal outputs rose from 147 million tons in 1880 to the all-time peak of just over 287 million tons in 1913 (Galloway, 1969). The peak employment occurred in 1921 with 1.25 million people working in Britain's coal industry (Coal Authority, 2019). In 1994, the coal industry was privatised, and the Coal Authority was established to address issues set out in the Coal Industry Act (Coal Authority, 2019). As the use of imports became more prevalent, coal mining quickly declined in the 20th century, which led to several mine water treatment schemes across Britain. Although coal mining is no longer implemented today, it remains an important part of British history.

While the coal mining industry occurred all over the country, the North East was particularly known for coal production and its associated economic growth. In the Great Northern coalfield, comprised of Northumberland and Durham, many mines were developed during the fourteenth century mostly on the banks of the Tyne, where natural facilities existed for carrying on a coal Trade (Galloway, 1969). During the Industrial Revolution, engineering, mining, ship-building, and chemical industries grew along with the populations in Newcastle and Gateshead (Natural England, 2013). By the end of the 18th century, two-thirds of the national output of coal was produced on the banks of the Tyne and Wear (Hill, 1991). The Great Northern coalfield is bounded on the north by the river Coquet and extends southward nearly to the Tees river with an area of approximately 800 sq. mi (Leifchild, 1968). Although most of the collieries were in Newcastle, a considerable number of mines were developed on the south side of the Tyne in Gateshead (Galloway, 1969).

In Gateshead, much of the early coal mines were drift mines and 'bell' pits and eventually mines had to be dug deeper to reach the coal, which caused issues with the underlying water (Gateshead Council, 2011). The deeper the mines were dug, the more problems there were in terms of mineworker safety. Gateshead has a unique history of mining accidents, which led to its history of strikes and reform changes (Gateshead Council, 2011). One of the reform changes largely influenced by the mining incidents in Gateshead was the formation of the Miner's Association of Great Britain, which is an important part of Gateshead's coal mining history (Gateshead Council, 2011).

There are two main mine workings blocks in Gateshead, which include the Lumley/Chaterhaugh in the east and Central Durham North/Kibblesworth in the centre, as well as other smaller blocks in the west of the borough; Within the Kibblesworth block, the Coal Authority continues to pump to control water levels, where the abstraction rate has remained constant since the 1980's; however, water levels have risen in the east of borough (Keeble, 2019). The Lumley block is controlled by an engineered gravity outflow at Chaterhaugh and the other western mine water blocks have recovered to their natural levels; the implementation of a gravity drain system in the Chaterhaugh block will likely result in a 15m rebound in groundwater levels, increasing the mine water levels in Gateshead to around 10m AOD (Keeble, 2019). In the study area, the potential discharge points for mine water are shown in figure 2.

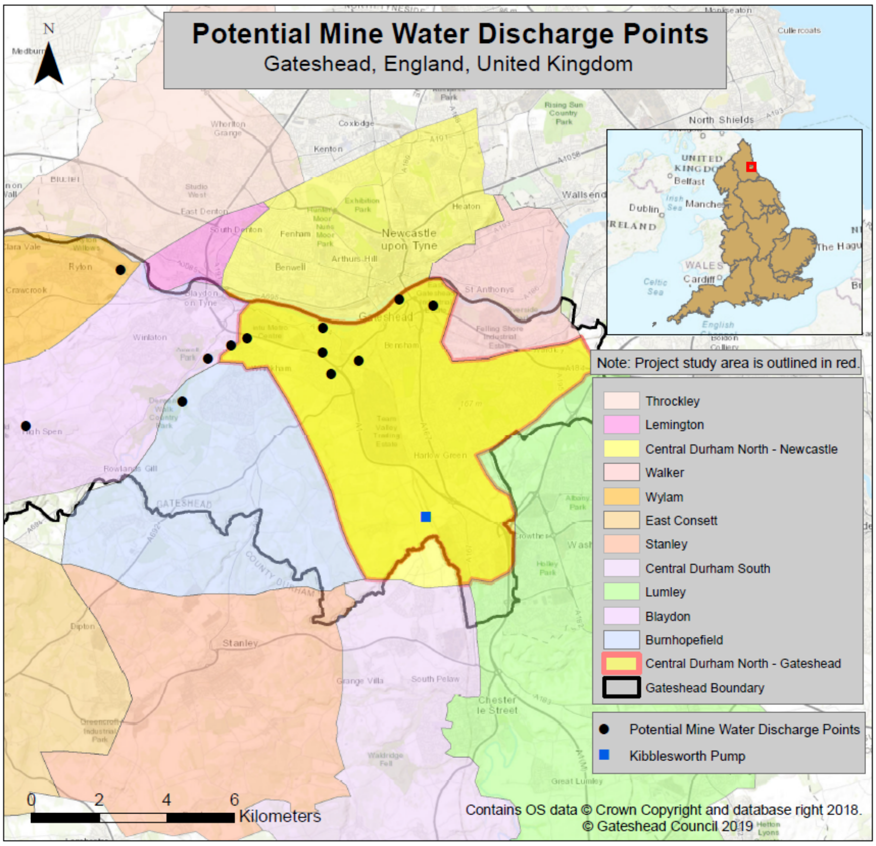

Figure 2 - potential mine water discharge points in Gateshead.

Mine water/groundwater flooding incidents have occurred in Gateshead, particularly in low lying areas of the borough such as Addison, Eslington, Park area, Derwenthaugh, and Clockburn; During the winter of 2015/2016, one of the worst mine water flooding incidents occurred from a mine adit at JJ Stanley scrapyard, at the former Swalwell Colliery, because of prolonged rainfall and the failure of one of the mine water pumps at Kibblesworth (Keeble, 2019). The flooding incident stressed the importance of continued mine water pumping at Kibblesworth and indicated the need for addressing mine water and groundwater rebound problems.

2.4 Topography, land-use, and surface hydrology

The Tyne and Wear region is characterised by its undulating well-wooded landform of gently rolling hills incised by the broad river valleys of the Tyne and Wear and their tributaries and is dominated by its widespread urban and industrial development (Natural England, 2013). The elevation across the county ranges from -2 m below sea level to a height of 177 m with an average elevation of 64 m above sea level (Natural England, 2013). The legacy of coal mining and its associated spoil heaps and open cast sites have significantly impacted the structure of the landscape. Today, much of the restored mining sites have been incorporated into the landscape and serve varying uses including agriculture, forestry, industry, housing, and amenity uses (Natural England, 2013). Evidence of coal mining on the landscape include locally prominent coal soil heaps, open-cast extraction areas and artefacts of mining (Natural England, 2013).

The Tyne and Wear form two major catchments, with the headwaters at the west in the North Pennines; the catchments drain remote moorland flowing through narrow, steep valleys, over soils often saturated by heavy rainfall, which can lead to downstream flood risk to major settlements in the Tyne and Wear Lowlands (Natural England, 2013). The key water bodies and catchments include the River Browney (10 km), River Derwent (4 km), River Tyne (32 km), and the River Wear (48 km) (Natural England, 2013). Although, there are few natural water bodies in the region, many subsidence ponds have formed in the hollows due to the collapse of underground mine workings (Natural England, 2013). The development pressures in this region have impacted the quality of these water bodies and may continue to do so.

In Gateshead, the landscape is characterised by four local character types including coalfield upland fringe, river valley with settlements, lowland valley terraces, and urban area (White Young Green, 2007). The coalfield upland fringe represents a rural landscape heavily influenced by the mining industry with pastoral farming on higher ground in the west and arable/mixed farming in the valleys and to the east (White Young Green, 2007). The river valley with settlements is characterised by the major transport route linking east/west through the Pennines while the lowland valley terraces is characterised by irregular woodland cover, sparse but well-wooded, steep, valley sides, estates with mixed woodland, and plantations on restored heaps; additionally, the lowland valley terraces is bounded by the Limestone escarpment and plateau to the east and the upland fringe coalfields to the west (White Young Green, 2007). The topography and elevation of the region are shown in Appendix A, figure 36.

The borough is split into smaller urban areas, the Team Valley being one of them. The Team Valley is bounded to the east by the southern edge of Gateshead and by Birtley and is characterised as a trading estate with diverse landscape uses within the area to the south of Kibblesworth, such as water treatment works, caravan parks, a reclaimed quarry, and the Kibblesworth landfill site (White Young Green, 2007). Within the Team Valley, the elevation varies from 10-15 m AOD in the valley bottom to a high point of 216 m AOD in the west at Burdon Moor (White Young Green, 2007).

The Team Valley drains an area of 86 km^2 and comprises the River Team, which is a tributary of the River Tyne (Keeble, 2019). The River Team drains in the northerly direction towards its divergence with the River Tyne that is tidally influenced (Davies, 2014). One of the most significant changes in the hydrology of urban areas is the culverting of previously open water courses and infilling of small valleys (Parkin, 2015). Within the Team Valley, the River Team has been heavily modified and is contained with an open straight concrete rectangular channel interspersed with culverts to the centre of the Team Valley Trading Estate where the river remains on a modified straight trajectory until it meanders more naturally as it meets the River Tyne (Davies, 2014).

The left bank of the of the River Team is relatively rural and is drained by three tributaries that all discharge into the stormwater network; on the right side of the bank the catchment is heavily urbanised and is drained via the combined sewer network; The Trading Estate within the Team Valley drains an area of 22 km^2 into the River Team and generates surface runoff resulting as a source of flood risk (Davies, 2014; Keeble, 2019).

2.5 Geology of Gateshead

2.5.1 Bedrock geology

The bedrock geology of the northeast is made up of Carboniferous rocks, which include the Carboniferous Limestone, Millstone Grit, and Pennine Coal Measures and are sub-divided into the Dinantian, Namurian, and Westphalian age groups (Abesser *et al.*, 2005). The following geology review describes the geology of the Tyne and Wear district.

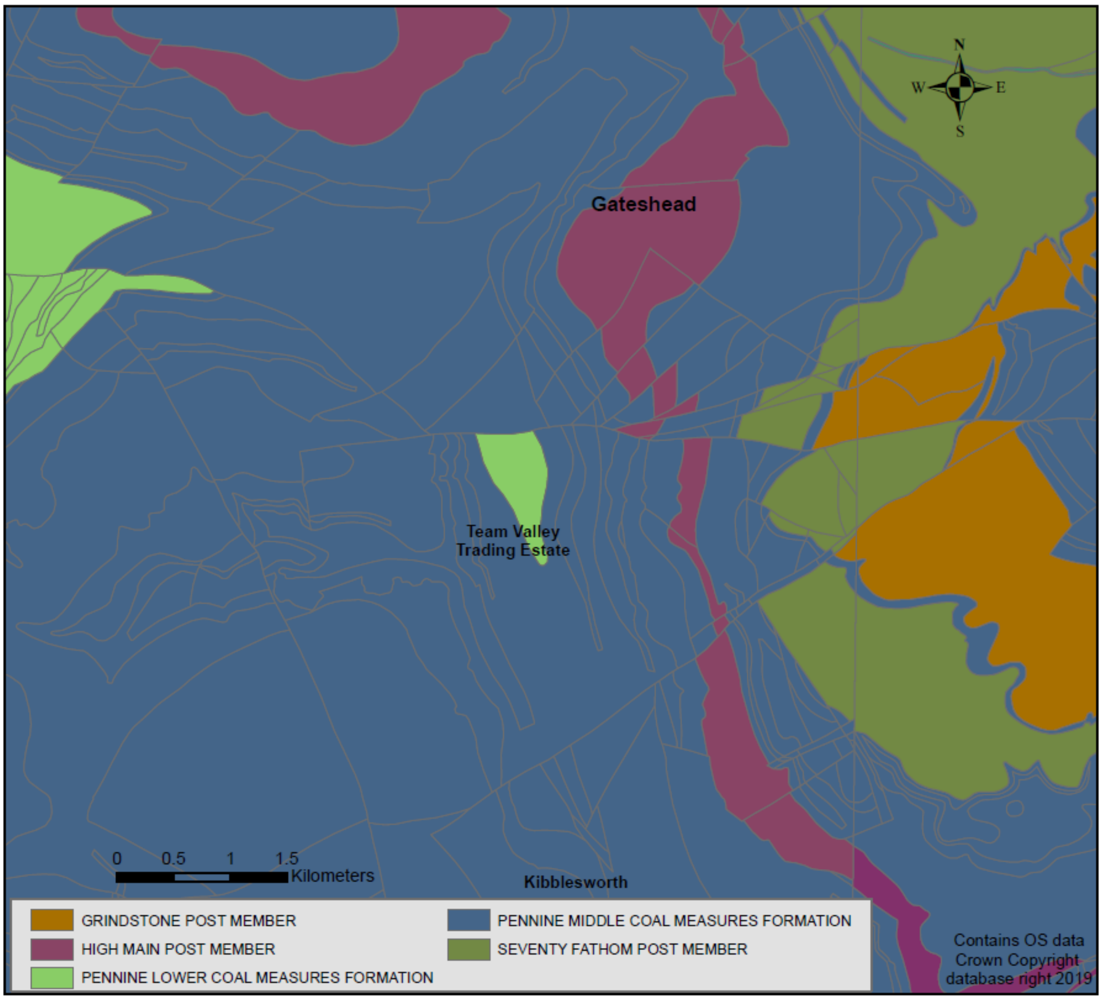

Figure 3 - bedrock geology of Gateshead. Created in ArcMap by Villasenor, 2019.

The bedrock geology of the Tyne and Wear largely consists of sedimentary rocks from the Carboniferous period (figure 3). The Pennine Coal Measures Group is the most prevalent and comprises a Lower, Middle, and an Upper formation, each of which consists of mudstones, siltstones, and sandstones, and in the lower formations, numerous coal seams (Mills and Holliday, 1998). The Lower Coal Measures are dominated by successive flooding events, the Middle Coal Measures consists of many marine bands with generally thinner and poorer quality coals, and the Upper Coal Measures is characterised by the lack of flooding events, generally thin coals, and significant distributary channels in the upper part of the formation (Waters, 2009). The Permian rocks generally overlie the Pennine Coal Measures Group cropping out in areas at Tynemouth and Whitley Bay and consist mainly of soft sandstones and dolomitic limestone (Natural England, 2013). In Gateshead, the geology is predominantly made up of the Lower and Middle Coal Measures, about 480 m in thickness, of the Westphalian A, B, and C age, which outcrop all over the district (GMBC *et al.,* 2005).

According to Richardson (1983), the Lower Coal Measures is made up of ten coal seams with the **Quarterburn Marine Band** at the base of the Westphalian A strata. The list of coal seams following the Quarterburn Marine Band in ascending order are (using the Durham name classification) Ganister Clay, Marshall Green, Victoria, Brockwell, Three-Quarter, Bottom Busty, Top Busty, Tilley, Hodge, and Harvey.

The strata between the base and the **Ganister Clay Coal** range up to 60 m in thickness across the Tyne and Wear region and is made up of sandstone ranging from fine to coarse grained and are cross-bedded in places (Mills and Holliday, 1998). The **Marshall Green Coal** is rarely over 0.5 m thick and is predominantly sandstone. The **Victoria Coal**, up to 0.6 m thick, is typically split into the top and bottom seams separated by up to 11 m of argillaceous strata; the top of the Victoria Coal is characterised by thin sandstones while the bottom seam is characterised by thin beds of ironstone and fauna fossils.

The **Brockwell Coal** is one of the most widely worked seams and can range up to one metre thick. The seam splits into several thin coals separated my mudstone beds and only in parts of the north and north-east forms a single seam (Richardson, 1983). The **Three-Quarter Coal** is prevalent across the region and ranges between 0.4 and 0.7 m in thickness. The seam is characterised by local variations in lithologies, with the southern region of the Tyne and Wear dominantly sandstone, and with many fauna fossils present throughout (Mills and Holliday, 1998). The **Bottom Busty Coal** ranges between 0.76 and 1.2 m thick while the **Top Busty Coal** ranges between 0.6 to 1.0 m thick, both of which are dominantly sandstone and sandy beds.

Only small areas of the **Tilley Coal** have been worked and ranges from a single stratum between 0.5 and 0.7 m in the western part of the district to groups of thin coals separated by layers of sandstone (Mills and Holliday, 1998; Richardson, 1983). The **Hodge Coal** lies in the strata between the Tilley and Harvey coals but is not persistent throughout the district and difficult to trace. The top-most seam of the Lower Coal Measures Group is the **Harvey Coal**, which is marginally the most widely worked coal in the Westphalian A strata and ranges between 0.55 and 1.14 m thick in the worked areas of good quality (Mills and Holliday, 1998). Beneath the Team Valley and Gateshead, the seam ranges up to 0.5 m thick and is unworked, but little is known about the coal beneath the north part of Gateshead (Richardson, 1983). A summary of the strata between coal seams, thickness range, and bedrock composition are shown in table 1.

Table 1 – Summary of the strata between the coal seams in the Lower Coal Measures Group including the thickness range and bedrock composition (Mills and Holliday, 1998; Richardson, 1983).

Strata between coal seams	Thickness range	Bedrock composition
Quarterburn-Ganister Clay	45-60 m	Sandstone (Third Grit), mudstone, coal, mudstone, sandstone
Marshall Green-Victoria	9.75-17 m	Sandstone, thin-bedded and flaggy; mudstone and siltstone beds, mudstone and siltstone; thin shaly sandstone beds, sandstone, yellow and grey-brown, often cross-bedded but mainly medium-to-coarse grained; micaceous and carbonaceous
Victoria-Brockwell	10-13 m	Coal, shale, coal, shaly and carbonaceous, mudstone, siltstone, and seatearth
Brockwell-Three Quarter	8.5-20 m	High proportion of sandstone, thick-bedded and medium-to-coarse grained
Three-Quarter-Busty	4.57-22 m	Large proportion is sandstone or sandy beds; no clear relationship between thickness and lithology; thin argillaceous measures at top and base
Busty-Tilley	8-16 m	High proportion of sandstone; medium-to-coarse grained, or sandy ‘mixed beds’, coals and seatearths present
Tilley-Harvey	7.3-24 m	Mostly sandstone; argillaceous rocks with thin sandstones or sandy beds, locally with thin ribs and nodules or ironstone; interbeds of sandstone, siltstone and mudstone

The Middle Coal Measures contain strata and coal seams from both the Westphalian B and C ages. The list of coal seams in ascending order following the Harvey Coal from the Lower Coal Measures (using the Durham name classification) are Ruler, Hutton, Brass Thill, Durham Low Main, Maudlin, Bottom Main, Top Main, Five-Quarter, Metal, High Main, Moorland, Ryhope Little, and Ryhope Five-Quarter (Richardson, 1983). The **Ruler Coal** is up to 0.3 m thick and has been worked west of the Team Valley in the Lobley Hill area while the **Hutton Coal** ranges between 1.1 and 1.8 m in thickness across the north-east district (Mills and Holliday, 1998). The **Brass Thill Coal** is commonly split into two leaves where the bottom seam ranges between 0.7 and 1.3 m thick and the top (known as the **Durham Low Main Coal**) ranges between 1.1 and 2.0 m in thickness. The **Maudlin Coal** is a thin and washed out seam only present in the eastern edge and south-east parts of the Tyne and Wear district ranging between 0.6 and 1.4 m thick.

In the southern part of the district around Gateshead, the **Main Coal** has been extensively worked and forms a good quality seam ranging between 1.3 and 1.8 m thick and splits into the top and bottom seams towards the east and south-east (Mills and Holliday, 1998). The **Five-Quarter Coal** forms a single seam ranging between 0.6 to 2.7 m thick and borehole records indicate that it has been worked beneath Gateshead in the Spital Tongues to Hunters Moor area (Richardson, 1983). The **Metal Coal** is one of the thin coals embedded between the Five-Quarter and High Main coals and has been worked locally in Gateshead and in parts of Newcastle. The **High Main Coal** is one of the thickest and most consistent seams in the district, generally over 2m thick, where the early mining industry was largely based on this coal (Mills and Holliday, 1998).

The **Moorland Coal** is a thin coal between the High Main and Ryhope Little and is only present in Tynemouth. With a thickness ranging between 0.6 and 0.7 m, the **Ryhope Little Coal** was mainly worked in the Jesmond and Gosforth areas (Richardson, 1983). Finally, the **Ryhope Five-Quarter Coal** is a single seam up to 0.7 m thick in some areas and splits into two leaves characterised by having mudstone beds. A geological cross-section of the seams from Wickham Hill through the Team Valley is shown in figure 4.

Table 2 - Summary of the strata between the coal seams in the Middle Coal Measures Group including the thickness range and bedrock composition (Mills and Holliday, 1998; Richardson 1983).

Strata between coal seams	Thickness range	Bedrock composition
Hutton-Brass Thill	3-18 m	Varies considerably in lithology; no consistent pattern of sediment type; argillaceous strata tend to predominate
Brass Thill/Durham Low Main-Maudlin	8-35 m	Mostly sandstone with impersistent coals; high proportion of argillaceous measures present in the north Newcastle area
Maudlin-Mains	13-18 m	Predominantly argillaceous but include up to four thin sandstones; thin coals are locally present
Main-Five Quarter	14-18 m	Argillaceous in nature; sandstone present locally in the south; higher proportion of sandstone in the north-east
Five-Quarter-High Main	15-36 m	Predominantly argillaceous; thin sandstones present; up to three coals (thin and impersistent) present locally (including Metal Coal in Gateshead)
High Main-Ryhope Little	12-33 m	Predominantly argillaceous; high proportion of sandstone near eastern margin and south part of Gateshead; 1-2 thin coals present equated with the Moorland coal in Tynemouth
Ryhope Little-Ryhope Five-Quarter	8-20 m	Argillaceous and sandy in the western part of the outcrop; sandstone dominant in the south of Gateshead and Jesmond Dene areas

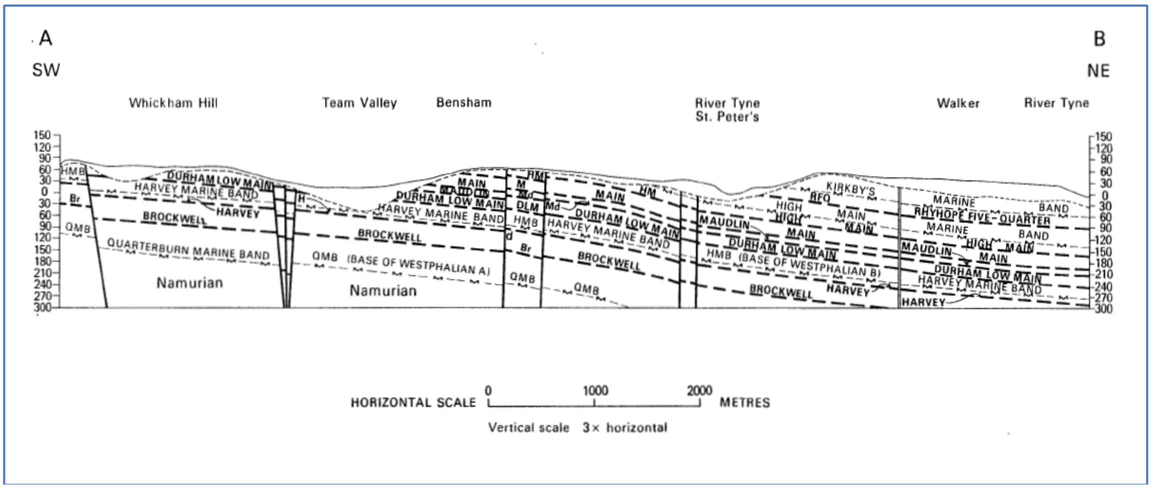

Figure 4 – Geological cross-section from Wickham Hill to the River Tyne through the study area in a west to east direction (Richardson, 1983).

During the late Namurian and early Westphalian, syndepositional faulting occurred on a small scale with regional subsidence; later in the Westphalian age the depositional environment is thought to have changed from an upper deltaic plain (Mills and Holliday, 1998). The faulting and changing of the depositional environment are thought to have formed a part of the Coal Measures Group. According to Mills and Holliday (1998), the Ninety Fathom-Stublick Fault System was a major influence on Carboniferous sedimentation and formed by reactivation of a major basement shear zone. In the Gateshead area, the Felling and Heworth faults are also important structures, although syndepositional displacement are likely to have been small (Mills and Holliday, 1998).

Subsidence of swamps resulted in the presence of fauna and flora fossils and ironstone ribs and nodules within the coal seams. The sandstones in the Coal Measures have two main forms, ‘sheets’, and ‘channels’, and may show considerable lateral and vertical variation (Mills and Holliday, 1998). The exploitation of coal from the underlying Coal Measures since the Roman times largely influenced the landscape today; thus, the Pennine Coal Measures were highly valuable for the country’s economy (Natural England, 2013). Additionally, the coal deposits have been a major influence on the development of Gateshead since the start of coal mining in the medieval period and continue to be an integral part of development planning as artificial pumping of abandoned coal mines are managed.

2.5.2 Superficial deposits

The drift sediments in the Tyne and Wear district formed in the Quaternary Late Devensian Stage during the advance and retreat of the Pleistocene ice sheets and the disappearance of the ice (Mills and Holliday, 1998). The superficial deposits are primarily composed of boulder clay, flow till, laminated clay and silt, sand and gravel and several types of superficial clay (Richardson, 1983; figure 5). Alluvium and some peat are also present in the main river valleys (Keeble, 2019). Generally, the deposits range up to 10 m in thickness but in some areas, especially in the buried valleys of the Tyne, Derwent, and Team, can range up to 90 m (Mills and Holliday, 1998). Boulder clay is the most widespread deposit; however, in the Team Valley, laminated clay and silt predominate. The glacial lake deposits within the Team Valley resulted from the eastward flow of the region’s rivers against the North Sea ice at one time.

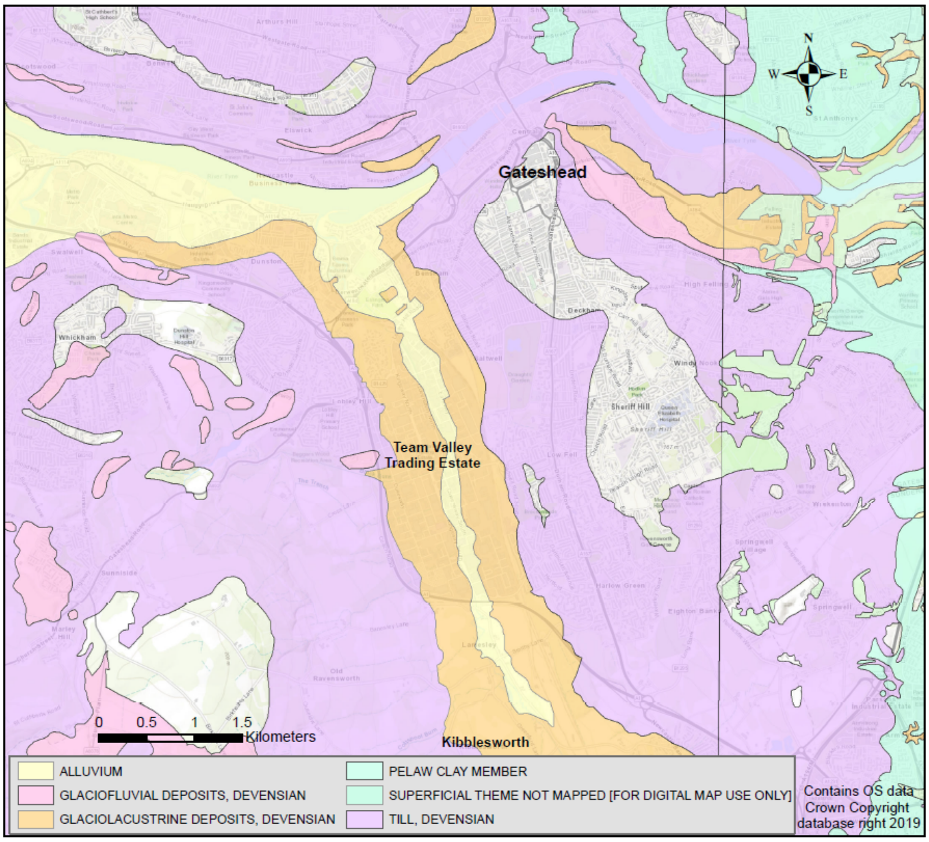

Figure 5 - superficial deposits underlying Gateshead. Created in ArcMap by Villasenor, 2019.

Boulder clay (till) is the most widespread and covers nearly 60 percent of the district; the boulder clay ranges up to 10 m in thickness but can have a maximum thickness of 30 m outside the confines of the buried channels; **Glacial sand and gravel** do not overlie the study area but are prevalent across the northeast district and range from fine-to-medium grained, well sorted, and evenly bedded sands composed mostly of sandstone with coal grains and fragments. The location of sands and gravels are consistent with the deposition from seasonal streams and sheets of water under wasting or stagnant ice in a subglacial environment (Mills and Holliday, 1998).

Laminated clays and silts are also widespread over the district. These deposits are generally dark-brown to purple-brown, generally even-bedded with films, laminae, and fine beds of micaceous silt and mud, and can range up to 40 m in the buried valleys of the rivers Tyne, Derwent and Team (Mills and Holliday, 1998). Many boreholes in the Team Valley region show that laminated clays and silts appear at the surface. Due to the high-water content of laminated clays and silts, they are a major geotechnical problem in mining activities (Mills and Holliday, 1998).

The **upper stony clays**, consisting of pelaw and prismatic clays, are brown and purple-brown silty clays and range from 1.0 to 2.0 metres thick at the surface (Richardson, 1983). Cox (1983) found that these clays are widely present on lower grounds along the east side of the Team Valley, more so north of Birtley. **Buried valley deposits** are largely found in the buried valleys of the rivers Tyne and Team and comprise a combination of sand and gravel, boulder clay, and laminated clay and silt (Mills and Holliday, 1998). The rockhead contours in the region are shown in appendix A, figure 37 demonstrating where present valleys are filled with deposits between the zero to 15 m contours.

Postglacial and recent deposits in the Tyne and Wear consist of alluvium, peat, landslip, river terrace deposits, alluvial fan deposits, and made ground. Based on borehole scans, alluvium is found in the Team Valley overlying the buried valley deposits. Made ground occurs primarily where mining and industrial activity persisted the longest and includes deposits from chemical and industrial waste, colliery and quarry spoil, overburden piled up from excavations, and surface material from landscaping (Mills and Holliday, 1998). The made ground deposits vary in depth and extent across the district and have presented foundation and engineering problems.

A geological cross-section is shown in figure 6 as an example of the underlying geology. The cross section covers boreholes over Kibblesworth, Oak Lodge, Team Valley, and just south of Bensham to represent a vertical section of the Central Durham mine water block from the south-north direction.

The geological cross-section was first created in the British Geological Survey's Groundhog for Desktop using borehole data from GeoIndex. The cross-section was hand-drawn to simplify the geology due to numerous lithology codes. Thus, it should be noted that the SOIL code represents soil, topsoil colliery waste, and artificial made ground with various materials. The sandstones type is a mixture of pure sandstones, sandstones with boulders, sandstones with mudstones, and sandstones with silt and clay. The sandstones layers may also contain beds of ironstone and hard sandstone beds. The cross-section was oversimplified for the purpose of demonstrating the layers of coal seams present across the study area.

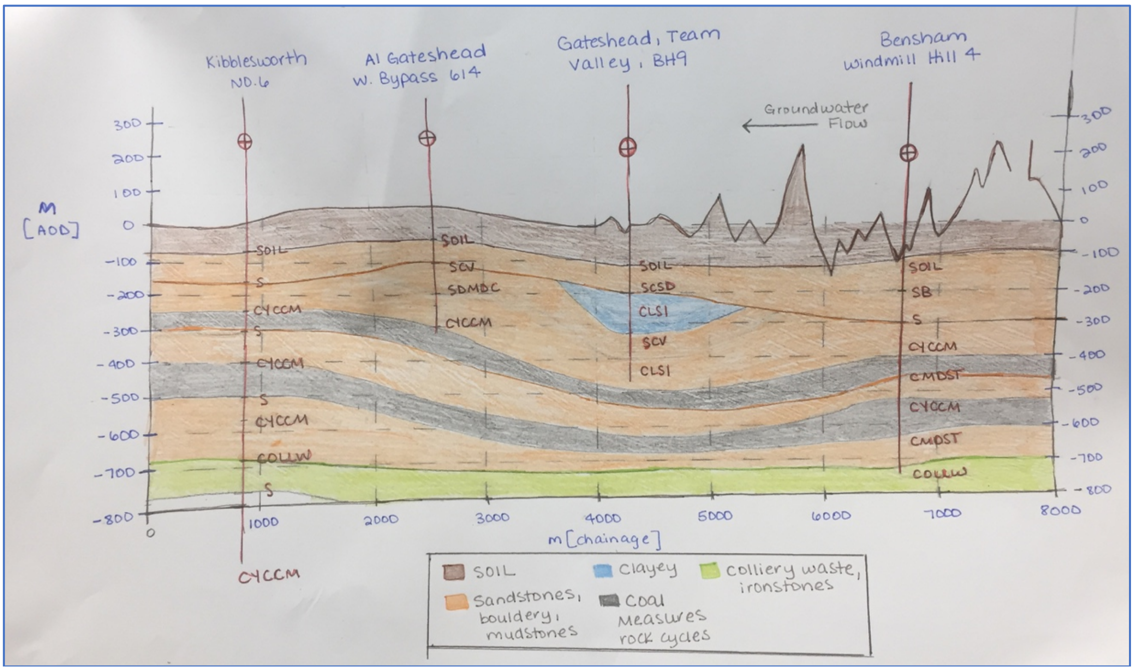

Figure 6 - geological cross-section of the study area from Kibblesworth to Bensham.

According to Mills and Holliday (1983), the Team Valley is a major example of the divergence between the locations of pre-glacial and postglacial river systems and is considered to be highly modified by glacial and postglacial events. During the late Devensian glaciation, the melting of glacial ice sheets is thought to have deepened or widened the Team Valley.

2.6 Hydrogeology of Gateshead

The hydrogeology of the Tyne and Wear district is complex and poorly understood. The legacy of coal mining drastically influenced the hydrogeology of the region. As groundwater was pumped in the mine workings, the water table was substantially lowered. However, the closure of mines and cessation of pumping has caused groundwater to rebound as the water table rises to near previous levels. There are no major aquifers underlying the north-east and only 14% of public water supply comes from groundwater (Environment Agency, 2006). The small percentage of potable water comes from surface water reservoirs in the North Pennines through a transfer system.

The argillaceous strata of the Coal Measures Group act as aquitards or aquicludes, generally isolating the thicker sandstones; additionally, the extensive folding and faulting of the Coal Measures have created the isolated aquifers, which restrict lateral water movement (Mills and Holliday, 1998). The sandstones are very well-cemented, hard, and dense and contain very little primary porosity or intergranular permeability; thus, the characteristics of the sandstones in the Coal Measures, in addition to the influence from mining-induced subsidence, allow groundwater storage and movement to occur predominantly through fractures (Jones *et al*., 2000).

The flow of groundwater is generally towards the north-east and south-east. In areas around the margin of worked coalfield there may be a modification of the flow direction (Mills and Holliday, 1998). Jones *et al*. (2000) note that measurements of porosity and permeability from the Westphalian Coal Measures are not available; however, Minett *et al.* (1986) report that packer testing obtained permeability values of 8.6×10^{-2} to 8.6×10^{-3} m/d for mudstones, sandstones, and coal seams in Northumberland.

Jones *et al*. (2000) note that aquifer test data for transmissivity values are not available for the Westphalian strata and the only recorded value obtained from recovery data when pumping ceased in an old shaft penetrating the Lower Coal Measures is 15,000 m^2/d; however, the extremely high value may not reflect the true transmissivity of the Coal measures and may indicate the influence of anthropogenic activity. For reference, transmissivity values recorded in the neighbouring North Derbyshire/Yorkshire coalfield range between 4-40 m^2/d (Crawley, 2016; Banks, 1997).

The hydrogeology of shallow groundwater is highly influenced by the overlying superficial deposits, which can influence localised discharges to the ground surface under wet conditions (Parkin *et al*., 2015). In general, made ground deposits are considered permeable because of their heterogeneity, which overlie parts of Gateshead (Price *et al.,* 2006). Buried channel deposits and river terrace deposits are also generally permeable and may overlain by laminated clays. Laminated silts and clays are weakly permeable; thus, the nature of these deposits renders them effective as an aquitard (Price *et al.,* 2006). Understanding the hydrogeological properties of superficial deposits is important for assessing the extent to which recharge into the groundwater or mine workings systems will influence rebound.

2.7 A review of mine water rebound modelling

Mine water rebound can have consequences such as water pollution and surface flooding and may pose risks for public health and urban development. Modelling of mine water rebound is useful for assessing the hydrogeological and environmental risks and time-scales associated with mine water rebound and for assessing the risks of subsidence in areas of development (Younger *et al.*, 2002). There are numerous methods for modelling mine water rebound and may be performed using manual calculations or computer-based models. It is important to note that the conceptual model should be established before applying a numerical model to better understand and interpret the behaviour of mine water rebound in a system.

Three approaches for modelling mine water rebound using manual calculations are on a void filling basis, specific yield approach, and by fitting an exponential curve to the observed data. The void filling basis method predicts rebound by determining the volume of coal extracted in a pond and comparing that volume with a long-term average recharge rate; however, this method is overly simplistic, neglects head-dependent flows, and assumes that all voids remain open (Younger *et al*., 2002). The specific yield approach takes into account that goaf panels and roof-strata are modelled as layers with specific yield values that align with the high specific retention of virgin Coal Measures (Younger and Adams, 1999). Fitting an exponential curve to observed data uses a method of extrapolation where head-dependent inflows are significant; however, it does not take into account the changes in specific yield.

Computer-based models can be semi-distributed 'pond' modelling or physically-based distributed modelling. Physically-based models include VSS-NET and SHETRAN. Developed by Newcastle University, SHETRAN models the surface and subsurface processes together into an integrated, fully 3-D model of water flow and transport, where VSS (Variably Saturated Subsurface) is a component for modelling of 3-D groundwater flow in variably saturated porous media (Younger and Adams, 1999).

The approach of VSS-NET, which is a member of the SHETRAN family, is to simulate mine water rebound by coupling the pipe network model to the porous medium model to calculate the exchange of water between each pipe element and porous medium based on Darcy's Law (Younger *et al.*, 2002). MODFLOW is a commonly used groundwater model but is not appropriate for modelling mine water rebound because it is based on Darcy's Law while GRAM is non-Darcian and avoids unreasonable assumptions about equivalent permeabilities (Gandy and Younger, 2007).

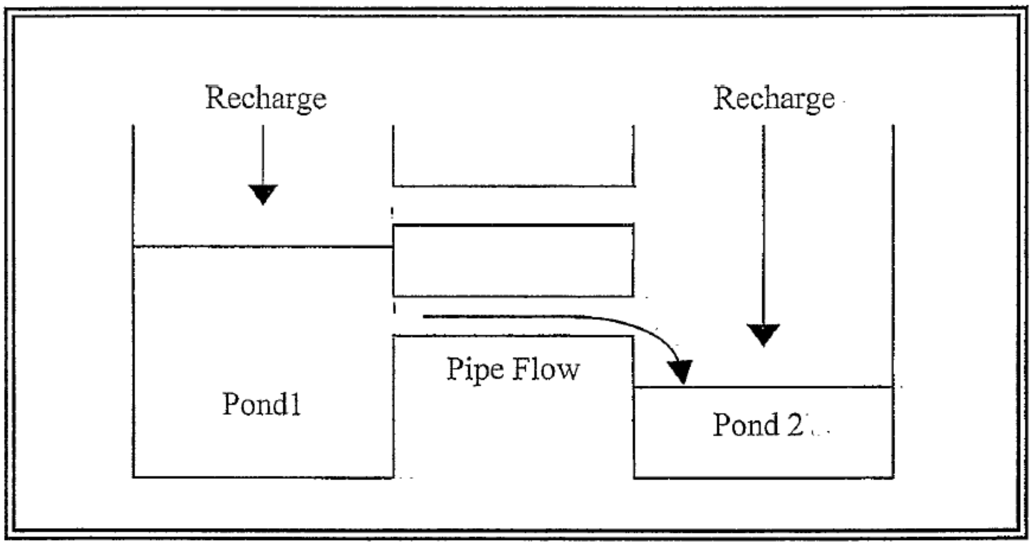

Figure 7 - Schematic diagram of flow between two ponds in a roadway, showing the logic of using pipe-flow equations to model water transfer (Younger and Adams, 1999).

GRAM is a semi-distributed model and is designed to simulate the process of mine water rebound in extensive systems of mine workings (Younger and Adams, 1999). GRAM has been applied to several coalfields across the UK and is based on the concept of ponds where a mass balance is calculated for all ponds in a multi-pond system based on recharge, flow between ponds, and dewatering (Gandy and Younger, 2007). The volume of inter-connected workings and "floodable volumes" in the pond system are estimated to determine the rates, time steps, and water levels at which mine water rebound will occur. Figure 7 demonstrates the method behind the GRAM model, which is to simulate the water budgets of each of a series of inter-connected ponds, including inter-pond flows via mutual features (Younger *et al.*, 2002).

3.0 Methodology for assessing post-closure hydrogeology

Using the information discussed in the literature review, a further conceptual understanding of the hydrogeological behaviour and interconnection with mine workings will be developed using data provided by the Coal Authority and Gateshead Council. The data provided includes GIS geospatial plans of abandoned mine workings, water levels and abstraction rates, and shapefiles for the potential mine water discharge points and historical flooding incidents from 1976-2016.

The conceptualisation of the data will be used to develop a conceptual understanding of the geological and hydrogeological influences on mine water rebound and of the interconnection of mine workings. The data will also be used to implement a numerical model for predicting groundwater rebound and estimating the rate of water level rise under different recharge and pumping scenarios.

The framework and steps for assessing post-closure hydrogeology and mine water rebound are 1) define and identify the pond system, 2) calculate the area of workings within the ponds, 3) define and identify the pond interconnections and outflow features, 4) quantify water inflow and outflow rates, 5) calculate the rate of water level rise, and 6) predict mine water rebound. The first three steps make up the conceptual model and the last three steps make up the numerical model. The framework used in this project is based on a similar method from Younger (2016) as shown in Appendix B, figure 38.

3.1 Data analysis and conceptualisation

3.1.1 Abandoned mine plans

The mine plans for the Gateshead area were obtained from the Coal Authority as GIS vector data. The specific data provided include the underground mine workings, roadways, in-seam level contours, in-seam levels, mine entrance points, seam summary table, licence areas, and working dates. Data for the potential mine water discharge points was provided by Gateshead Council as a GIS Shapefile. The data will be used to define and identify the pond system, pond interconnections, and to calculate the area of the workings within the ponds, which will be incorporated into the numerical model.

According to the British Geological Survey (2019), mine plans should be used with the understanding that they only represent a snapshot at a point in time and are subject to misrepresentation of the actual mine workings. It is important to note that prior to the 1872 Coal Mines Regulation Act, coal mines were not required to record the depth of the workings and were only required to demonstrate the boundaries of the workings before abandonment. Additionally, many mine plans prior to 1972 were not recorded, thus, the knowledge and understanding of those workings were lost (British Geological Survey, 2019). This suggests that mine plans may be incomplete and unreliable, which has implications for estimating the areal extent and rate of water level rise.

3.1.2 Collieries within Gateshead

The major collieries in the study area were identified to develop a further understanding of the mine workings geometry and the worked coal seams. This step is essential prior to applying the framework for assessing the post-closure hydrogeology to gain a better understanding of the interconnections between workings. The collieries were identified using an image of the distribution of the collieries within Gateshead provided by Gateshead Council and the Durham Mining Museum's online list of *mines under the Coal Mines Act* and *Reid's Handy Colliery Guide*. The image provided by Gateshead Council is shown in Appendix B, figure 39. The total number of collieries identified included some of those outside the study area to account for any interconnections in the mine workings. Borehole scans of the coal seams from Mills and Holliday (1998) were also used to further understand the interconnections between the worked seams.

A total of 23 major collieries were identified across the Central Durham North, Burnhopefield, Blaydon, and parts of the Stanley and Central Durham South mine water blocks. The distribution of collieries is shown in figure 8. It should be noted that some collieries were historically merged together with other collieries in the area, according to the image provided by Gateshead Council, and were thus merged together for spatial representation. These collieries were not considered to be major collieries and were not accounted for in the final count. Table 4 in appendix B shows the list of collieries, years active, location, and worked coal seams. It should be noted that the Durham coal seam classification is used throughout this report and is derived from Richardson (1983).

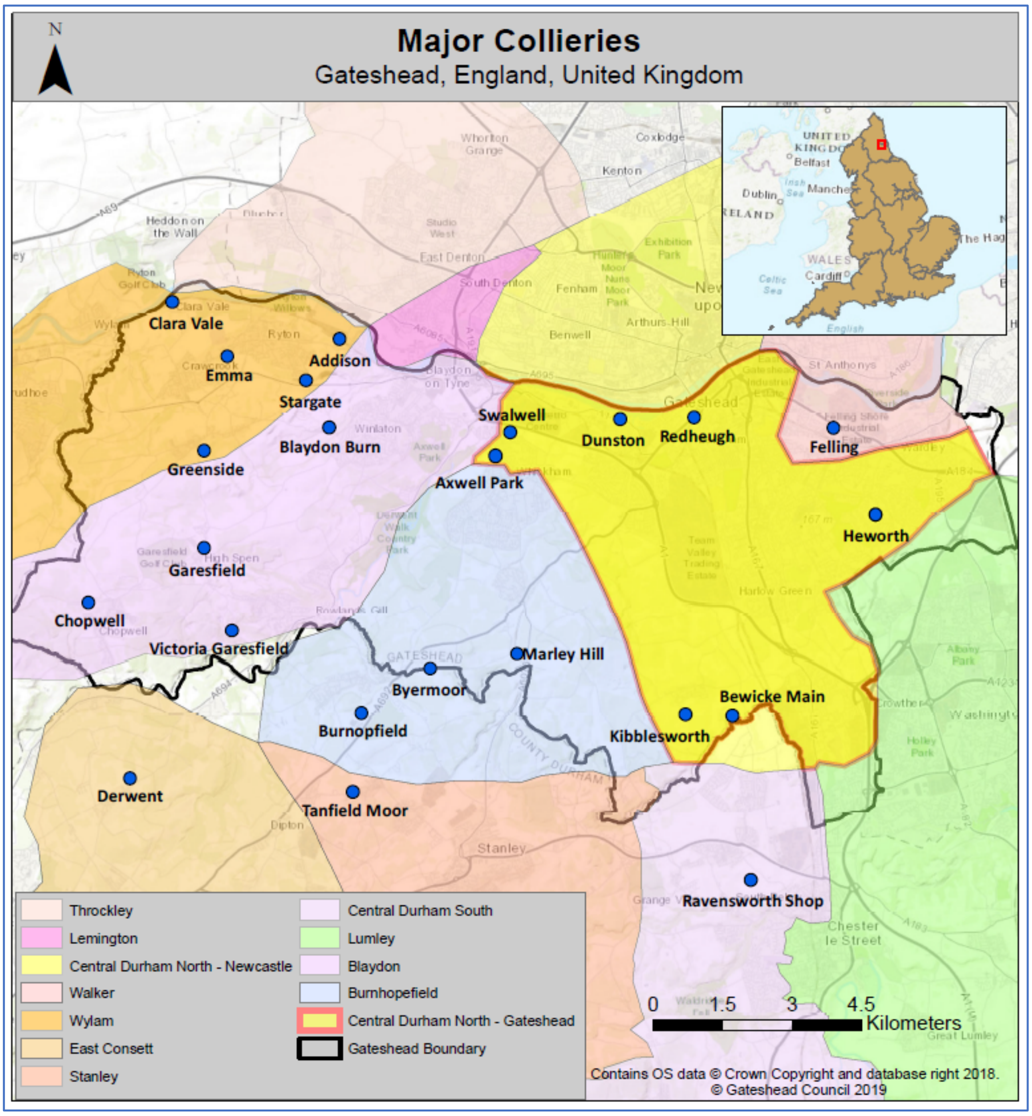

Figure 8 – spatial distribution of collieries used in the process of defining and identifying the pond system.

3.1.3 Water level and abstraction data

Water level and abstraction data was provided by the Coal Authority and provides an understanding of the impacts of mine water pumping and the hydrogeological response to abstraction after the abandonment of coal mining. The data will be used to determine the initial water level in the mine system and to calibrate the model. This provides a relative starting point in determining the level at which mine water will begin to rebound. Additionally, the data provides a basis for modelling various recharge and pumping scenarios. Water level data for only a few boreholes were provided. The list of site names, mine water blocks, location, and recording period is shown in table 3.

Table 3 – Description of water level and abstraction data provided by the Coal Authority.

Site Name	Site Sub-Title	Mine Water Block	Type	Location	Recording period
Blaydon Main	Hazard Shaft	Blaydon	Monitoring	NZ1916362798	10/07/06-17/10/14
James	Shaft, Wylam	Wylam	monitoring	NZ1222264854	10/10/08-11/02/19
Freeman Rd	EA possibly to high main	Central Durham North	Monitoring	NZ2591767373	11/03/11-9/05/19
Kibblesworth	Glamis Pumping Shaft	Central Durham North	Pumping Station	NZ2435856232	12/11/94-12/06/19
Chatershaugh	No. 2 shaft discharge	Lumley	Monitoring	-	25/10/95-14/05/19
Lumley 6th	Pumping Shaft	Lumley	Monitoring	-	12/11/94-14/05/19
Nicholsons	Old pumping shaft	Lumley	Inactive	-	12/11/94-14/05/19

The boreholes at James and Freeman Road were compared to each other because they had similar recording periods. The graph showed a relatively consistent pattern in water levels between 2008-2019 (figure 9). However, they are not within the study area and thus were not used in the analysis. The Nicholsons borehole dataset was also not used due to the discontinuation of water level monitoring. The Lumley Chatershaugh and 6th boreholes showed rebound of about 3-7 m starting in October 2009 (figure 10).

These boreholes were outside the study area and were not used in the numerical model. However, they were still compared and analysed to gain some insight into any potential connections outside the study area. As a result, water levels in the Lumley mine water block may be useful to incorporate into future work surrounding mine water rebound in Gateshead but were not directly used in this project due to time constraints.

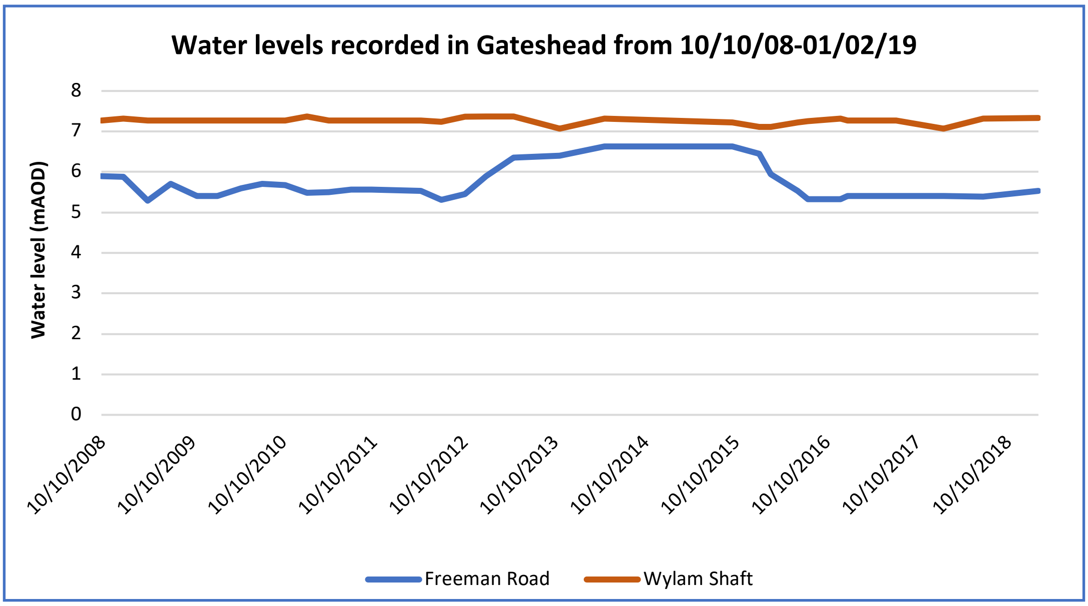

Figure 9 – Water level recordings from two monitoring boreholes located at Freeman Road and James, Wylam in Gateshead (see details in table 3).

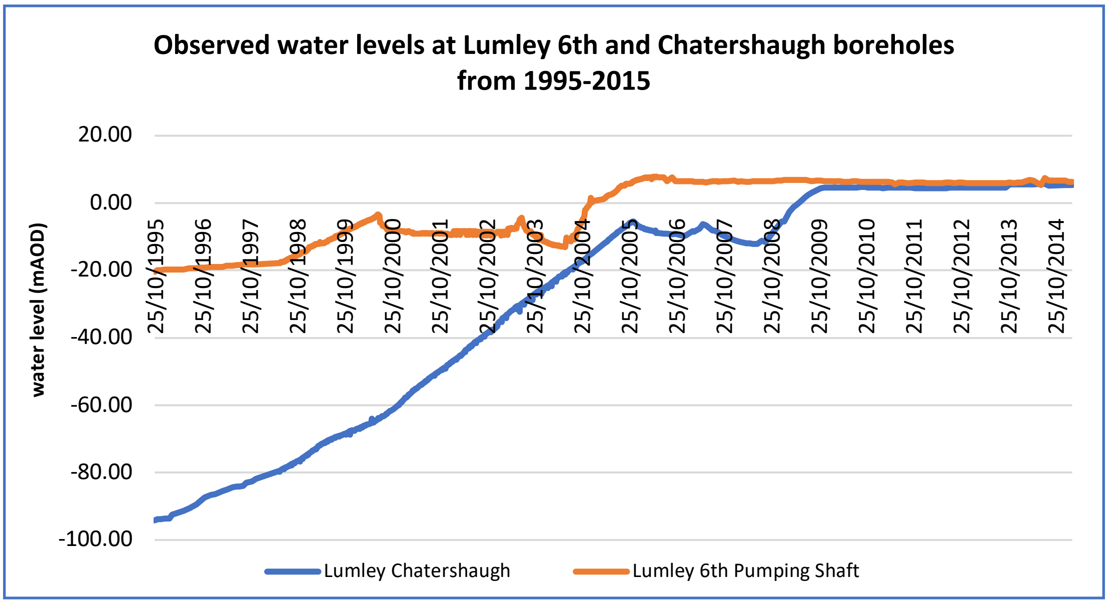

Figure 10 – Water level recordings from the Lumley at Chatershaugh monitoring borehole in Gateshead (see table 3).

At Kibblesworth, rebound of about 0.5-3 m began to occur in late 2006/early 2007 and in 2011 water levels decreased again (figure 11). However, pumping during this period did not increase by a notable amount, thus the decrease in water levels suggest that there may have been a change in recharge/discharge into and out of the system around July 2018. The initial water level used in the numerical model is the water level at Kibblesworth at the start of the analysis period in 01/07/2006, which is -22.89 m.

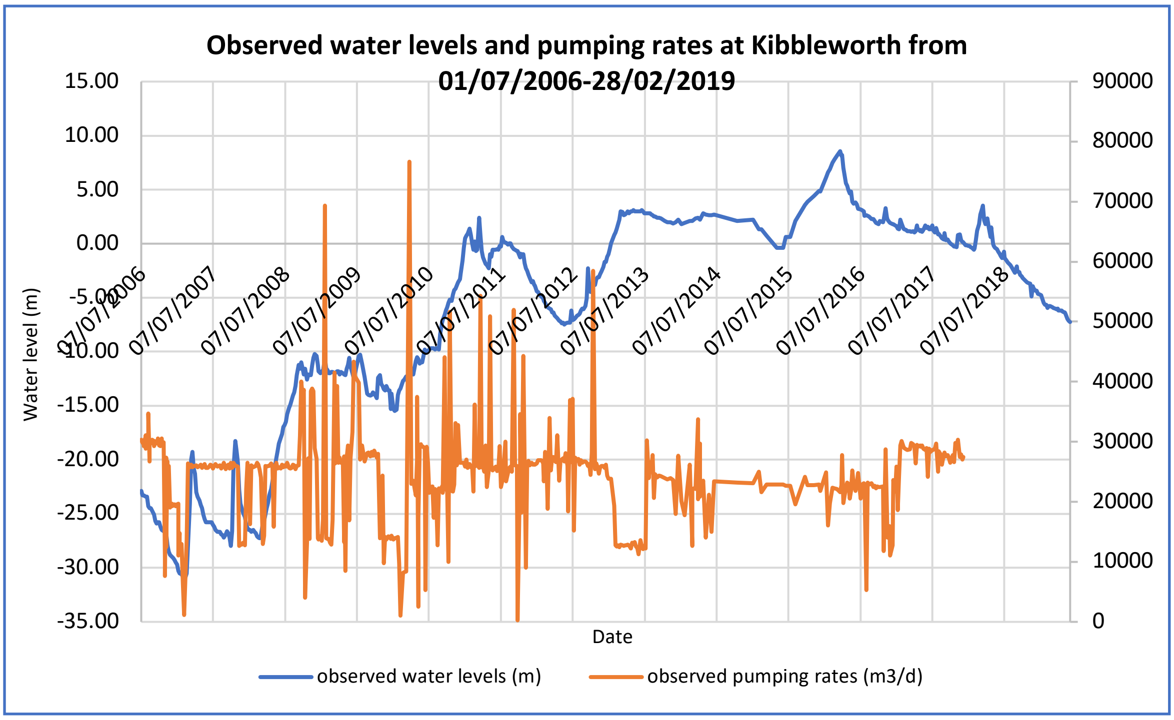

Figure 11 - water levels and pumping rates in Kibblesworth from 01/07/2006-28/02/2019.

When analysing the data, several duplicates of dates were found with empty data in the water level columns. These duplicates were removed from the datasets for simplicity. The Kibblesworth dataset had an error from the recording period between 03/01/2003 and 12/11/1994 where the data in the metres below datum (mBDAT) and water level at metres above ordnance datum (mAOD) were switched. The error was corrected by simply swapping the two columns of data between this period.

The Lumley 6th dataset also had an error where the mBDAT values were 1m less than those for the same dates in the "prior to 2015" dataset. Both datasets for the Lumley 6th borehole overlapped from a period between 2008 and 2012 but had a difference of 1m for all water level recordings. For example, 24/02/12 in the recent dataset had a value of 42.9 mBDAT while the recent dataset had a value of 43.9 mBDAT for the same date.

The values in the historical dataset were used in the analysis to maintain the consistency of recorded mBDAT values. However, the values from 2013-2019 were only provided in the recent dataset and thus were used in the analysis. Therefore, it is important to note that the water level values between 2008-2012 compared to those between 2013-2019 are inconsistent and differ by approximately 1m.

3.1.4 Potential discharge points and flooding incidents

The potential mine water discharge points data was provided by Gateshead Council as GIS vector data. Flooding incidents from groundwater and mine water between 1979 and 2016 were also provided by Gateshead Council as a GIS Shapefile. The potential discharge points were used in the analysis to identify the ponds with surface discharge.

Figure 12 shows the spatial distribution of potential mine water discharge points across the pond system. Determining the elevation at the discharge points is important for the numerical model because it represents the point at which mine water will rebound to the surface. The discharge point outlined in red represents the point used in the numerical model with an elevation of 13 mAOD. The elevation was determined using a topographical map of the area provided by Gateshead Council. Specific flooding incidents will be discussed further in the discussion section.

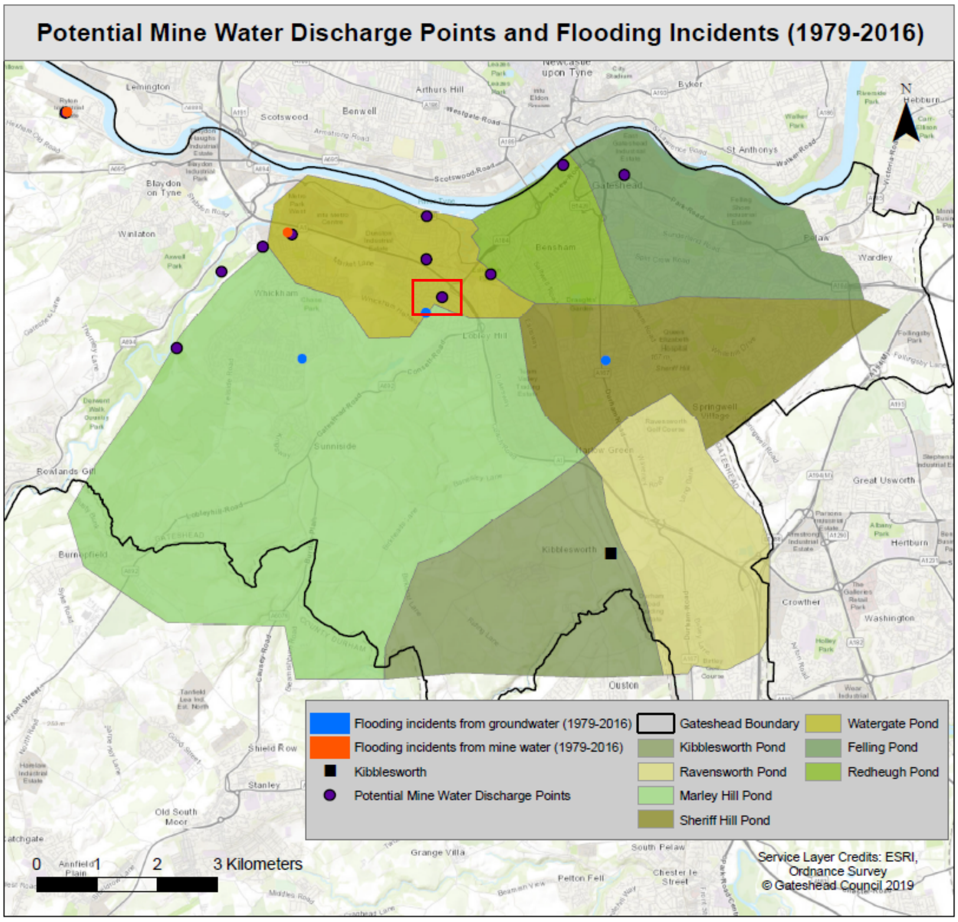

Figure 12 - potential mine water discharge points and flooding incidents in the study area.

3.1.5 Rainfall data

Daily rainfall data for the northeast of England was retrieved from the Met Office Hadley Centre Observation Data. Rainfall values will be used as an input into the numerical model to represent the recharge into the system. The model calculates a mass balance for all ponds in a multi-pond system in daily timesteps which includes recharge, flow between ponds, and dewatering (Gandy and Younger, 2007). Therefore, the rate of water level rise in any one pond is dependent on the recharge to the pond as rainfall, in addition to the storage capacity.

Rainfall data covered the period from 01/07/2006 to 28/02/2019 to coincide with the available water level data, which allows the model to be calibrated over the same period (figure 13). The data contained values of -99.99 in place of the 31st day in months with only 30 days. These values were removed so that the data represented the appropriate number of days in each month over the 13-year period. Two values were considered to be errors because the values were highly unlikely to be the daily rainfall for that day in Gateshead. These values were corrected by averaging the rainfall values of the day before and after the error value.

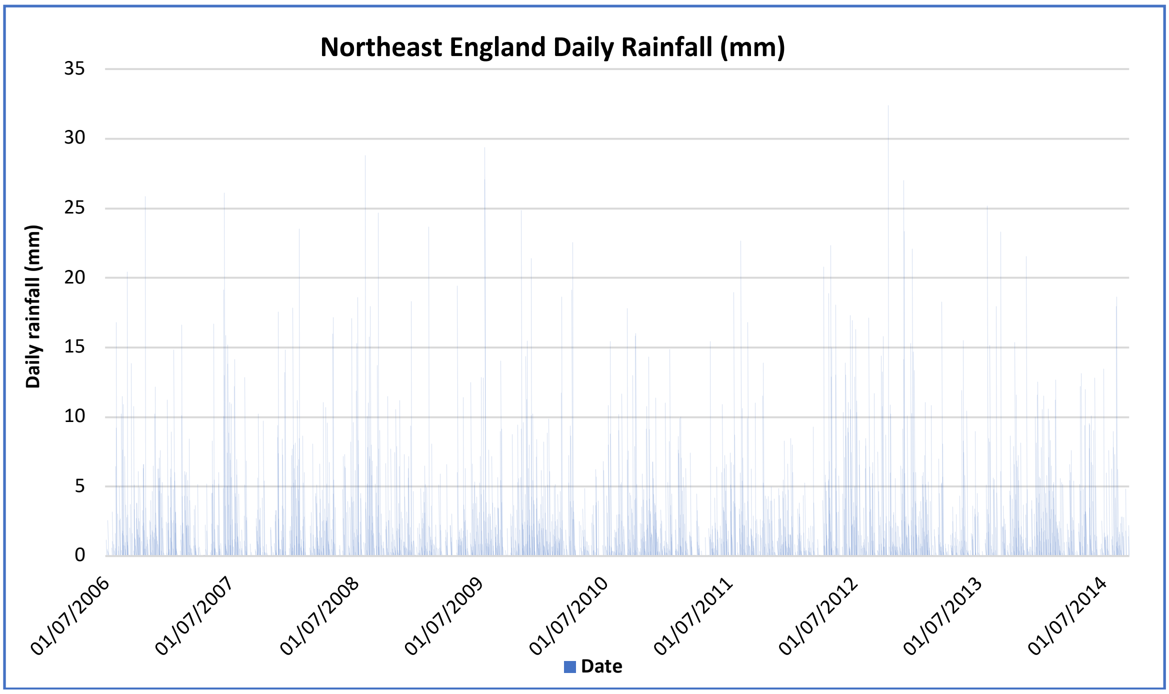

Figure 13 – Daily rainfall for the northeast of England from 01/07/2006 to 28/02/2019. Data was retrieved from the MET Office.

3.2 Building the conceptual model

3.2.1 Defining and identifying the pond system

After analysing the data, the mine workings underlying the study area were further conceptualised by allocating a pond system based on the distribution of collieries, coal seams, and the interconnections in the mine system. The numerical model is based on a pond system and requires the details of each pond to estimate rebound; thus, defining the pond system is a crucial step in the process of modelling mine water rebound. The hydrogeologist uses the concept of ponds to describe the interconnections within the mine workings so that the water level in any one pond is consistent throughout that pond (Gandy and Younger, 2007).

The Master Seam defines the most widely-worked seam and provides the bulk of inter-connectivity across the coalfield, which in the study area is the Brockwell coal (Younger, 2016). Ponds and more isolated seams are typically connected via overflow points, which includes roadways, an area where two adjoining goaf panels coalesce, old exploration boreholes, or permeable geological features (Younger and Adams, 1999). Goaf is the debris resulting from roof collapses in the mine workings. Rebound occurs when the water level in one or more ponds reaches an overflow point.

ArcMap was used to define the pond system using the Shapefile data provided by the Coal Authority. Younger and Adams (1999) provide a guide for defining and identifying ponds. First, the lowest worked seam in the area was analysed to determine where the seams were isolated and to identify connections. Each isolated area was identified as a potential individual pond. The process was performed for the remaining seams up sequence to determine if the isolation of seams was consistent for all coal seam layers.

Cross-sections of the Lower and Middle Coal Measures across several boreholes over Newcastle and Gateshead shown in Richardson's (1983) *Geological notes and local details for Newcastle upon Tyne and Gateshead* report were also used to analyse and understand the spatial representation of the coal seams across the ponds. An example of these cross-sections is shown in Appendix B, figure 40.

Figure 14 shows an example of this process using the Brockwell coal seam where ponds were created based on the isolation of the Brockwell workings. This process was repeated for the Hutton, Harvey, Main, Low Main, Top Busty, Bottom Busty, Brass Thill, Maudlin and Tilley coals seams, which further validated the selection and distribution of ponds. Seven individual ponds were defined and were named based on the major collieries underlying the area. However, only three ponds were used in the numerical model for simplicity and due to time constraints.

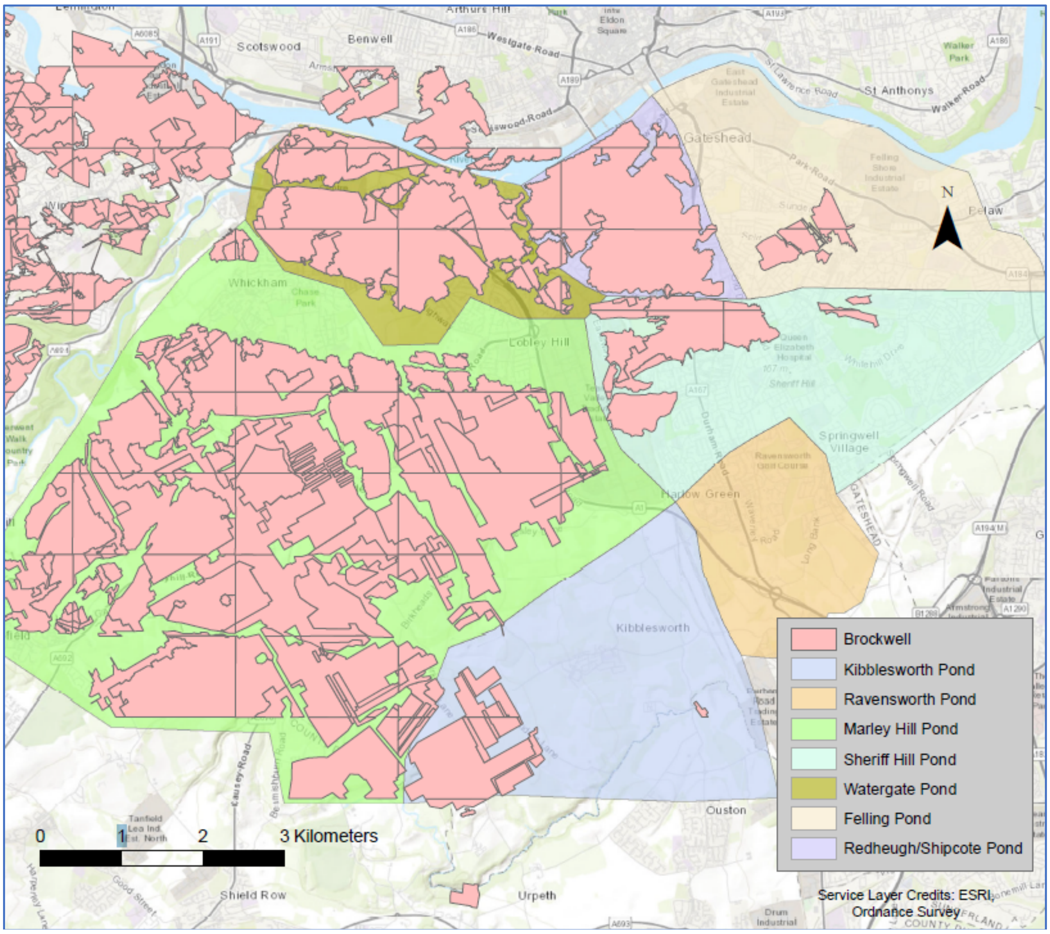

Figure 14 - Brockwell coal seam across the pond system demonstrating how the ponds were chosen based on isolated sections of the coal seam.

In some cases, the workings overlapped between ponds. However, if the overlap was not significant, the area and/or shape of the pond was not changed. For example, in figure 14 the Brockwell seam in the Marley Hill pond overlaps the Kibblesworth pond. However, the pond areas were kept the same because all other coal seams were consistently separated within the two ponds and the overlap itself was not significant.

Based on the methodology of defining ponds by Gandy and Younger (2007), the chosen ponds were further validated by grouping the collieries in the area into ponds. It was determined that the ponds defined by collieries correlated with those defined by the coal seam workings. Building a representative pond system is necessary for calculating the areal extent of the workings within each pond, which is one of the major inputs into the numerical model. Additionally, the pond system is the basis of the numerical model for modelling and predicting mine water/groundwater rebound.

3.2.2 Calculating the area of workings within the ponds

Once the pond system was established, the area of workings within each pond was calculated and used as an input into the numerical model. The **total pond area** and **pond recharge area** for each pond are two parameters needed in the water balance equation for modelling predictive water levels.

First, each coal seam was clipped within each pond in ArcMap to isolate the seam within a given pond in a new GIS layer (figure 15). The spatial representations of all other coal seams are shown in Appendix B, figures 41-48. The resulting attribute tables provided the areal values of each coal seam within each pond. The total pond area was then calculated by taking the average of all areal coal seam values within each pond. It should be noted that not all coal seams were found in every pond; therefore, the total pond areas are only an estimate of the relevant seams within a given pond. The pond recharge area was calculated by simply estimating the surface area of the pond. The areal values for total pond area and pond recharge area are shown in table 4.

It should be noted that some small overlaps between ponds were split as a result of the 'Clip' function in ArcMap (figure 15 - between the Marley Hill and Kibblesworth Ponds). Therefore, the calculated total pond areas are only approximate values. The resulting areal values are also subject to error due to the limitations associated with the mine workings themselves. As mentioned, they are only a snapshot in time and may not accurately represent the spatial distribution of mine workings.

Table 4 – The areal extent of each coal seam within each pond averaged together to estimate the total pond area of each pond. The pond recharge area was estimated in ArcMap as the total surface area of the pond.

Ponds	**Marley Hill**	**Watergate**	**Redheugh**	**Felling**	**Sheriff Hill**	**Ravensworth**	**Kibblesworth**
Areal extent of pond (m^2)							
High Main	-	-	-	3,368,468	5,108,307	1,375,269	101,305
Top Main	-	-	-	-	32,214	7,37,254	-
Bottom Main	-	-	-	-	-	2,469,728	-
Maudlin	-	-	-	3,851,683	6,120,140	6,614,190	-
Durham Low Main	593,863	-	190,292	2,608,364	1,366,435	2,795,505	1,863,729
Brass Thill	761,998	-	-	3,142,979	6,336,320	6,071,955	7,962,445
Hutton	13,359,572	-	1,169,228	6,903,831	7,483,118	8,584,908	13,701,882
Harvey	2,726,225	4,599,852	2,389,499	2,881,797	6,215,626	1,953,493	578,938
Tilley	5,078,780	502,651	81,659	-	1,969,440	2,767,338	6,893,879
Top Busty	8,481,261	2,681,333	2,892,492	-	3,053,818	3,481,386	5,716,594
Bottom Busty	6,368,143	3,385,636	-	-	410,383	75,241	3,211,289
Three-Quarter	2,685,485	591,346	94,758	-	143,620	1,372,209	-
Brockwell	21,289,861	5,245,261	3,504,238	1,598,057	1,826,068	-	1,843,421
Average Total Pond Area (m^2)	**6,816,132**	**2,834,347**	**1,474,595**	**3,479,311**	**3,338,791**	**3,414,657**	**4,652,609**
Pond recharge area (m^2)							
	34,972,087	**6,866,684**	**4,139,092**	**7,940,398**	**10,007,686**	**8,728,518**	**10,749,861**

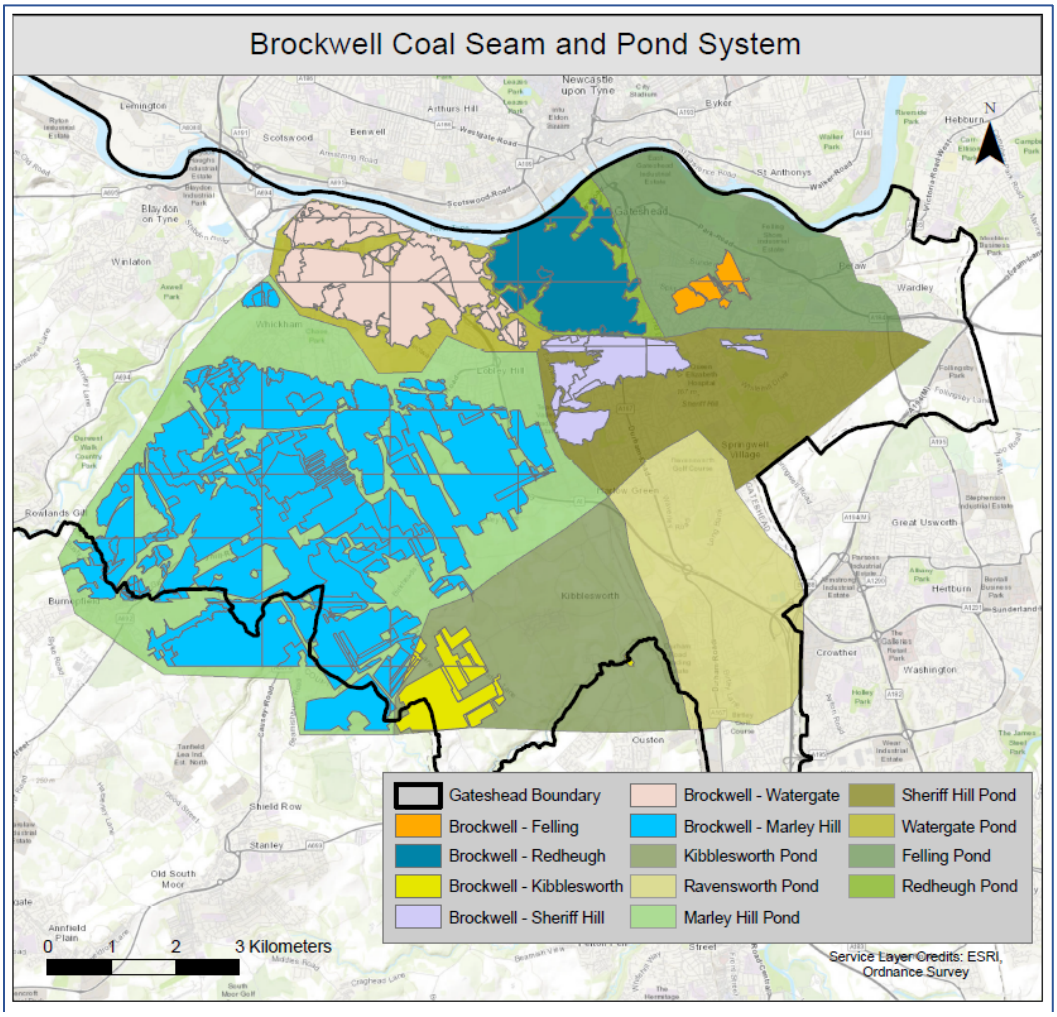

*Figure 15 – Example of a new GIS layer created in ArcMap using the Clip function to isolate the Brockwell seam into each pond. This process was performed for all other coal seams up the sequence (*Appendix B, figures 41-48*).*

3.2.3 Defining pond interconnections and outflow features

Defining the pond interconnections and identifying the outflow features is necessary for further conceptualising the mine workings. The numerical model also requires the elevations of possible discharges to calculate the time for each pond to rebound to the surface where the elevations are representative of the height of the connection (Gandy and Younger, 2007). The elevations of the interconnections are important for determining the height of water level rise at which rebound will occur or height where water will flow into an adjoining pond.

The pond interconnections were defined using GIS shapefiles of the most worked coal seams and of spine roadways provided by the Coal Authority. Five connections were identified based on intersecting roadways between ponds. The remaining two connections were identified based on the overlap and interconnection of the coal seams and the collieries between ponds. The Brockwell, Hutton, and Harvey coal seams, in addition to the colliery mine plan shapefile, were primarily used for identifying two of the seven interconnections. The pond connections are represented by figure 16.

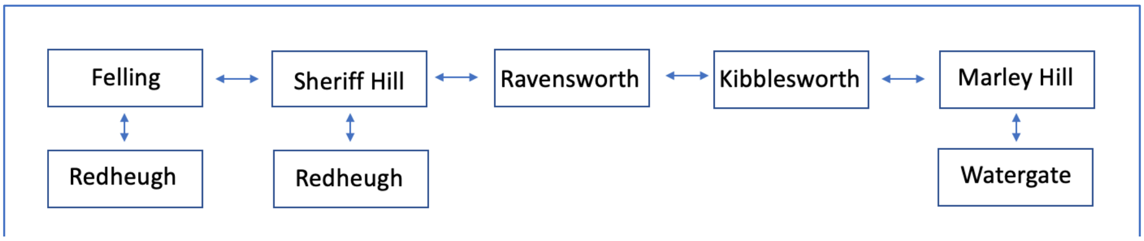

Figure 16 - conceptual model showing the ponds and their interconnections.

The height of each connection was determined using a topographic map provided by Gateshead Council and the in-seam levels shapefile provided by the Coal Authority. The length and diameter for the connections defined by roadways were provided in the attribute table. The length and diameter values for the connections defined by collieries and coal seams were assumed to be an average of the five roadway connections due to lack of any real data (table 5). The roughness coefficient for all connections was 0.012 and was derived from Gandy and Younger (2007) for another coalfield.

A discharge coefficient for each of the four connections was calculated and used as an input into the model to estimate the ease at which water can move from pond to the other. This was done using the Colebrook-White equation, which is useful for estimating the friction factor in a pipe system. The head loss in the connection system was calculated using the Darcy Weisbach formula which is given by the equation: $h_f = \lambda \frac{L}{D} * \frac{V^2}{2g}$, where λ is the Darcy friction factor (dimensionless), L is the length in metres, D is the diameter in metres, V is the velocity of the flow through the pipe, and g is gravity.

The Darcy friction factor equation is given by the equation: $\lambda = 0.316/Re^{0.25}$, where Re is the Reynold's number. According to Nalluri (2019), a Reynold's number of 3,000 suggests that the flow is turbulent. Younger and Adams (1999) propose that water flowing through a mine system is turbulent, thus, a value of 3,000 was used in the calculation. The discharge coefficient consists of all values in the Darcy Weisbach equation except the velocity. Although initial values of the discharge coefficient were estimated, they were adjusted during the calibration of the numerical model (table 5). Using the Darcy Weisbach and discharge equations ($Q = A * V$), an equation was created in the model to calculate the discharge through the pond connections. The discharge coefficients are only rough estimates and are subject to several assumptions and limitations; therefore, many adjustments were made during the calibration process to represent a reasonable discharge through the connection.

Since the numerical model was simplified to a 3-pond system, only two connections between ponds were used including the Kibblesworth-Marley Hill and the Marley Hill-Watergate connections. Two additional connections were added to represent the discharge to the surface in the Watergate pond at 13 mAOD and the discharge/recharge to and from the mine workings north of the River Tyne using observed water level data from the Tyneside House borehole in Newcastle.

Table 5 – pond interconnections and their attributes, including height, length, diameter, roughness coefficient and type of connection. Data retrieved from GIS shapefiles provided by the Coal Authority.

Connection	Height (mAOD)	Length (m)	Diameter (m)	Discharge Coefficient (m)	Type
Kibblesworth-Marley Hill	-74	333.59	1.38	calibrated	roadway
Marley Hill-Watergate	-72	485.974	1.002	calibrated	colliery
Connection 3 – surface discharge	13	-	-	calibrated	Drain boundary
Connection 4 – Tyneside (river boundary)	-	-	-	calibrated	River boundary
Other connections between the 7-pond system but not used in the numerical model					
Felling-Redheugh	-44	485.974	1.002		colliery
Sheriff Hill-Redheugh	-187	92.68	0.91		roadway
Felling-Sheriff Hill	-118	1010.32	0.87		roadway
Sheriff Hill-Ravensworth	-146	753.52	0.94		roadway
Ravensworth-Kibblesworth	-106	239.76	0.91		roadway

The fourth connection was treated as a boundary condition. In modelling terms, the river is a specific head boundary where the flow is calculated based on the hydraulic gradient between the river and the aquifer in either direction (Parkin, 2018; figure 17). In this case, the mine workings act as the aquifer. The model determines the flow direction to or from a cell based on a certain threshold (Harbaugh, 2005). The threshold was defined as the elevation where water levels recovered at the Tyneside House and at which discharge through the connection will change direction. Defining the river boundary as the fourth connection will provide a basis for understanding the potential interconnections with mine water blocks to the north of the study area.

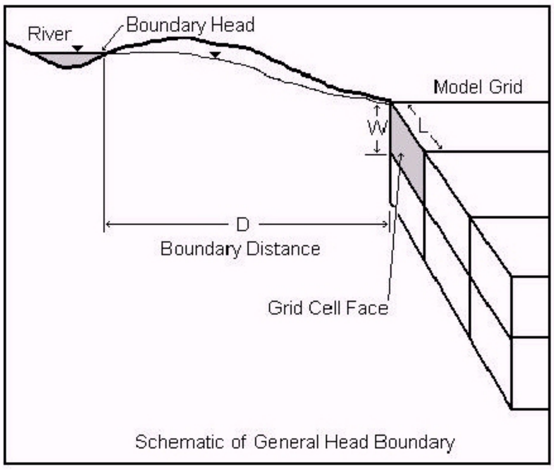

Figure 17 - schematic of a specific head (general head) boundary used for defining the River Tyne boundary (MODFLOW, 2019).

3.2.4 Conceptual model assumptions and limitations

There are several assumptions and limitations regarding the data and methodology for assessing the hydrogeology. For the data analysis and conceptualisation, one limitation is that the mine plans may be incomplete and unrepresentative of the study area due to the past legislative requirements in the coal mining industry. Therefore, the areal calculations and determination of the pond system are subject to error.

When defining the pond interconnections, one limitation is that the equation for estimating the discharge coefficient or friction factor is designed for a pipe system when, in reality, the connections are actually roadways in the mine workings. As a result, the values were adjusted and calibrated as needed to better represent the system. One major limitation in defining the pond system and interconnections is the lack of information and understanding of potential connections to the north and south of the pond system. Connections outside the study area may have an impact on the recharge or discharge in the system and will thus impact the rate of water level rise.

3.3 Construction and application of the numerical model

The GRAM model was to be initially used in the project. However, the model failed to accurately represent the behaviour of the pond system. One potential reason for this may be due to the fact that the water level in the first pond was already higher than the height of the connections, which caused the model to falsely illustrate the water levels.

Another problem with the GRAM model was the inability to troubleshoot the errors due to the lack of any coding and/or programming information behind the model. Although GRAM is useful for estimating mine water rebound, it lacks the potential to add complexity to the model for making predictions. Therefore, a numerical model was constructed in Excel but was based on a similar concept of the GRAM model in using a pond system to estimate mine water rebound.

When creating a numerical model, the conceptual model must be evaluated to define the model construction (geometry, boundary conditions, and hydraulic properties) (Martinez *et al.,* 2010). The next steps for building a numerical model should include calibration, a sensitivity analysis, validation, predictions, and an uncertainty analysis (Parkin, 2018). The numerical model built in Excel was based on the conceptual understanding of the mine workings and interconnections derived in section 3.2.

Columns were created for the date, rainfall, recharge, abstraction, observed water levels, modelled water levels for the three ponds, and discharges through the connections. A separate tab was created for all the observed and calibrated parameters. Two equations were created to predict the modelled water levels (based on a hydrogeological water balance) and the amount of discharge/recharge to each pond.

It should be noted that numerical modelling is based on an iterative process in which the reasonableness of the results in each step should be checked before proceeding to the next step (Martinez *et al.,* 2010). This is important to understand when developing a numerical model that is based on several assumptions and limitations. Once the numerical model was constructed, calibrated, and validated, it was used to make predictions of water level rise under various recharge and discharge scenarios.

3.3.1 Model requirements and data inputs

A list of requirements and data inputs for the numerical model are shown in table 6. The data inputs were either retrieved from the Coal Authority or Gateshead Council or were calculated using the data provided in the conceptual model. As mentioned, daily rainfall data was retrieved from the MET Office. The daily evaporation rate was estimated by averaging the monthly rates using data from the Centre for Ecology and Hydrology.

Table 6 – list of requirements and data inputs for the numerical model. Data was either directly used or calculated in the conceptual model using data provided by the Coal Authority and Gateshead Council.

Model requirement	Details
Precipitation	Daily rainfall for the period 01/07/2006-28/02/2019
Evaporation	Constant average of 1.09 mm/d from monthly data
Pumping rates	Kibblesworth pumping rates for the period 01/07/2006-28/02/2019
Water levels	Observed water levels for Kibblesworth for the analysis period used to calibrate the model and to determine the initial water level in the ponds. The initial water level in each pond was -22.89.
Pond areas	Calculated in section 3.2.2
Pond recharge areas	Calculated in section 3.2.2
Connection properties (height and discharge coefficient)	Calculated in section 3.2.3
Storage coefficient	Calibrated. A value of 0.3 was chosen because goaf has a similar porosity as gravel which has a storage coefficient of 0.3 (Younger and Adams, 1999)

3.3.2 Quantifying water inflow and outflow rates

The recharge and discharge into and out of the system was quantified to model the predicted water levels across all three ponds under certain conditions. Determining the inputs and outputs was based on the method behind the GRAM model for a multi-pond system and a simple groundwater storage water balance (figure 7; figure 18).

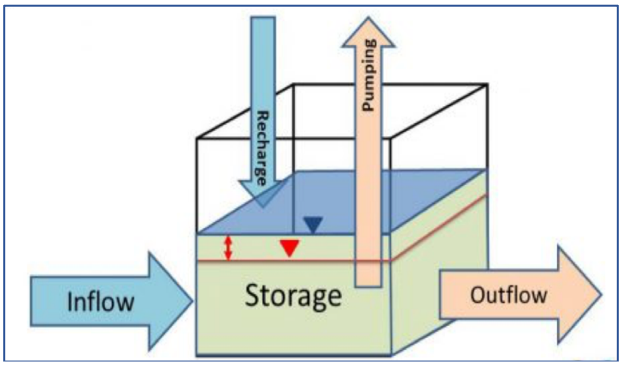

Figure 18 - water balance for groundwater storage used in building the concept of the numerical model.

The recharge into the system was calculated by simply subtracting the evaporation from the precipitation for each value across the analysis period of 4,626 days and multiplying the resulting value by the runoff coefficient. It was assumed that 70% of the study area is impervious cover based on the development coverage in the Team Valley.

The abstraction rates for the analysis period at Kibblesworth were used as one of the outputs in Pond 1. The equation used to estimate the discharge through the connections was the discharge coefficient multiplied by the square root of the difference in head levels. The discharge through the connections was used as another output/input for each pond. The recharge and abstraction were the initial inputs/outputs in the system.

The model was then calibrated using observed water levels at Kibblesworth and the inputs/outputs to adjust the parameters. During calibration, the pumping rates were orders of magnitude greater than the recharge into the pond system. This indicated that there was an additional recharge into the system at pond 1 (Kibblesworth). After analysing the mine water blocks geometry and water level/pumping rate data, it was determined that there was an additional input from the Lumley mine water block.

Pumping in the Lumley mine water block ceased in 2008, which led to surface discharge across the area. The discharge at the surface indicates that some of the water enters nearby mine water blocks as recharge through the mine workings. One limitation is that the amount of recharge from the Lumley mine water block is unknown and requires a further conceptual understanding of the connections to the south of the study area. Therefore, the input added in the model to account for the additional recharge from Lumley was an arbitrary number used solely for calibration.

Through calibration, it was also determined that there was an additional discharge out of pond 3. An output was created to represent the amount of discharge through the River Tyne to the north of the study area. Observed water levels at the Tyneside borehole in Newcastle were retrieved from a previous student project and were used to determine the threshold at which the water levels recovered. The discharge to and from the north of the River Tyne was used as the fourth pond interconnection.

In summary, figure 19 shows a cross-section of all the recharge and discharge inputs/outputs to and from the pond system. The discharge/recharge to and from the Tyneside House changes from recharge into the system initially to discharge at the threshold date when the water levels at Tyneside recover.

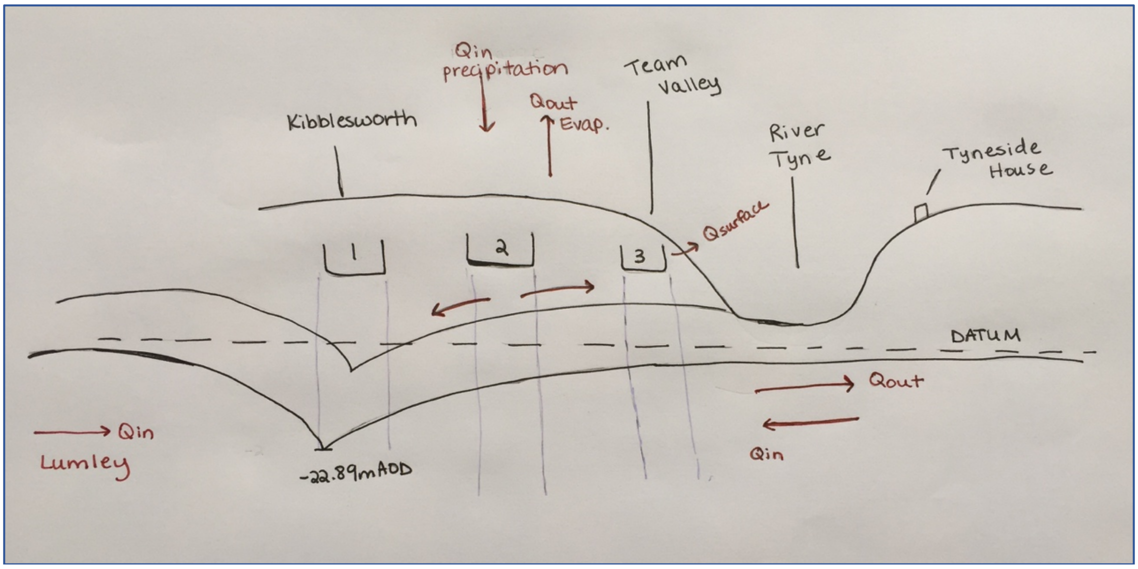

Figure 19 - Water balance for the project area, including all inputs and outputs to and from the pond system.

3.3.3 Model calibration, sensitivity analysis, and validation

The model construction and conceptual model must be evaluated during the calibration stage to achieve a reasonable calibration. A good calibration should be obtained by using various parameters to get a good representation of the different trends in water levels, drawdown, and inflows and outflows rather than by matching the observed levels and making specific changes (Martinez *et al.,* 2010). Calibration must be performed to fit the model output to the observed data and is crucial in the process of constructing a numerical model.

The model was calibrated against the observed water levels at Kibblesworth (pond 1) to estimate the storage and discharge coefficients. These parameters are not well understood in the mine system and thus, needed to be calibrated to ensure accurate outputs of predictive mine water rebound. As previously discussed, calibration was also useful in understanding the additional inputs and outputs to and from the pond system.

Due to the lack of observed water level data for ponds 2 and 3, a sensitivity analysis was crucial in estimating the modelled water levels for these ponds. A sensitivity analysis is the effect of adjusting model parameters by a fixed amount on the model output and is used to improve calibration and model structure and to identify sensitive parameters (Parkin, 2018). This was done by initially using constant rainfall and abstraction as inputs into the model to understand the effects of the discharge coefficient on water levels.

In this hypothetical situation with constant recharge and discharge, it was determined that water in pond 2 flows both to ponds 1 and 3 due to the influence of abstraction at Kibblesworth. This helped to understand any other potential inputs and outputs into the system and suggests that the abstraction has a major influence on the overall pond system. The observed parameters were used in the validation stage to validate the calibration and sensitivity analysis and ensure that the model is behaving appropriately.

3.3.4 Calculating the rate of water level rise

Once the model was calibrated, the rate of water level rise during the analysis period between 01/07/2006 to 28/02/2019 was calculated. As mentioned in section 3.3.2, the calculation of water level rise was based on a simple water balance defined by the equation $\sum Q_{in} - \sum Q_{out} = Q_{storage}$. By rearranging the equations for a water balance and for Storativity ($S = V/A * \Delta h$), a new equation was created to estimate the modelled water levels across all three ponds, which is given by the following:

$$\frac{\sum Q_{in} - \sum Q_{out}}{A * S} = \Delta h$$

In terms of the inputs and outputs to and from the pond system, the equation is:

$$\frac{\sum Recharge \pm connection\ discharge - \sum Abstraction \pm connection\ discharge}{pond\ area * storage\ coefficient} = \Delta h$$

The estimated values from the equation were then added to the previous water level value for any given pond so that the calculated value represented the cumulative water level. The discharge through the connections before or after a pond was treated as both an input or output to allow for water to flow to and from any one of the ponds to another in the multi-pond system. This method largely influenced the water level in any one pond and accounted for the influence of abstraction on the system.

Allowing the discharge through the connection to flow in either direction was one of the advantages of constructing a numerical model in Excel as opposed to using GRAM. The GRAM model only allowed for water to spill into the next pond in a single direction, which did not accurately characterise the influence of abstraction at Kibblesworth. Once the historical rate of water level rise between the analysis period was estimated using the calibrated parameters, mine water rebound under various theoretical scenarios was predicted and quantified.

3.3.5 Predicting future mine water rebound

Once the rate of water level rise over the analysis period was calculated, predictions of mine water rebound were made. Four various scenarios of a changed climate and/or pumping regime were created and modelled to estimate the rate of predicted water level rise. The prediction period used in the model was for four years from 01/03/2019 to 01/03/2023. The initial date was chosen based on the lack of data past February 2019.

A summary of the four scenarios is shown in table 7. For the scenarios without a change in rainfall, the precipitation values for the previous four years from 28/02/2015 to 28/02/2019 were used as the predicted values of precipitation. These scenarios assume that the climate remains consistent in comparison to the climate over the past four years. For the other two scenarios, an increase of 20% in rainfall was chosen based on the predictions of precipitation due to climate change in the United Kingdom.

As mentioned in the literature review, the Coal Authority will be exploring possible sustainable and cost-effective alternatives to the pumping regime at Kibblesworth. Therefore, the scenarios include a mixture of pumping regimes. Three scenarios involve a reduced pumping rate to reflect the interest in cost-effective alternatives by the Coal

Authority. The pumping rates for the previous four years between 28/02/2015 and 28/02/2019 were used for making predictions. The observed values between those years were multiplied by either 0.5 or 0.25 to estimate the pumping rate at which abstraction is reduced by a quarter or by half of the observed amounts.

Table 7 – summary of the four scenarios created for predicting mine water rebound.

Scenario	Precipitation (mm)	Abstraction (m^3/d)
1	Observed rainfall values as previous four years (2015-2019)	Abstraction reduced by half of observed values from 2015-2019
2	Rainfall increased by 20% of observed values for previous four years (2015-2019)	Observed values as previous four years from 2015-2019
3	Rainfall increased by 20% of observed values for previous four years (2015-2019)	Abstraction reduced by half of observed values from 2015-2019
4	Observed rainfall values as previous four years (2015-2019)	Abstraction reduced by a quarter of observed values in the first year (19-20), then by half in the second year (20-21), then to zero in the last two years of the prediction period

Various other scenarios using constant rainfall and abstraction were used initially for the purpose of understanding the model outputs. In general, an increase in rainfall and a decrease in pumping rates were expected to increase the water levels and discharge through the connections. Switching the pumps off completely was also expected to increase the water levels at a much faster rate than by decreasing abstraction slowly.

Although only four scenarios were used in this report, they provide a starting point for investigating changes in the pumping regime at Kibblesworth. Making predictions of mine water rebound is helpful for understanding the impacts of abstraction and recharge on the pond system.

3.3.6 Numerical model assumptions and limitations

There are several assumptions and limitations associated with the numerical model, which should be acknowledged when predicting mine water rebound. Firstly, as with any numerical model, it is only an approximation based on several assumptions which limits the accuracy of the outputs (Parkin, 2018). Another limitation associated with the model is its inability to explicitly model the behaviour of the unsaturated zone and of the river-aquifer interactions (Younger, 2016). This limitation suggests that there may be additional connections with the River Tyne or Team that are not accounted for.

One major assumption of the GRAM model is that rebound occurs in a uniform gradient; however, in reality, the water table is not usually flat within a pond and will result in a rebound curve (Younger and Adams, 1999; figure 20). This assumption may indicate that the initial water level predictions are not correct, which is important to consider in this project due to the lack of water level data for ponds 2 and 3.

Younger and Adams (1999) note that although the assumption implies that the initial conditions are inaccurate, the time taken for rebound to occur does not change. Although GRAM was not used, this assumption may still apply to the numerical model created in Excel due to the linearity of the modelled water levels in some of the outputs.

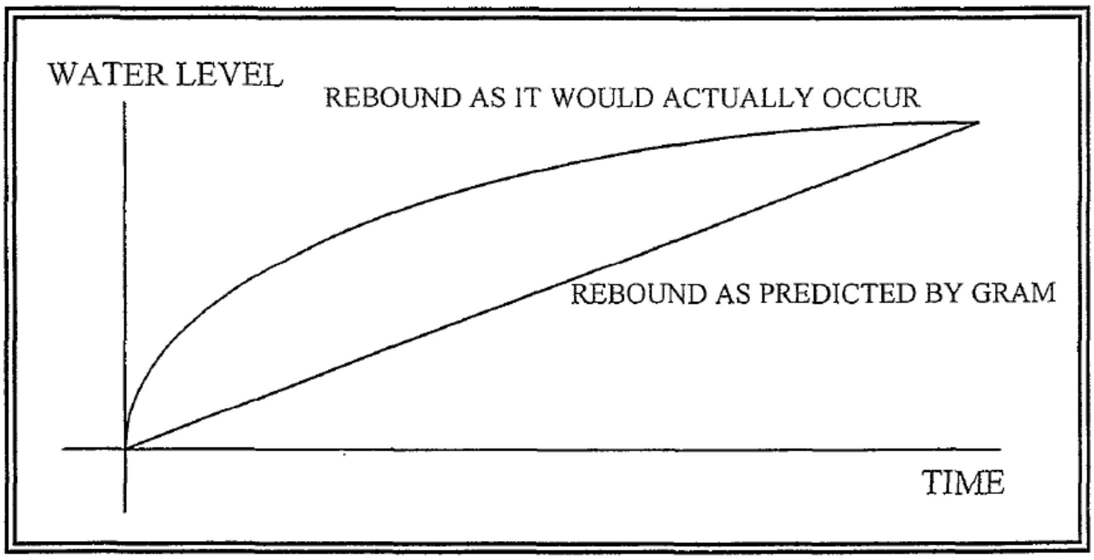

Figure 20 - comparison of the actual rebound trend in a pond without an entirely flat initial water table and a linear rebound trend predicted by GRAM (derived from Younger and Adams, 1999)

There are also limitations associated with the initial and final conditions of the model. First, defining the initial water level comes with uncertainties because the details of local hydraulic gradients in the strata around the deepest workings are often not known (Younger *et al.,* 2002). This applies to the initial water level conditions in ponds 2 and 3. Second, the resulting discharge rate and water level are limited due to the difficulty in understanding the role of effective rainfall in the mine workings and the oversimplification of head conditions (Younger *et al.*, 2002). The rate of flow at the discharge points are also unknown, which limits the accuracy of the resulting rates.

In relation to the discharge through the connections, one limitation is that the model treats all of the inter-pond flow mechanisms as a pipe system; however, other mechanisms may transmit greater volumes of water such as a roadway (Younger and Adams, 1999). This is important to consider because most of the connections were defined as roadways across the pond system. Also, the model assumes that the water level within each pond is horizontal and the flow through the connections is turbulent, which may not accurately represent the mine system (Gandy and Younger, 2007).

When making predictions for future mine water rebound, one limitation is that the model may not accurately represent the hydrogeological processes in the system because an assumption was made based on a constant change in rainfall or abstraction, when in reality, the projected changes may vary spatially and seasonally (Kilsby, 2018). Additionally, the model assumes that the estimated water level rise is solely from groundwater rebound, but in reality, water level can also rise due to potential leakage from sewers and/or distribution pipes (Younger, 2016).

All of the assumptions associated with the numerical model may limit the accuracy of the results, which suggests that the outputs can only be used as an approximation for quantifying water level rise and mine water rebound. Although there are a number of assumptions and limitations associated with the numerical model, one major advantage is its ability to provide a fundamental understanding of rebound in abandoned mine systems. Understanding mine water rebound may be useful when determining the consequences of a changed pumping regime at mine water pumping stations.

3.4 Estimating time taken to fully rebound in workings

3.4.1 Quantifying voidage of underground workings

Quantifying the voidage of the coal seams within the mine workings is useful for providing an understanding of the volume of material removed within the underground workings. Knowing the approximate voidage and storage coefficient in the system allows for an estimate to be made of the time it will take to completely fill the underground workings and for water to fully rebound.

The volume of each of the coal seams was calculated by multiplying the areal values by the seam thickness. The thickness of each coal seam shown in table 8 is an average of the range of thickness derived from Mills and Holliday (1998) *Geology of the district around Newcastle upon Tyne, Gateshead and Consett* as described in section 2.5.1.

Table 8 – average thickness for each coal seam derived from Mills and Holliday (1998).

Seam	Thickness (m)	Seam	Thickness (m)
High Main	2	Harvey	0.8
Top Main	1.6	Tilley	0.6
Bottom Main	1.6	Top Busty	0.8
Maudlin	1	Bottom Busty	1
Durham Low Main	1.6	Three-Quarter	0.6
Brass Thill	1	Brockwell	1
Hutton	1.5		

The effective volume was then calculated by multiplying the average pond volume by the storage coefficient for that pond. This was done because Younger (2016) suggests that the effective voidage is essentially a function of the total volume and the amount of open space, where the storage coefficient represents the volume of water released from storage per unit decline in the hydraulic head. Since a storage coefficient was only estimated for three of the seven ponds, the effective volume and time taken to completely fill the voids was only calculated for the 3-pond system.

It is important to note that the voidage only gives a minimum value for the volume of pore space that must be flooded before water level recovery will be complete; this is due to the varying levels of drainage due to processes of coal extraction, goaf formation, and deformation of the overlying strata (Younger, 2016). For example, sandstones are more likely to drain while siltstones and mudstones will never fully drain.

This means that when the system of mine workings begins to flood, the water will encounter two distinct types of floodable storage space including drained pores available for re-filling due to heavily fractured mine voids and filling based on elastic storage from the still-saturated argillaceous/perched arenaceous strata (Younger, 1993). These processes are usually reflected in the storage coefficient values.

3.4.2 Estimating time taken for water level recovery

Once the voidage was calculated, the time taken for water to completely fill the voids was estimated using the rate of inflow into the system. The time taken for full water level recovery in the underground workings was calculated by dividing the average and effectives volumes by the maximum dewatering rate. Younger (2016) suggests that the maximum rate of inflow corresponds to the peak dewatering pumping rate before closure. Therefore, the rate of inflow used was the earliest observed pumping rate at Kibblesworth in 12/11/1994, which was approximately 24,878 m^3/d.

An adjustment was made to account for the widespread observation that the rate of water inflow decreases as the head difference between the interior of the mine and the surrounding rock mass decreases during water level recovery; this is because water inflow to a pumped void is head-dependent, which is a universal principle in hydrogeology (Younger, 2016). Therefore, the adjustment is based on experience in various exposed coalfields in the UK which suggest that the head-dependent component of inflow typically amounts to 60% to 70% of the peak inflow rate represented by the maximum dewatering rate before closure (Younger, 2016). Estimating the time taken for groundwater to completely fill the voids in the underground mine workings provides an understanding of the influence of coal mining on the hydrogeology.

4.0 Results

4.1 Construction of the numerical model

During the process of constructing a numerical model, random values for all of the parameters were used for the sole purpose of developing a working model. The values include a storage coefficient of 0.3 for all ponds and discharge coefficients of 1000, 2000, 1000, and 3000 for the connections. However, it should be noted that these values are unrealistic for a pipe system, which is assumed in the calculation of this parameter.

Figure 21 shows the accepted output for determining that the model worked. The graph demonstrates the modelled water levels over a given number of days for all three ponds under constant abstraction and rainfall, which is expected to rise at a constant rate.

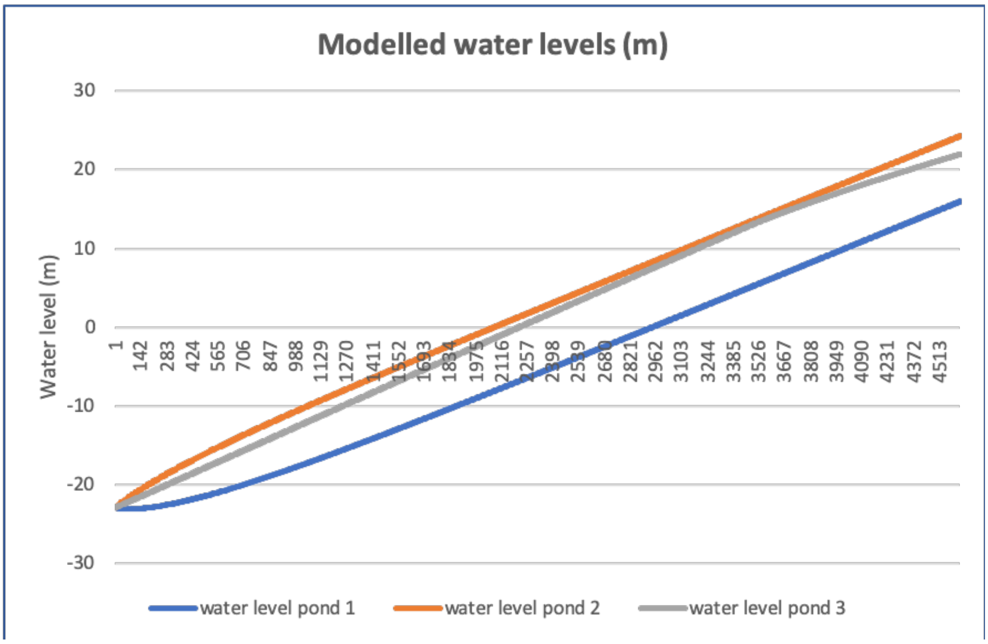

Figure 21 – example of the final model output for water levels when constructing the numerical model in Excel.

Figure 22 shows the discharge rate through the connections as well as the direction at which discharge occurs through the connection. The positive/negative values indicate the direction of spillage between the ponds. For example, the discharge through connection 1 flows to pond 1 rather than forwards to pond 2. This implies that the abstraction at Kibblesworth has an influence on the discharge to and from pond 2, which is important for understanding the impacts of the pumping regime on the pond system.

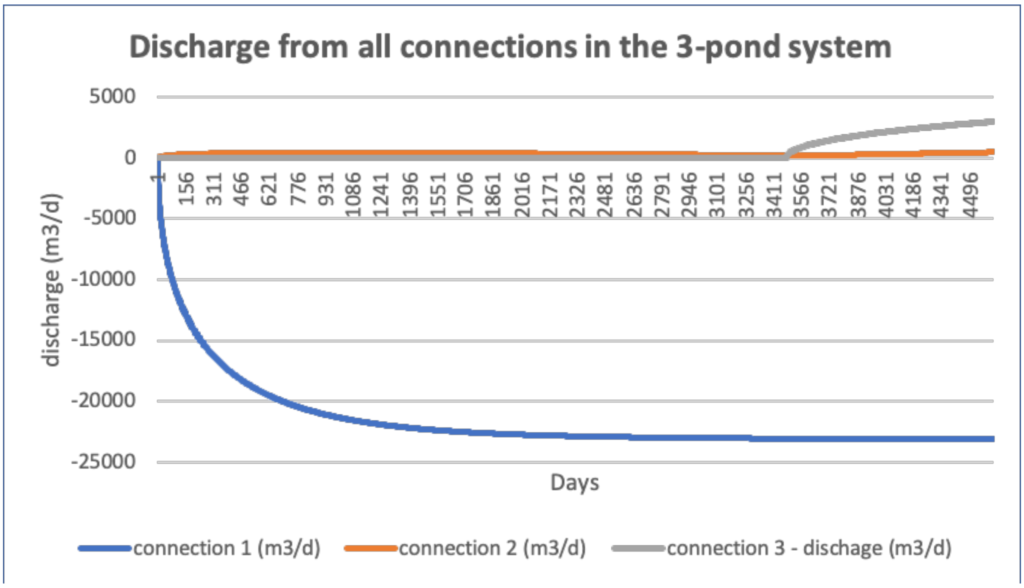

Figure 22 - example of the final model output for discharge when constructing the numerical model in Excel.

Figure 23 demonstrates another way of explaining how the abstraction at Kibblesworth (pond 1) influences the direction of discharge through the connection between the ponds and the discharge to and from Marley Hill (pond 2). The discharge through connection 3 in figure 22 represents the expected behaviour of discharge at the surface once the elevation reaches the threshold of 13 mAOD, which was determined as the potential point of discharge in Watergate (pond 3). Ensuring that the model was behaving as expected and provided acceptable outputs was a critical step in the process of constructing a numerical model. Otherwise, the process of estimating water level rise and predicting mine water rebound would be inaccurate and misrepresented.

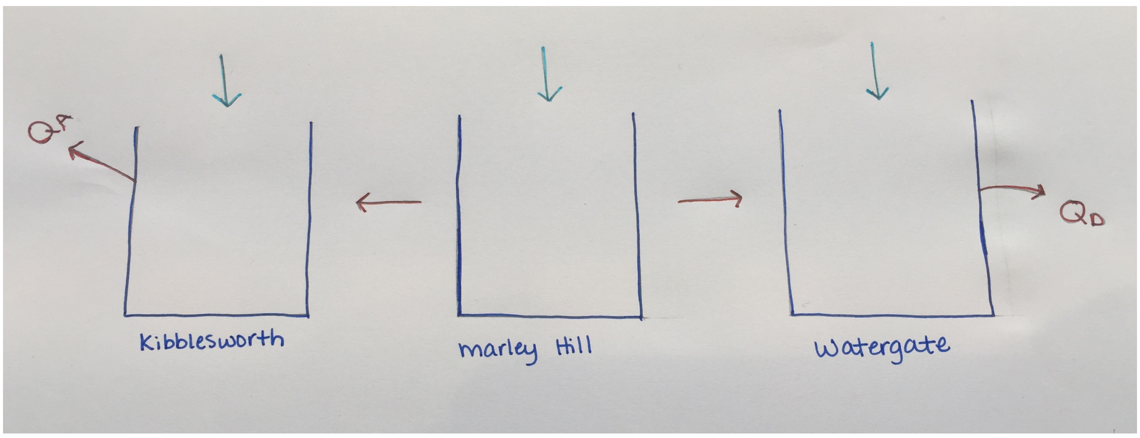

Figure 23 – conceptual model of the pond connection system as shown in figure 22 and demonstration of the influence of abstraction at Kibblesworth on the direction of discharge and of discharge to and from Marley Hill.

4.2 Calibrated numerical model of water level rise

Figure 24 shows the final calibration of the modelled water levels against the observed water levels at Kibblesworth. The model was calibrated using the parameters in tables 9 and 10. The initial water level in pond 1 was known based on the observed water level data. The initial water level for the other two ponds was unknown and was assumed to be the same as pond 1. The pond recharge area and total pond areas were calculated in the conceptual model section using data provided by the Coal Authority in ArcMap. The input from the Lumley mine water block was unknown and thus is an arbitrary value. As mentioned, the runoff coefficient was determined by assuming 70% impervious cover.

Table 9 – parameters used in the final calibrated model for the 3-pond system. The areas were calculated in ArcMap. Values for the input from Lumley, runoff coefficient, and initial water levels were estimated and the storage coefficients were calibrated.

Number	Pond	Recharge area (m2)	Pond area (m2)	Storage coefficient	Initial water level (m)	Input from Lumley (m^3/d)	Runoff coefficient
1	Kibblesworth	10,749,861.00	4,652,609.00	0.072	-22.89	14800	0.7
2	Marley Hill	34,972,087.00	6,816,132.00	0.58	-22.89	-	-
3	Watergate	6,866,684.00	2,834,347.00	0.362	-22.89	-	-

The connections between ponds were defined in section 3.2.3. The height of each connection was determined using a topographic map and an in-seam coal seam levels shapefile. The length and diameter values were given in the attribute tables for the roadway shapefile. The roughness coefficient was assumed based on a paper by Gandy and Younger (2007) for another coalfield in England. However, this value was not used in the equation for estimating the discharge coefficient. The resulting discharge coefficients were calculated using the Darcy-Weisbach formula to determine the flow and direction through the pond interconnections.

Table 10 – parameters for the discharge connection points used in the final model. The length, diameter, and heights were estimated using data provided. The discharge coefficient was calculated using the Darcy-Weisbach formula.

Number	Connection	Height (mAOD)	Length (m)	Diameter (m)	Roughness Coefficient (m)	Type	discharge coefficient
1	Kibblesworth-Marley Hill	-74	333.59	1.38	0.012	roadway	0.79
2	Marley Hill-Watergate	-72	485.974	1.002	0.012	colliery	0.57
3	discharge to surface	13	-	-	-	-	0.98
4	Tyneside House	-	-	-	-	-	0.98

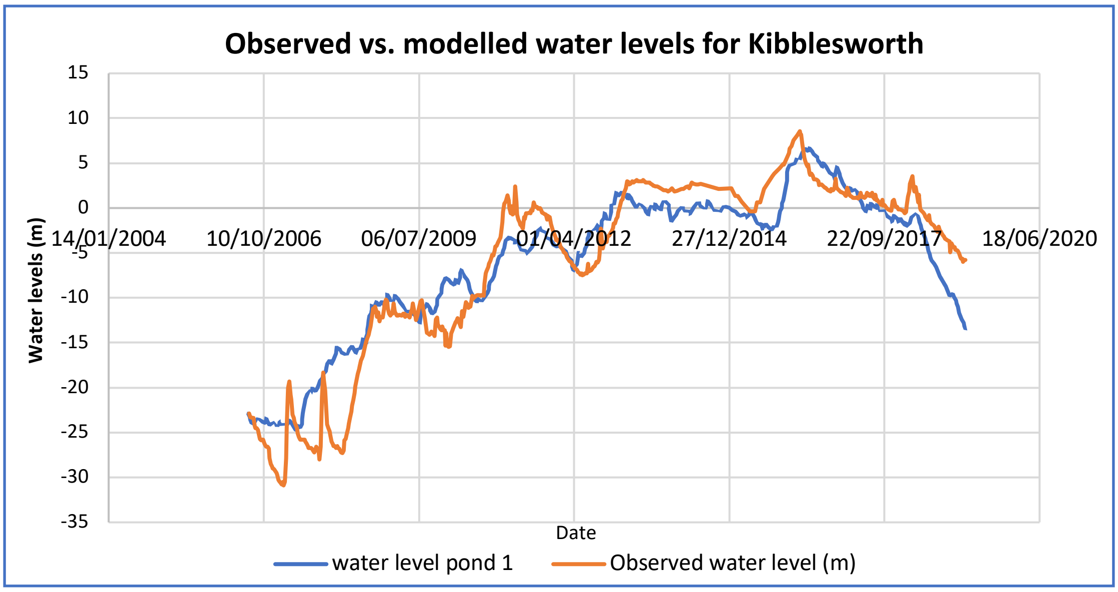

Figure 24 – calibrated simulation against the observed water levels using the parameters in tables 9 and 10.

Once the model was calibrated against the observed water levels at Kibblesworth, the parameters for the remaining two ponds and three connections were adjusted accordingly. In pond 2, the minimum discharge elevation was estimated using a topographic map to determine the calibration target of modelled water levels. This was done in place of having observed data. The water levels in pond 3 were calibrated based on the elevation for potential surface discharge. Figure 25 shows the modelled water levels for all three ponds, including the observed water levels at the Tyneside House across the River Tyne.

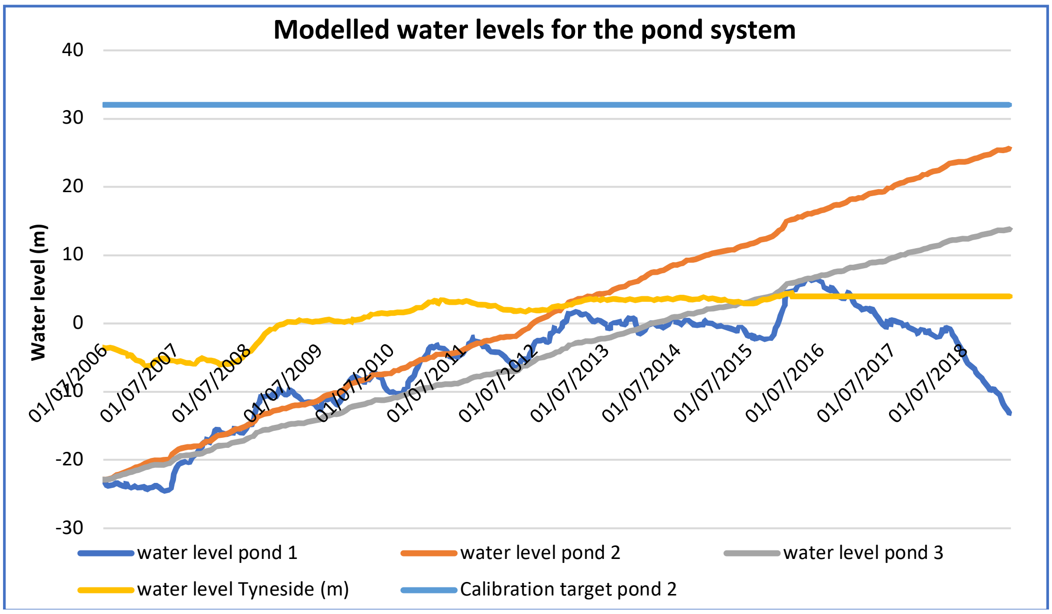

Figure 25 – modelled water levels for the pond system using the calibrated parameters.

The discharge through the pond interconnections are shown in figure 26. Connection 1 indicates that the water through the connection discharges into pond 2 in certain periods between 01/07/2008 and 01/07/2012 then discharges into pond 1 thereafter. Connection 2 indicates that water through that connection discharges into pond 3 at a steady rate because of the positive direction. Connection 3 shows that the discharge through the connection is zero until it reaches the surface discharge elevation of 13 mAOD around mid-late 2018. Connection 4 demonstrates that discharge from the north of the River Tyne discharges into the pond system but then discharges into the Newcastle area after 01/07/2015. In other words, the Tyneside is dewatered due to the influence of abstraction in the pond system until it reaches a net discharge.

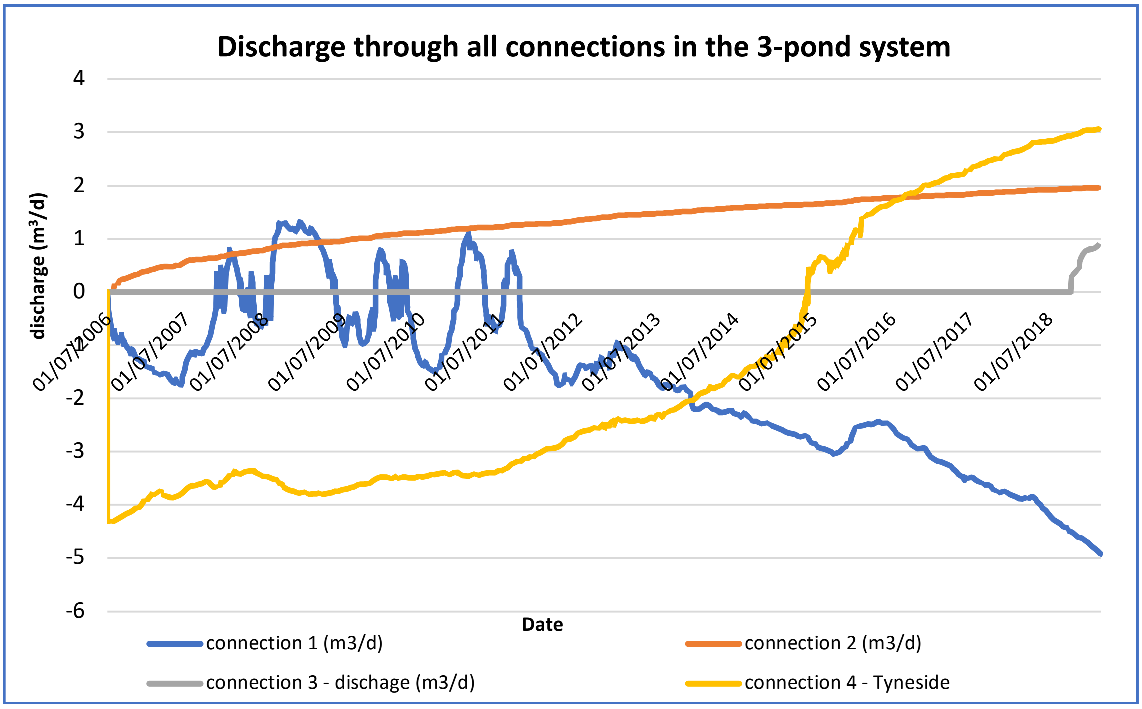

Figure 26 – discharge through the pond interconnections based on the calibrated parameters and water levels.

The discharge through the connections provides some insight into the relationship between abstraction and water levels in the abandoned mine system. It should be noted that the discharge flow rates in the pond system are not well understood or monitored; therefore, the actual values of discharge as indicated on figure 26 may be inaccurate. Once the modelled water levels and discharge through the connections were modelled and the expected outcomes were analysed and verified, predictions of future mine water rebound were made.

4.3 Predictions of future mine water rebound

Predicting future mine water rebound is useful for evaluating the impacts of various recharge and abstraction regimes. The constructed numerical model can be used to model a range of predicted scenarios to estimate mine water rebound in the Team Valley, Gateshead area. However, in this report, only four scenarios are discussed. These scenarios are only predictions and are based on several assumptions and limitations in the conceptual and numerical model. However, they provide a basis for understanding the impacts of a changed pumping regime on mine water rebound.

4.3.1 Scenario 1

In the first scenario, rainfall remained consistent over the next few years, but the abstraction rates were reduced by half. Figure 27 shows the resulting water levels under this scenario up to the year 2023. If abstraction was reduced by half, the water levels in ponds 1, 2, and 3 would all exceed their threshold. This would result in an increase in water levels and may lead to an increase in surface discharges and flooding incidents. The discharge through the connections all increased by approximately 2 m^3/d but followed a similar pattern as the discharge in figure 26.

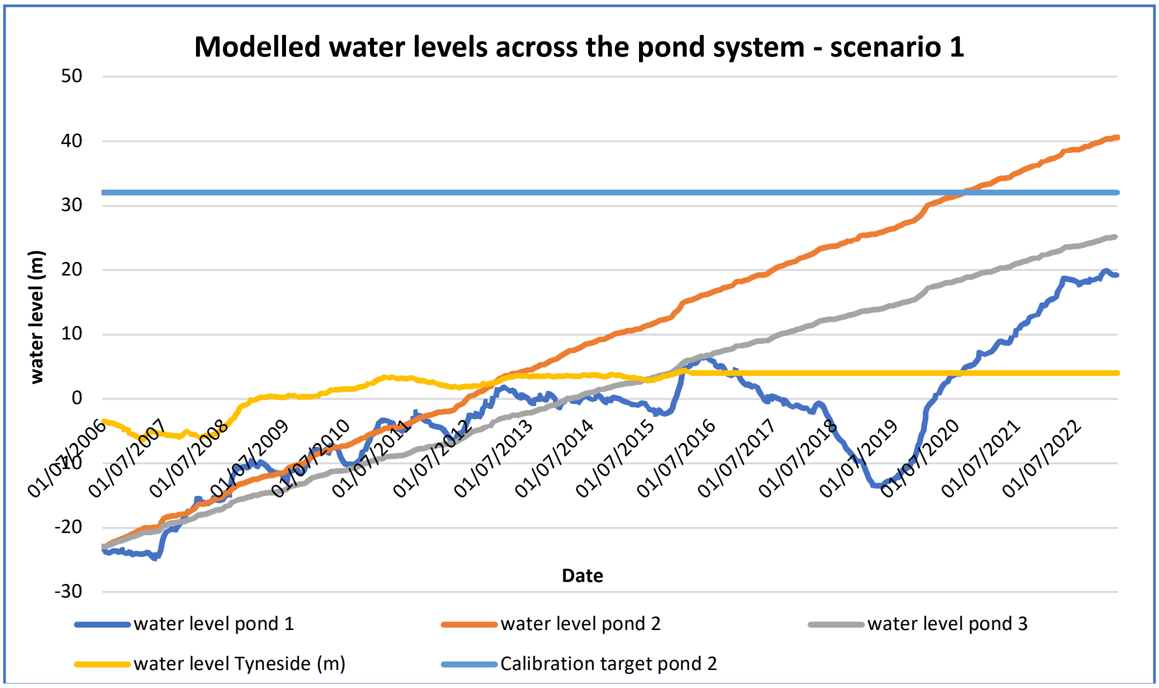

Figure 27 – model simulation of predicted water levels under scenario 1 with consistent rainfall and reduced abstraction.

4.3.2 Scenario 2

In the second scenario, rainfall increased by 20% compared to the previous four years and abstraction was assumed to continue at the current rates. The water levels in ponds 2 and 3 increased and exceeded their thresholds; however, the water levels in pond 1 remained constant. The discharge through all connections increased by approximately 0.4 m^3/d but followed a similar pattern as the previous models of discharge.

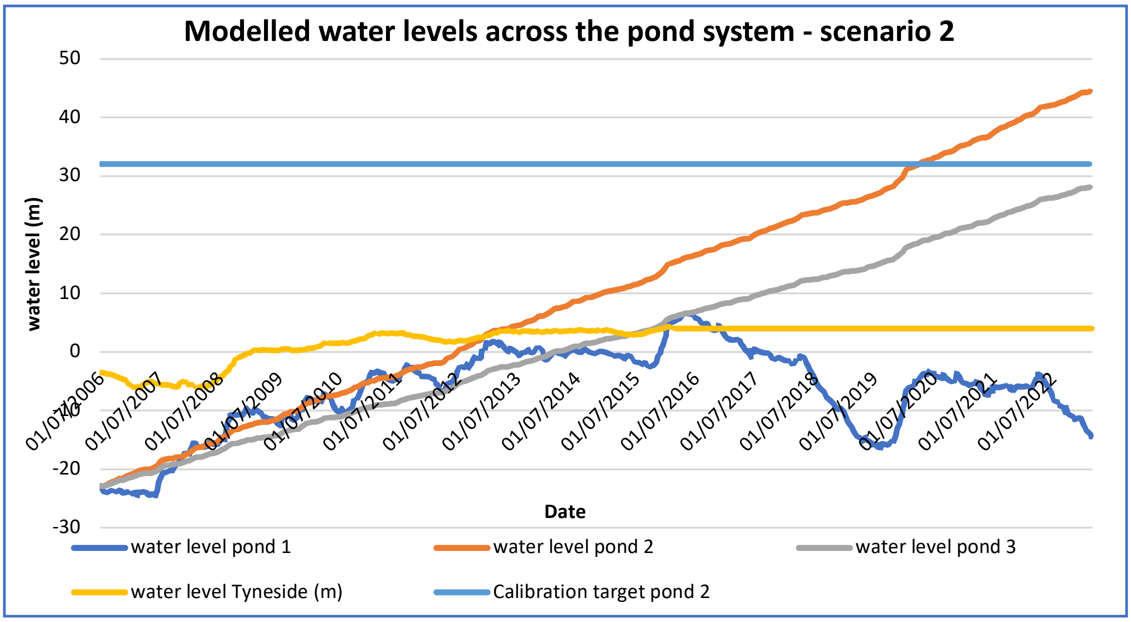

Figure 28 - model simulation of predicted water levels under scenario 2 with increased rainfall and continued abstraction at the current rates over the last four years.

This scenario indicates that rainfall may have an impact on the water levels in the pond system and may contribute to future mine water rebound if it increases as predicted with climate change. Figure 28 also indicates that the pumping at Kibblesworth has a major impact on the water levels in the immediate pond area. This figure also suggests that pumping at Kibblesworth may need to increase as recharge increases.

4.3.3 Scenario 3

In the third scenario, rainfall increased by 20% while abstraction decreased by half. Under these conditions, the water levels in all three ponds were expected to increase drastically. However, only the water levels in Kibblesworth increased drastically by about 45 m (figure 29). The water levels in ponds 2 and 3 still exceeded the threshold but remained consistent to those in figure 28. The discharge through the connections increased at a faster rate through Kibblesworth than through the other three connections, which may have an impact on the resulting water levels for ponds 2 and 3.

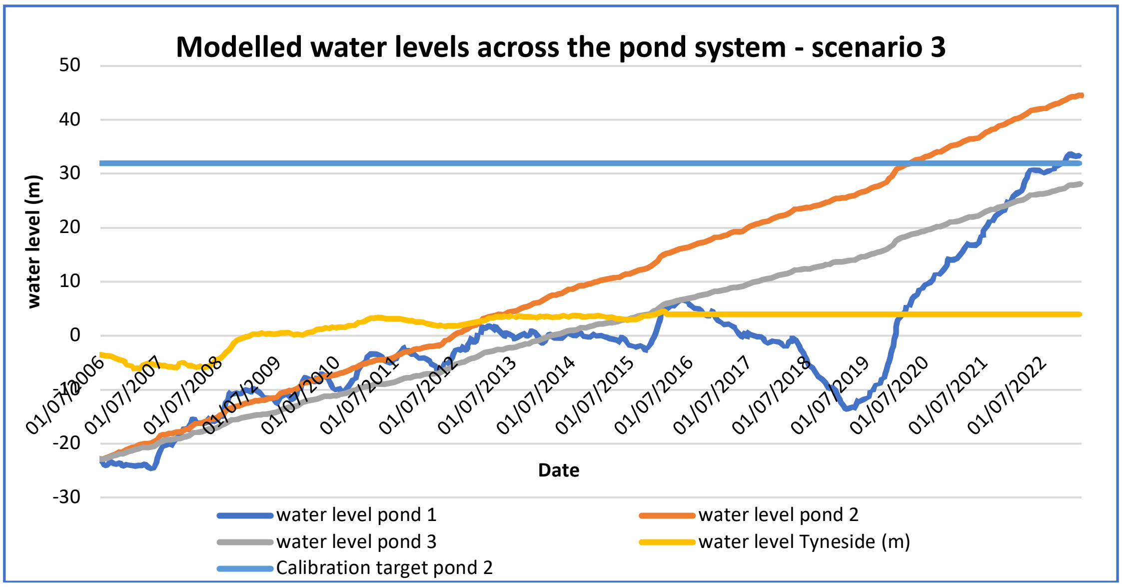

Figure 29 - model simulation of predicted water levels in the next four years under scenario 3 with increased rainfall and decreased abstraction.

4.3.4 Scenario 4

In the fourth scenario, rainfall increased by 20% and abstraction decreased slowly over time, which is likely to be the most realistic under the assumption that a decreased pumping regime is preferred. Over the next four years, abstraction was assumed to decrease by a quarter in the first year, half in the second year, and down to zero in the third and fourth years. Similar to the third scenario, the water levels in ponds 2 and 3 did not increase as much as expected. This pattern may indicate that the discharge coefficients of the interconnections are either unrepresentative of the mine system or that there are additional factors such as barriers in the mine workings, additional recharge or discharges, variations in the coal seams, or additional interconnections.

However, the water levels in pond 1 increased by an additional 10 m compared to those in the third scenario. This is expected under increased rainfall and a decrease in abstraction due to a greater recharge in the overall system. The discharge through connection 1 indicated a steady increase in discharge to pond 2 over the next four years.

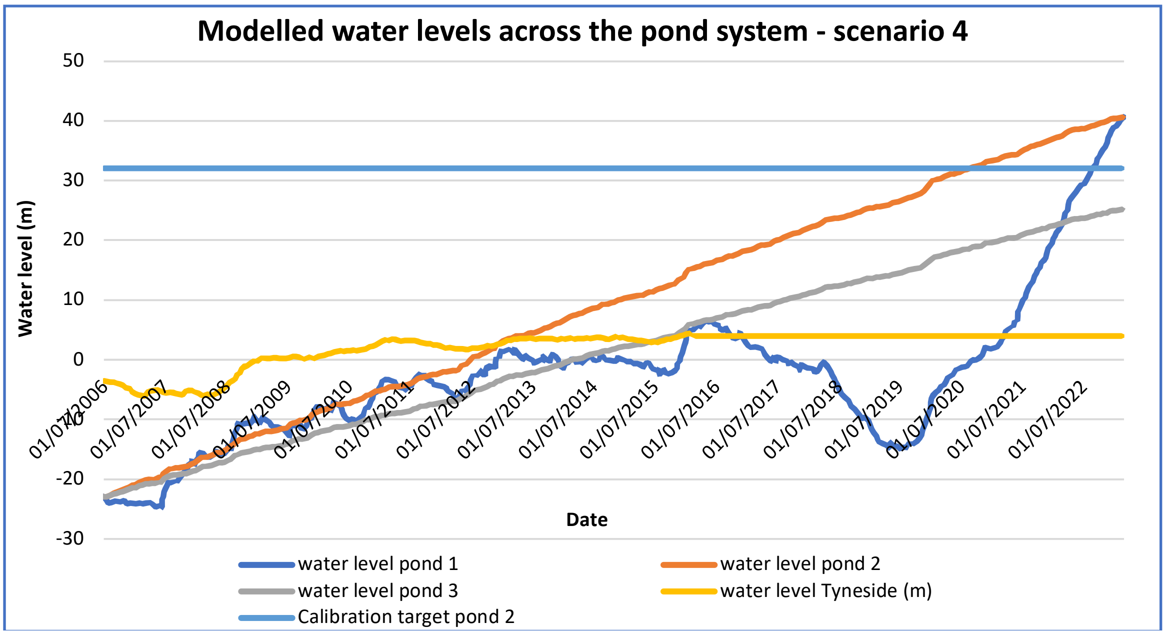

Figure 30 - model simulation of predicted water levels in the next four years under scenario 4 with increased rainfall and decreased abstraction over time.

This is expected if pumping is reduced because the water in pond 1 will have to discharge into the next pond under the concept of a multi-pond system. Figures 49-52 in Appendix C show the discharge through the connections under all four scenarios. All scenarios indicate that discharge at the surface in the Watergate pond has already occurred. This is due to the fact that discharge at the surface was already accounted for in the initial modelled simulation because flooding incidents have already been recorded in pond 3.

4.4 Estimating time taken to fully rebound in workings

Estimating the time taken for groundwater to completely rebound provides an insight into the impacts of coal mining on the hydrogeology of the area. The volume of underground mine workings and storage coefficients of the 3-pond system were necessary to determine the amount of floodable void space.

Table 11 shows the average pond volumes calculated using the areal extents and average thickness of the coal seams. Table 12 shows the parameters used in estimating the time taken for the workings in each pond to completely fill and result in rebound. The time taken for the Kibblesworth, Marley Hill, and Watergate ponds to completely fill the voids in the mine workings and rebound are 59, 653, and 147, respectively.

Table 11 – calculated volumes for each coal seam in each pond and average pond volume using thickness and area.

Ponds	Thickness (m)	Marley Hill	Watergate	Redheugh	Felling	Sheriff Hill	Ravensworth	Kibblesworth
	Volume of seams removed (m³)							
High Main	2	-	-	-	6,736,936	10,216,614	2,750,538	202,610
Top Main	1.6	-	-	-	-	51,542	1,179,606	-
Bottom Main	1.6	-	-	-	-	-	3,951,564	-
Maudlin	1	-	-	-	3,851,683	6,120,140	6,614,190	-
Durham Low Main	1.6	950,181	-	304,467	4,173,382	2,186,296	4,472,808	2,981,966
Brass Thill	1	761,998	-	-	3,142,979	6,336,320	6,071,955	7,962,445
Hutton	1.5	20,039,358	-	1,753,842	10,355,747	11,224,677	12,877,362	20,552,823
Harvey	0.8	2,180,980	3,679,882	1,911,599	2,305,438	4,972,501	1,562,794	463,150
Tilley	0.6	3,047,268	301,591	48,995	-	1,181,664	1,660,403	4,136,327
Top Busty	0.8	6,785,009	2,145,066	-	-	2,443,054	2,785,109	4,573,275
Bottom Busty	1	6,368,143	3,385,636	-	-	410,383	75,241	3,211,289
Three-Quarter	0.6	1,611,291	354,808	56,855	-	86,172	823,325	-
Brockwell	1	21,289,861	5,245,261	3,504,238	1,598,057	1,826,068	-	1,843,421
Average Total Pond Volume (m³)		**7,003,788**	**2,518,707**	**1,263,333**	**4,594,889**	**3,921,286**	**3,735,408**	**5,103,034**

The estimated values for the voids in the mine workings to completely fill and for rebound to occur are subject to several assumptions and limitations previously mentioned. Additionally, the calculation does not account for connections with other ponds and flow to other ponds. Kibblesworth would rebound earlier than the other two ponds, which may indicate the importance of the pumping regime.

Table 12 – parameters used to estimate time taken for workings in pond to completely fill and result in rebound.

Pond	storage coefficient	average pond volume (m³)	Max rate of inflow (m³/d)	effective volume (m³)	Time taken to rebound (days)
Kibblesworth	0.072	5,103,034	6,220	367,418	59
Marley Hill	0.580	7,003,788	6,220	4,062,197	653
Watergate	0.362	2,518,707	6,220	911,772	147

5.0 Discussion

5.1 Conceptual model for mine water rebound

The legacy of coal mining in the northeast of England has made a huge impact on the hydrogeology of the region. This is due to the fact that the underground mine workings alter the natural flow and characteristics of groundwater. Mine workings act as a series of aquitards and create a karstic and fractured type of aquifer environment, which introduces mine water rebound as a geohazard. Gateshead has experienced flooding at the surface due to mine water rebound. This geohazard creates several risks for current and new development, property, the water environment, and the local economy.

The development of a conceptual understanding of the mine workings is essential for understanding and predicting mine water rebound. The conceptual model provides a basis for understanding the seams worked within the study area, geometry of the underground workings, and interconnections of collieries and workings. Establishing the conceptual model prior to the development of the numerical model is essential because assumptions must be made about the system geometry and initial and final conditions.

The major assumptions are that 1) delineated zones of distinct permeability are inferred by mine plans and 2) external boundaries of the system are usually the boundaries of the mine workings but may also be geological features (Younger *et al.,* 2002). The assumptions and limitations in the conceptual model will impact the outputs of the numerical model; thus, it is important to develop a robust conceptual understanding.

5.2 numerical model for predicting mine water rebound

Construction of a numerical model for mine water rebound is useful for understanding the hydrogeological behaviour in the abandoned mine system. As opposed to GRAM, the numerical model created in this report comprises the flexibility for complexity to be added in future work. As mentioned, it should be well understood that numerical models in general are only approximations of the real world and should be used knowing how the associated assumptions and limitations impact the outputs. Due to time constraints, only three of the original seven ponds were modelled. However, it is predicted that water from the 3-pond system will act as recharge or discharge into the other ponds, which suggests that the rate of water level rise is subject to uncertainties relating to the defined pond system and interconnections.

Predicting mine water rebound under various recharge and discharge conditions may provide some insight as to how the climate and pumping regime impacts flooding at the surface. Additionally, estimating the rate of water level rise and the time taken for the voidage created by the workings to completely fill may be useful for understanding the impacts of mine water rebound on future development.

It should be noted that there are several other mechanisms of groundwater flooding that may contribute to the rise in water levels in the model. However, this report focuses on mine water rebound as a source of groundwater flooding and provides some insight into the importance of including mine water rebound in future flood risk management.

5.3 Mine water rebound assumptions and limitations

Several limitations and assumptions about the conceptual and numerical model have been discussed in section 4.0. However, some of the assumptions are further discussed here to provide an understanding of the limitations of predicting mine water rebound on a broader scale and potential solutions to improve the model.

First, one major assumption is that the storage coefficient is uniform throughout the pond but in reality, may have depth-zoned weighted averages, which means that the rate of water level rise will vary in the inter-seam intervals (Younger, 2016). One way to overcome the impacts of this assumption would be to calculate the rates separately for the worked seam and inter-seam intervals, develop a stepped profile of water level recovery, and/or develop a 3D conceptual model of the mine workings (Younger, 2016).

Second, the impact of drift deposits on recharge into the system was not considered in the model. However, the variation in drift deposits may have an impact on the amount of recharge regionally and may vary from one pond, or even sections of the pond, to another. One way to address this limitation is to add complexity to the numerical model by incorporating a recharge factor that accounts for the superficial geology.

Third, the discharge coefficients were estimated using an equation that was developed for a pipe system. However, the interconnections between ponds are roadways and mine adits, which may not be representative of a pipe. The discharge rates to and from the ponds are also not well understood and thus, were not modelled to accuracy in this report. Fourth, the recharge into the pond system was assumed to be uniform as a function of precipitation and evaporation but does not take into account seasonality. This suggests that the rate of water level rise and the occurrence of mine water rebound may vary seasonally and requires an additional factor in the numerical model.

One major limitation is the lack of understanding of the connections to the north and south of the overall pond system. There may be additional connections with collieries and ponds in the Newcastle or northern Durham coalfield area that may impact the rate of water level rise and/or water balance inputs and outputs in the 3-pond system (figure 31). When calibrating the model, it was determined that there were connections with the River Tyne and Lumley mine water block; however, the extent of the interconnection is still not well understood and may be incorporated into future work.

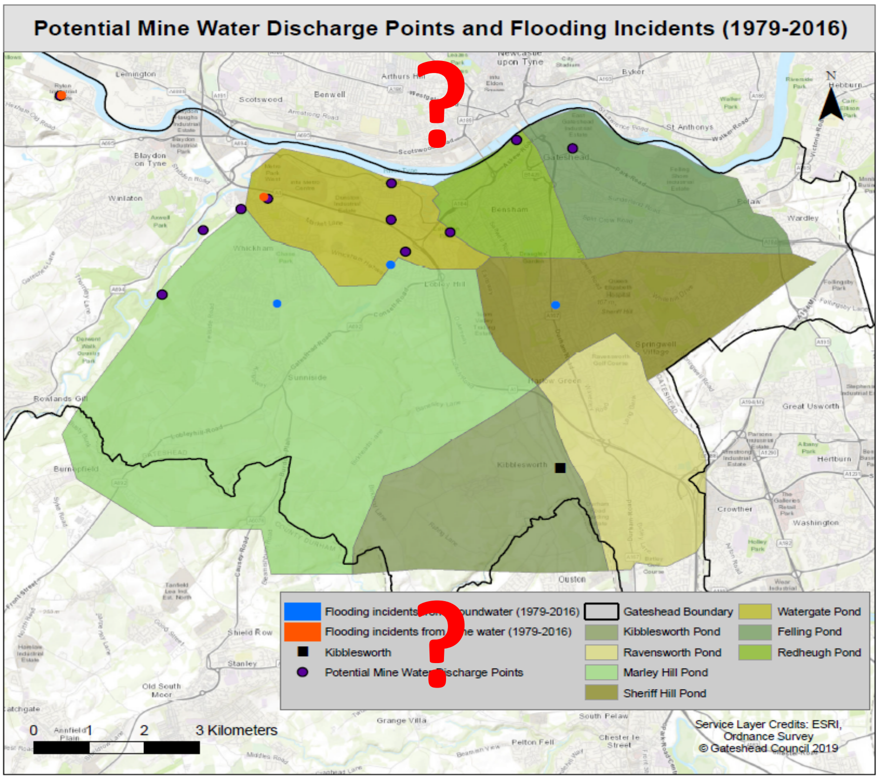

Figure 31 – map suggesting the lack of understanding of the connections to the north and south of the study area.

5.4 Importance of mine water rebound studies

Studies and literature relating to mine water rebound may be useful to consider when developing flood risk management schemes. In Gateshead, the flooding incident of 2015/2016 at JJ Stanley raised the awareness of groundwater flooding as a result of the coal mining legacy. Although the flooding incident occurred due to a pump failure, it suggests that mine water rebound would occur without continual pumping at Kibblesworth. The Coal Authority's interest in changing the pumping regime and the likelihood of an altered future climate due to climate change suggests the need for further investigation into mine water rebound and its impacts in Gateshead.

Many sites around Gateshead were visited on 29 July 2019 guided by a staff member at Gateshead Council. These site visits further suggest the importance of mine water rebound research in the Tyne and Wear district. Some of the sites include Redheugh Park, Clockburn drift mine, and the Kibblesworth pumping station. Figure 32 shows evidence of mine water rebound at Redheugh Park, which experienced a major flooding event in 2013. Figure 33 shows evidence of mine water rebound at the Clockburn drift mine through a pipe that was once used in the old collieries.

Figure 32 - evidence of mine water rebound at Redheugh Park (photo by Villasenor, 2019).

Figure 33 - evidence of mine water rebound through an old colliery pipe at the Clockburn drift mine site in Gateshead (photo by Villasenor, 2019).

Figures 34 and 35 represent the pumping shafts at Kibblesworth, for perspective. The evidence of mine water rebound at several sites around Gateshead suggests the need for further investigation and research. Understanding the causes of mine water rebound during each event may also be useful for developing preventative measures.

Figure 34 – mine water pumping station at Kibblesworth. Data in the numerical model was retrieved from these pumps (photo by Villasenor, 2019).

Figure 35 - sign showing the grid reference for the pumping station at Kibblesworth (photo by Villasenor, 2019).

Understanding mine water rebound is important for the design, implementation, and management of groundwater. Studies surrounding mine water research may be useful for determining groundwater control measures to mitigate geohazards and for preventing groundwater contamination. Sustainable Drainage Systems (SUDs) are one of the approaches for managing drainage in towns and cities by mimicking natural drainage patterns; these systems can intercept pollutants and reduce flood risk and are useful in urban design and planning (Environment Agency, 2006). SUDS may be useful for mitigating the effects of mine water rebound and is a point for discussion in future research surrounding mine water rebound as a geohazard and groundwater flooding.

6.0 Conclusion

Due to the legacy of coal mining in the northeast, Gateshead has a complicated set of mine water and groundwater issues. Historically, groundwater was pumped to artificially lower the water table for coal mining activities. After the abandonment of coal mines and the cessation of mine water pumping, rebound started to occur at coal mines across the country. Today, mine water is pumped at the Kibblesworth pumping station to prevent mine water rebound and groundwater flooding at the surface. However, the Coal Authority will be exploring cost-effective and sustainable alternatives to the pumping regime. This suggests the need for and importance of investigating the potential impacts of a changed pumping regime on Gateshead.

A conceptual model must first be developed prior to the development of a numerical model to provide a conceptual understanding of the geological and hydrogeological influences on mine water rebound and of the underground mine workings. In this report, the conceptual model provides an understanding of the geometry of the mine workings, area and volume of the underlying coal seams, pond system, inputs/outputs of the water balance, and interconnections in the pond system. These variables are required as inputs into the numerical model and thus, largely influence the outputs.

GRAM was the intended numerical model to be used in this report. However, due to several errors and the lack of flexibility, an alternative numerical model was constructed in Excel. The constructed model allows for complexity to be added for future work and uses relating to mine water rebound in Gateshead. A 3-pond system was used for simplicity using the Kibblesworth, Marley Hill, and Watergate ponds. The outputs of the model suggested that the pumping at Kibblesworth has a large influence on the amount and direction of discharge to and from the Marley Hill pond.

Additionally, the results suggest that changes in the pumping regime and climate will impact the water levels at the Kibblesworth pond and its immediate surroundings at a faster rate compared to other mine water blocks. It was also determined that the interconnections largely influence the outputs of the model. However, there is still a lack of understanding of the major connections to the north and south of the study area, which may impact the rate of water level rise and occurrence of rebound in Gateshead.

As with any numerical model, it is important to note that there are several assumptions and limitations. Overall, the outputs are only approximations of the real world and are limited to the complexity of the inputs. In this report, some of the major assumptions were that 1) the pond interconnections were representative of a pipe system, 2) the storage coefficient was uniform across the pond, 3) recharge was uniform and did not account for seasonality, 4) the mine plans are only a snapshot in time and may not accurately represent the true geometry, and 5) the discharge coefficients themselves were based on several assumptions during calibration.

Understanding mine water rebound is important for the design, implementation, and management of groundwater. Research surrounding mine water rebound and groundwater flooding may also be useful for determining groundwater control measures, preventing groundwater and surface water contamination, and for planning of current and new development. North East England has long been synonymous with coal mining and the industry has historically had a huge impact on the region both economically and culturally. The impacts of mine water rebound are yet another legacy of this industry that looks set to last well into the future.

7.0 Future work and uses

7.1 Groundwater flood risk and susceptibility mapping

Groundwater flood mapping is of growing interest in the field of groundwater research and is used to describe the risks and susceptibility of an area to groundwater flooding. However, there is a lack of robust groundwater flood maps and those that exist only describe areas that may have groundwater emergence rather than details of the extents, depths and rates (Morris *et al*., 2018).

Current groundwater flood mapping techniques include the Groundwater Emergence Maps (GEM), national map of areas susceptible to groundwater flooding produced by the British Geological Survey, and a GIS-based technique based on the geology and hydrology (Smith, 2015). Incorporating mine water rebound into future groundwater flood mapping may be useful for determining areas at risk and susceptible to flooding from mine water rebound. Additionally, the development of a groundwater flood risk and/or susceptibility map for mine water rebound in Gateshead may be beneficial.

7.2 Modelling alternatives to the pumping regime

After discussion with Gateshead Council, it was determined that incorporating alternatives to the pumping regime as scenarios in the model may be beneficial. These scenarios may provide insight as to how an alternative to the type of pumping rather the rates can be more cost-effective and sustainable than the current regime.

One example of a potential scenario would be to model the rate of water level rise and rebound from gravity outflow as an alternative to the pumping regime around Norwood. This area discharges directly into the River Team, which may influence the recharge and discharge into and out of the pond system. Due to time constraints, these types of scenarios were not modelled in this project but are worth investigating in future work. It may also be useful to directly model the impacts of pump failures on the rate of water level rise, rebound, and on the overall water balance in the system, especially in light of the incident resulting from pump failure at Kibblesworth. Flooding resulting from pump failures suggests the importance of a pumping regime in Gateshead.

7.3 Understanding the overall pond system

In this report, only a 3-pond system was used in the numerical model for simplicity and due to time constraints. However, the geometry of underground mine workings suggests that there are several additional interconnections with other mine water blocks. For example, it was found that there was an additional input into the Kibblesworth pond from the Lumley mine water block, which has a major impact on the outputs of the numerical model.

For future work, it would be useful to understand why pumping in the Lumley mine water block stopped in 2008. The cessation of pumping at Lumley may have altered the pumping regime and the water balance of the pond system; therefore, it is worth incorporating into future work relating to mine water rebound in Gateshead. The methodology in this report can also be repeated for the entirety of Gateshead, which may provide a broader and deeper understanding of the interconnections and water balance across the region. The Blaydon area of Gateshead also has a history of known mine water rebound and thus, may be useful to incorporate into future research.

7.4 Project potential uses

The outputs of the numerical model may be useful for evaluating the effects of mine water pumping on the Team Valley. The results of this study also suggest the importance of incorporating mine water rebound into flood risk management plans and flood risk and susceptibility mapping. The conceptual model may provide a deeper understanding of the geological and hydrogeological influences on mine water rebound, which are the main drivers of the behaviour of groundwater in the system.

The constructed numerical model can be used to further investigate the potential impacts of various scenarios. The model allows for complexity to be added, which is a major advantage over the GRAM model. The outputs of this report can also be used as a comparison tool for the Coal Authority's mine water constraints map. Overall, this report can be used to gain a conceptual understanding of mine water rebound in Gateshead and of the impacts of abandoned coal mine systems on the hydrogeology.

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9.0 Appendix A

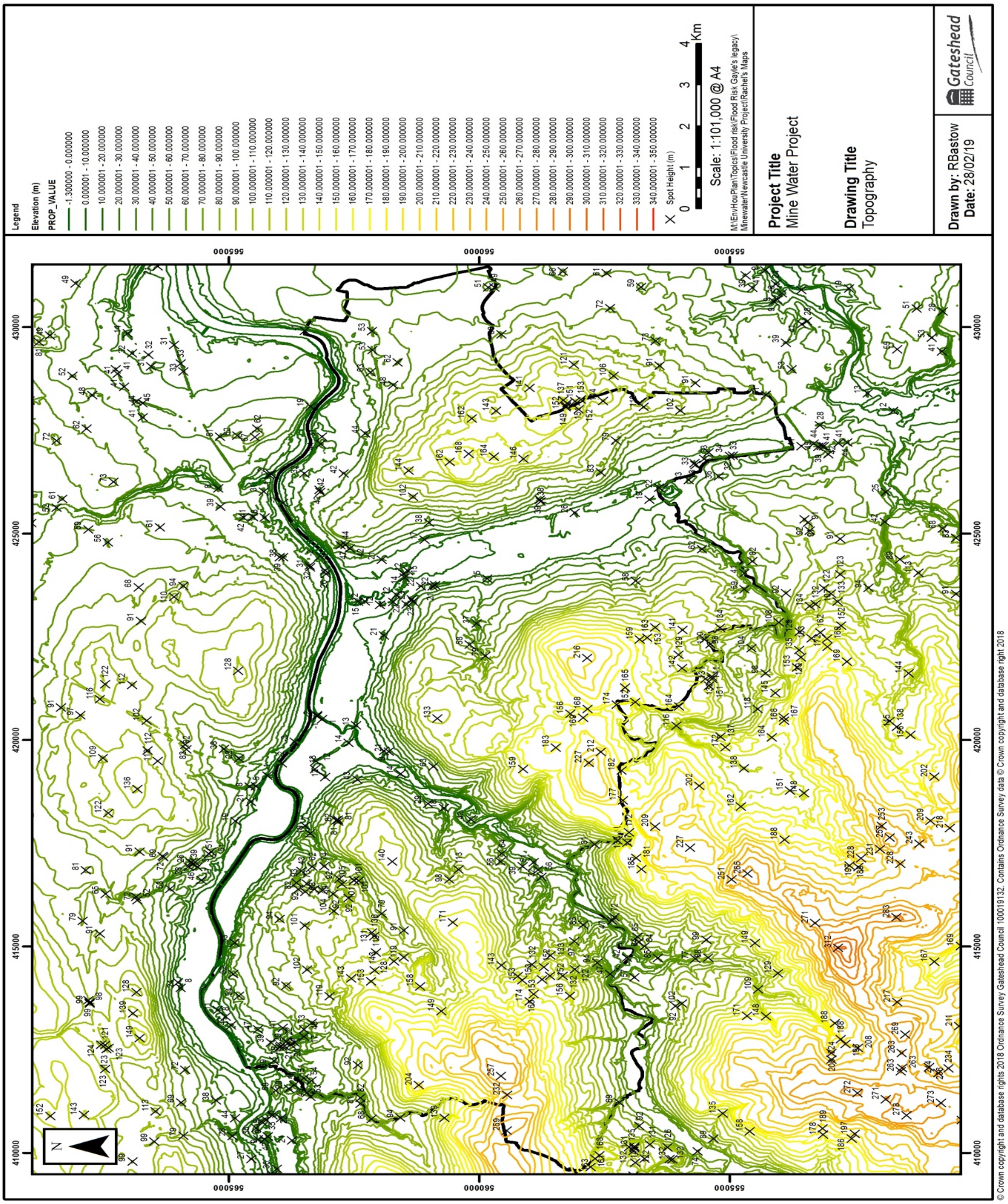

Figure 36 - contour map provided by Gateshead Council.

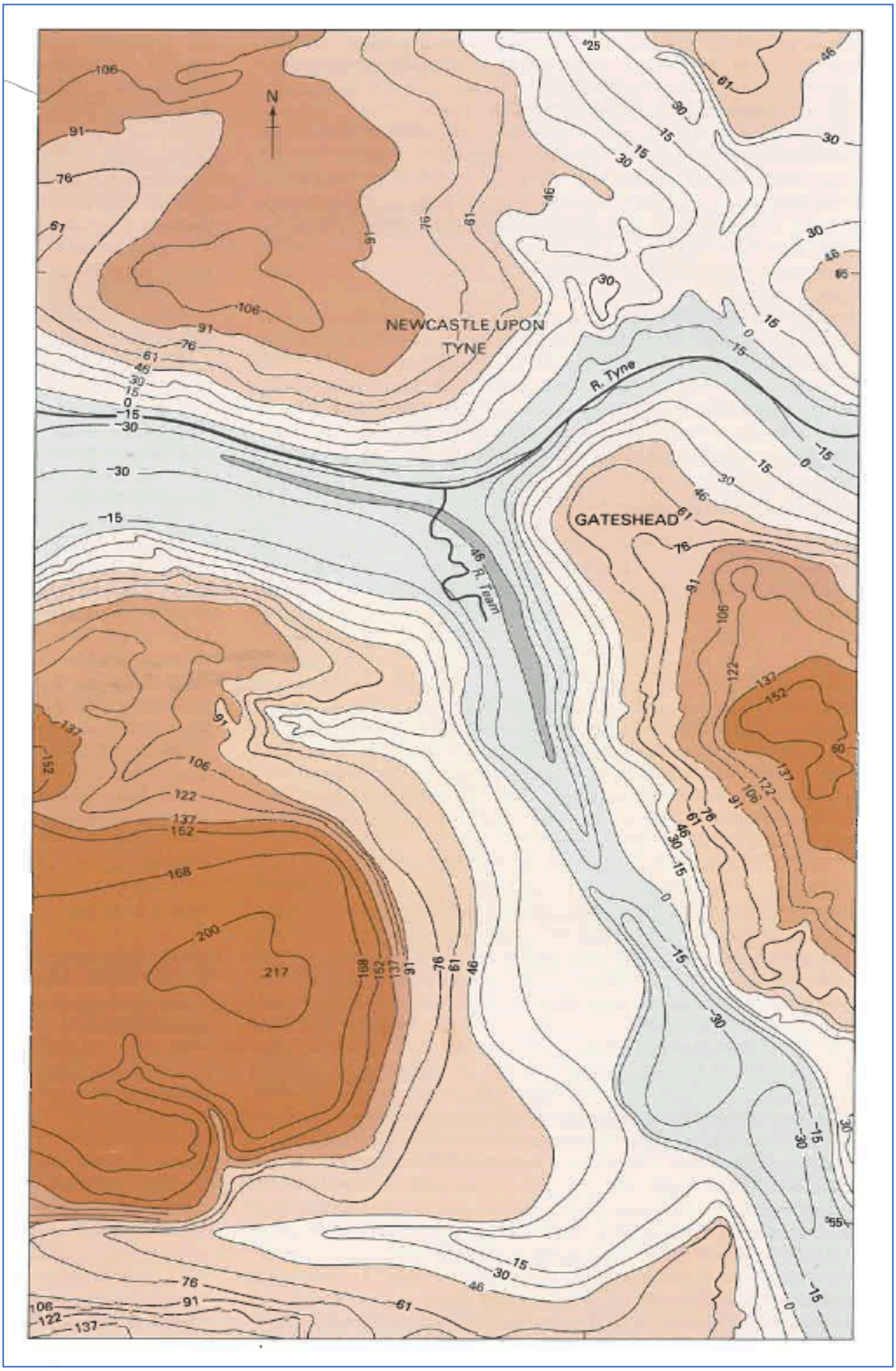

Figure 37 - Rock level contours for Newcastle and Gateshead. Buried valley deposits are present in the valleys in Gateshead between the 0-15 m contours.

10.0 Appendix B

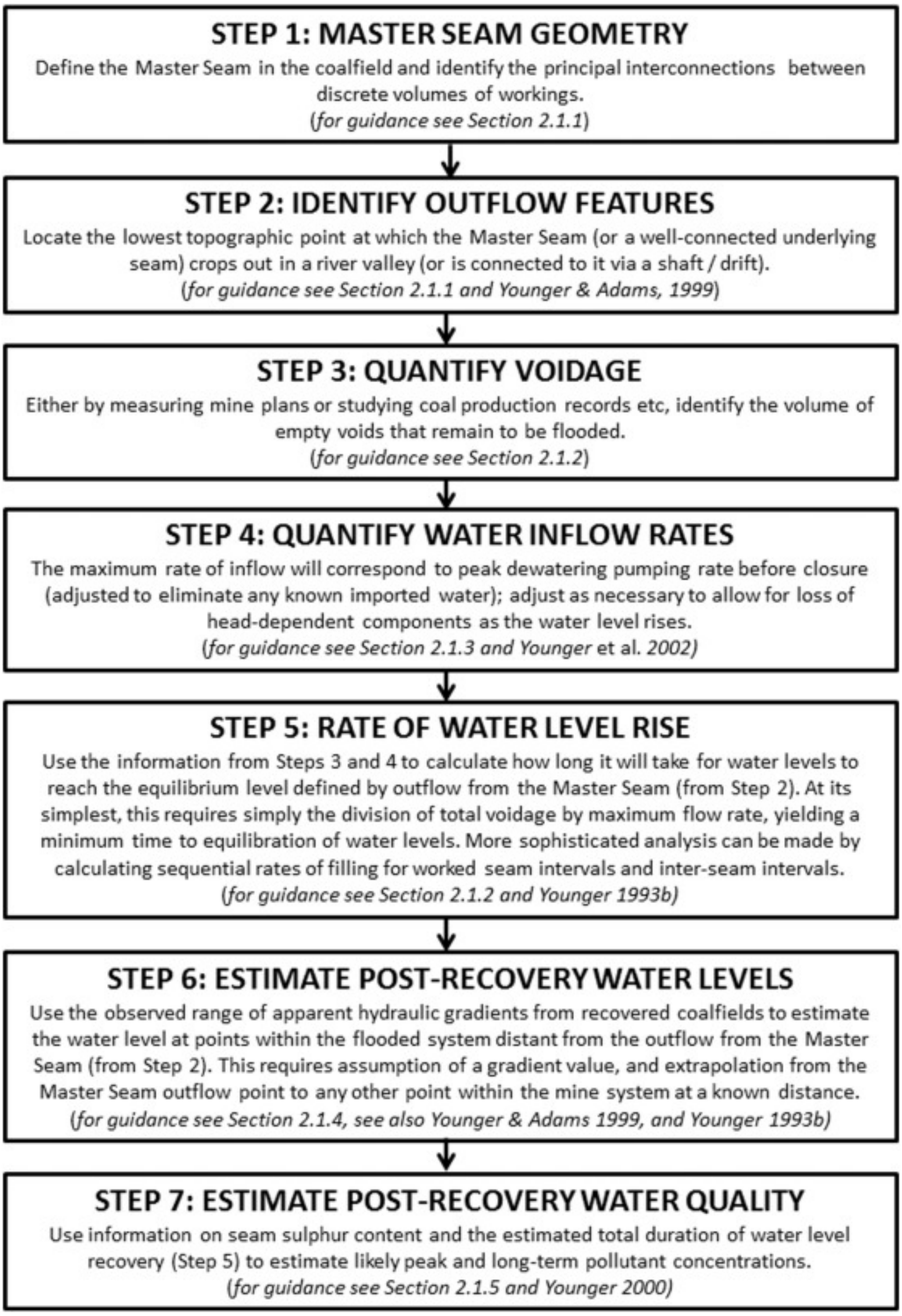

Figure 38 – Framework for assessing the post-closure hydrogeology of coal mines by Younger (2016). This methodology was used in this report to estimate groundwater/mine water rebound.

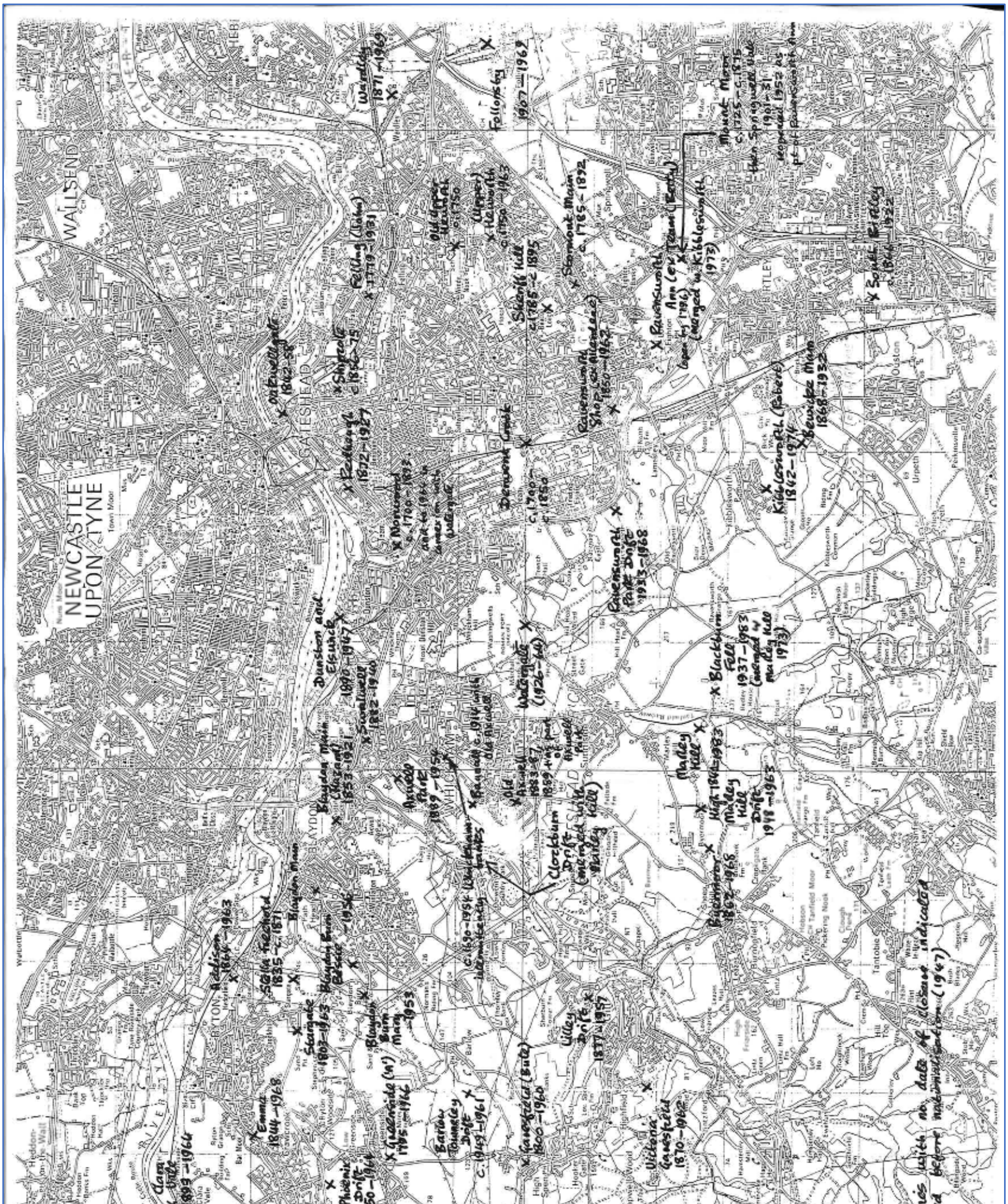

Figure 39 – Map of collieries with start and end dates provided by Gateshead Council.

Table 13 – List of collieries based on an image provided by Gateshead and Durham Mining Museum's online list of mines under the Coal Mines Act *and* Reid's Handy Colliery Guide including their location, years active, and coal seams worked.

Colliery Name	Location	Years active	Coal seams worked
Axwell Park	NZ202618	1889-1954	Beaumont, Brockwell, Five-Quarter, Stone Coal, Three-Quarter
Bewicke Main	NZ253561	1868-1932	Hutton, Low Main
Marley Hill	NZ206574	1842-1983	Brockwell, Busty, Hutton, Main, Three-Quarter, Brass Thill, Low Main, Tilley
Blaydon Burn	NZ166624	1872-1956	Barlow Field, Five-Quarter, Stone, Three-Quarter, Brockwell, Towneley, Victoria
Byermoor	NZ187571	1862-1968	Brockwell, Busty, Brass Thill, Three-Quarter, Tilley
Felling	NZ275624	1779-1931	Hutton, Low Main, Maudlin, Beaumont, Bensham, Six-Quarter
Garesfield	NZ139598	1800-1960	Brockwell, Five-Quarter, Stone, Barlow Field, Three-Quarter, Towneley, Ruler, Tilley
Victoria Garesfield	NZ145580	1870-1962	Brockwell, Five-Quarter, Stone, Three-Quarter, Tilley, Victoria
Emma	NZ144639	1844-1968	Brockwell, Five-Quarter, Stone, Three-Quarter, Tilley, Ruler
Swalwell	NZ205623	1882-1940	Brockwell, Five-Quarter, Tilley, Beaumont, Stone
Greenside	NZ139619	1795-1966	Brockwell, Five-Quarter, Stone, Three-Quarter, Tilley, Main, Ruler, Victoria, Towneley
Heworth	NZ284605	1750-1963	Beaumont, Bensham, Five-Quarter, High Main, Hutton, Yard, Six-Quarter, Hodge, Tilley, Three-Quarter
Kibblesworth	NZ243562	1842-1974	Five-Quarter, Hutton, Low Main, Main, Busty, Tilley, Maudlin, Brockwell
Stargate	NZ161634	1803-1963	Brockwell, Five-Quarter, Ruler, Stone, Three-Quarter, Tilley, Towneley, Hodge
Addison	NZ168643	1864-1963	Brockwell, Five-Quarter, Ruler, Stone, Three-Quarter, Tilley, Towneley, Marshall Green, Hodge
Redheugh	NZ244626	1872-1927	Brockwell, Busty, Harvey
Clara Vale	NZ132651	1893-1966	Brockwell, Five-Quarter, Stone, Three-Quarter, Tilley, Ruler, Towneley
Chopwell	NZ114586	1887-1966	Brockwell, Five-Quarter, Stone, Three-Quarter, Tilley, Hutton, Main, Towneley
Derwent	NZ123548	1700-1850	Hutton, Busty, Brockwell, Little, Main, Three-Quarter, Towneley, Thick
Dunston	NZ228625	1890-1947	Brockwell, Beaumont, Five-Quarter, Three-Quarter, Stone, Tilley, Busty
Ravensworth Shop	NZ257526	1850-1962	Beaumont, Hutton, Low Main, Tilley, High Main, Maudlin, Six-Quarter, Towneley, Busty
Burnhopfield	NZ173562	1742-1968	Busty, Main, Brass Thill, Hutton, Brockwell, Five-Quarter, Three-Quarter, Tilley
Tanfield Moor	NZ171545	1768-1948	Brass Thill, Five-Quarter, Hutton, Main

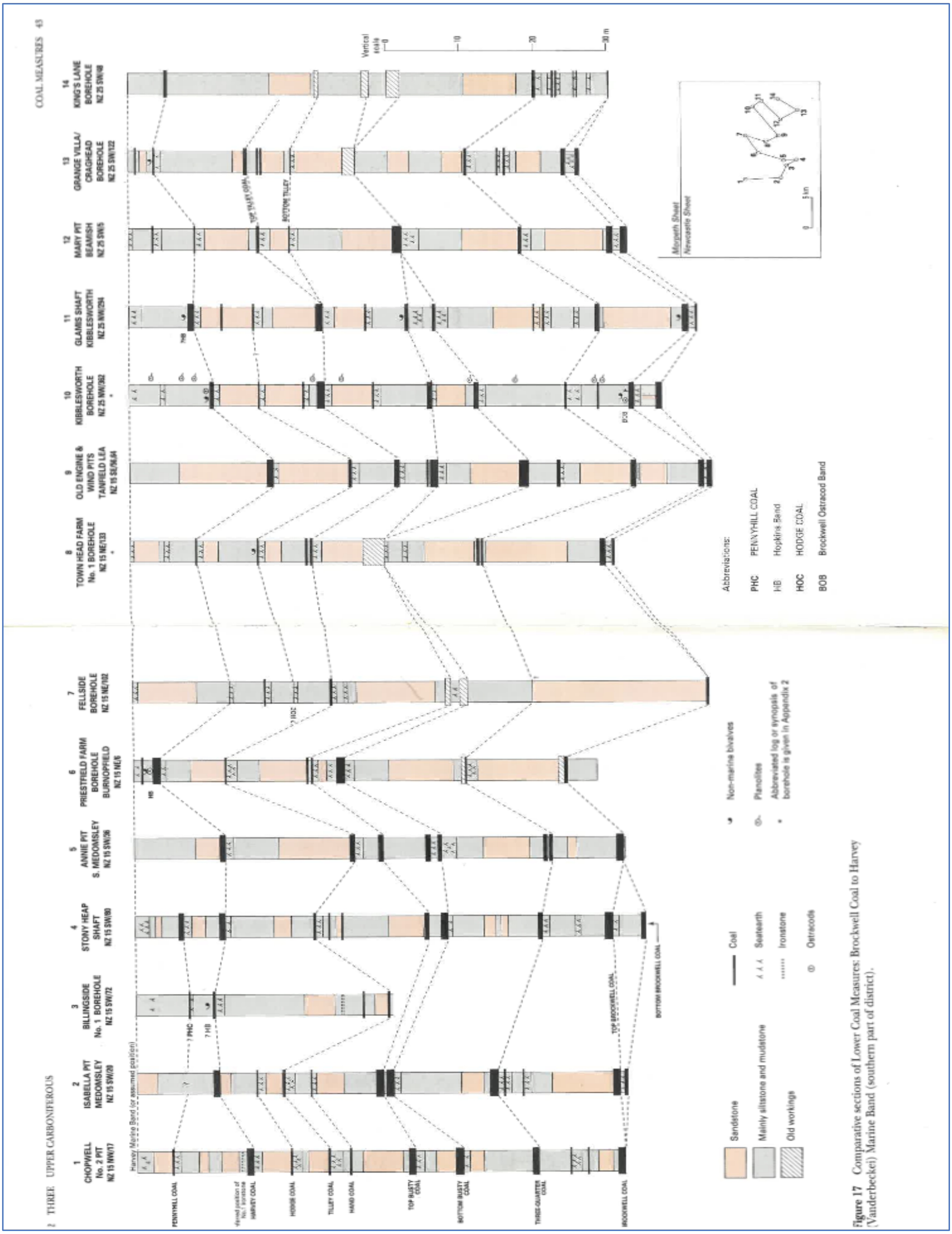

Figure 40 - Distribution of the Lower Coal Measures across several boreholes over Gateshead and Newcastle. Further comparisons for the Middle Coal Measures are shown in Richardson's (1983) Geological Notes for Newcastle upon Tyne and Gateshead.

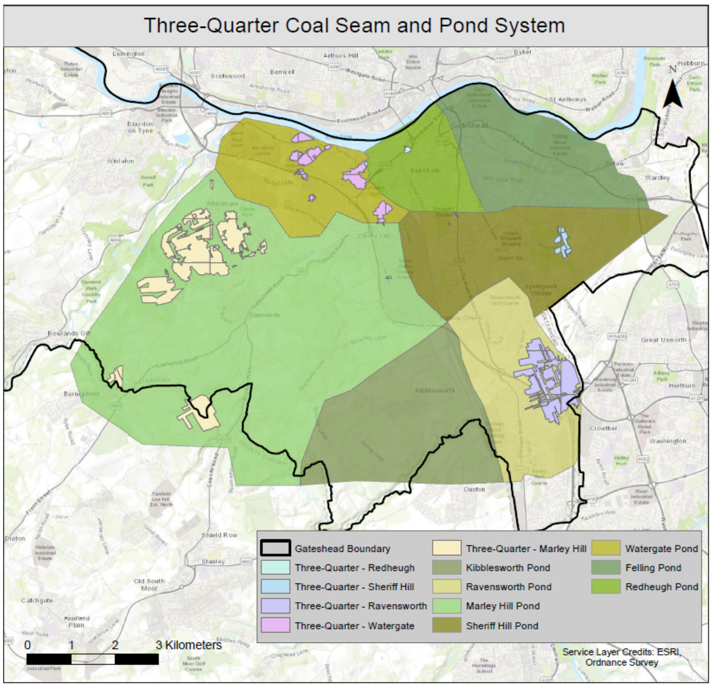

Figure 44 – spatial representation of the Three-Quarter coal seam across seven ponds.

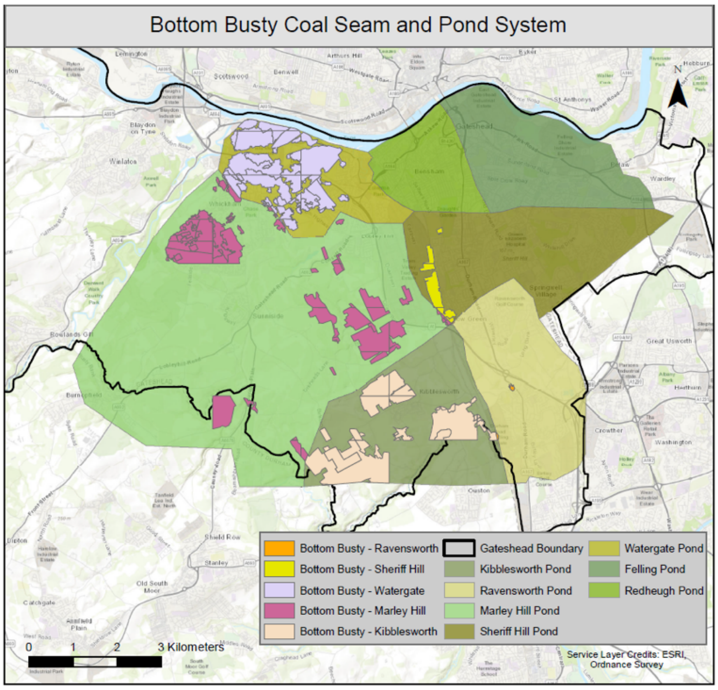

Figure 43 – spatial representation of the Bottom Busty coal seam across seven ponds.

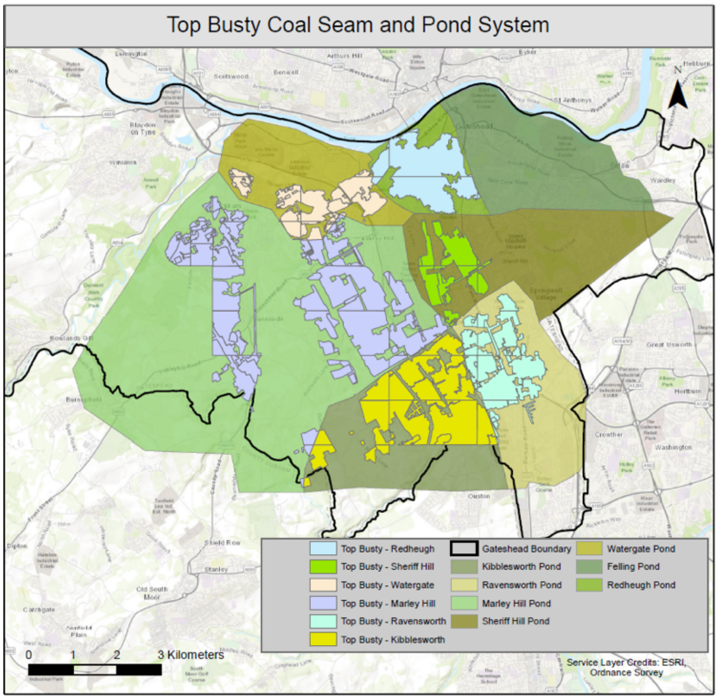

Figure 42 – spatial representation of the Top Busty coal seam across seven ponds.

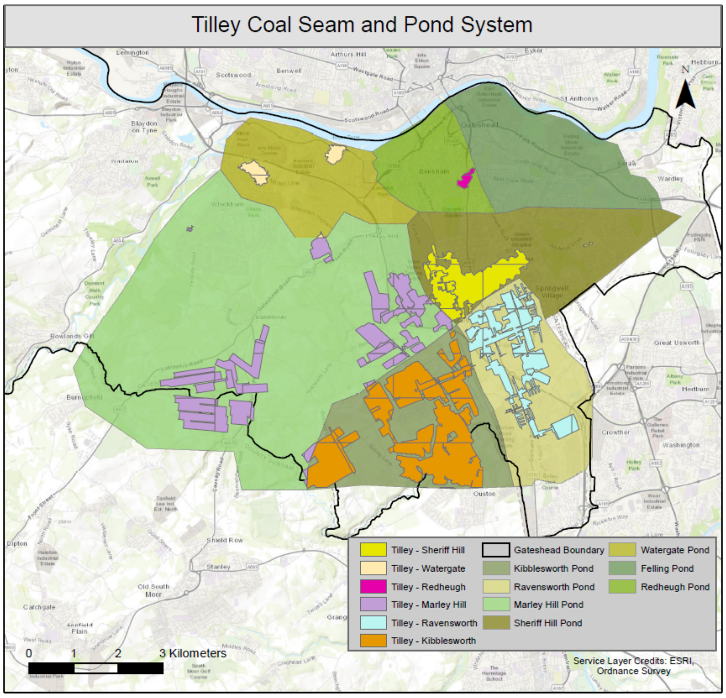

Figure 41 – spatial representation of the Tilley coal seam across seven ponds.

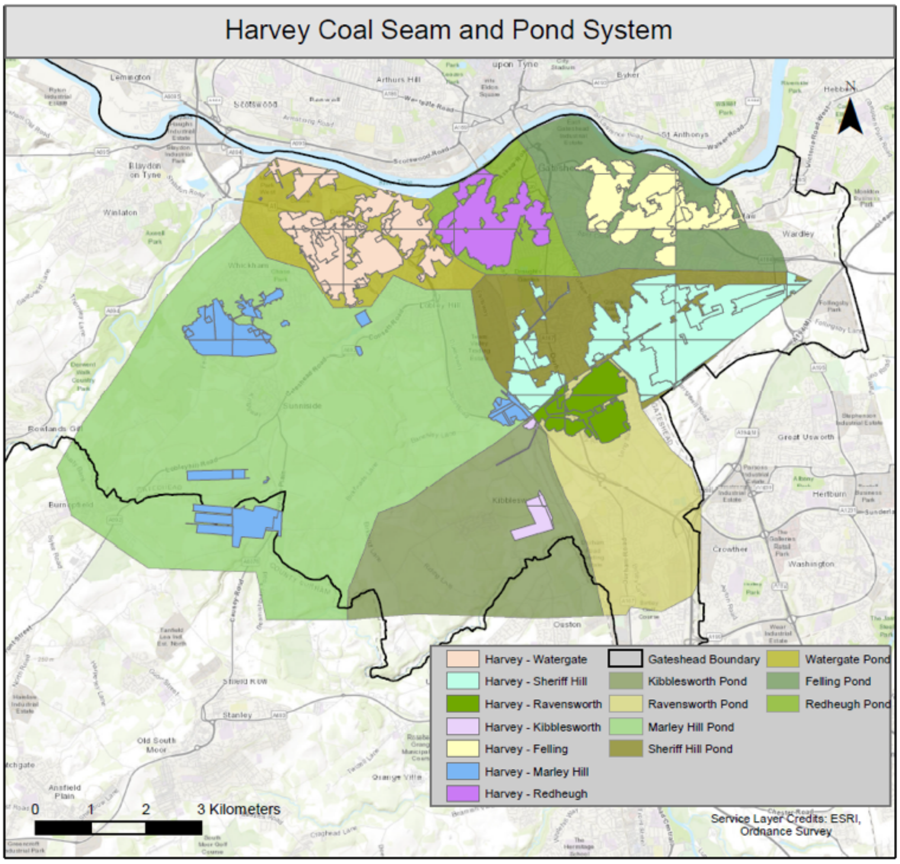

Figure 45 – spatial representation of the Harvey coal seam across seven ponds.

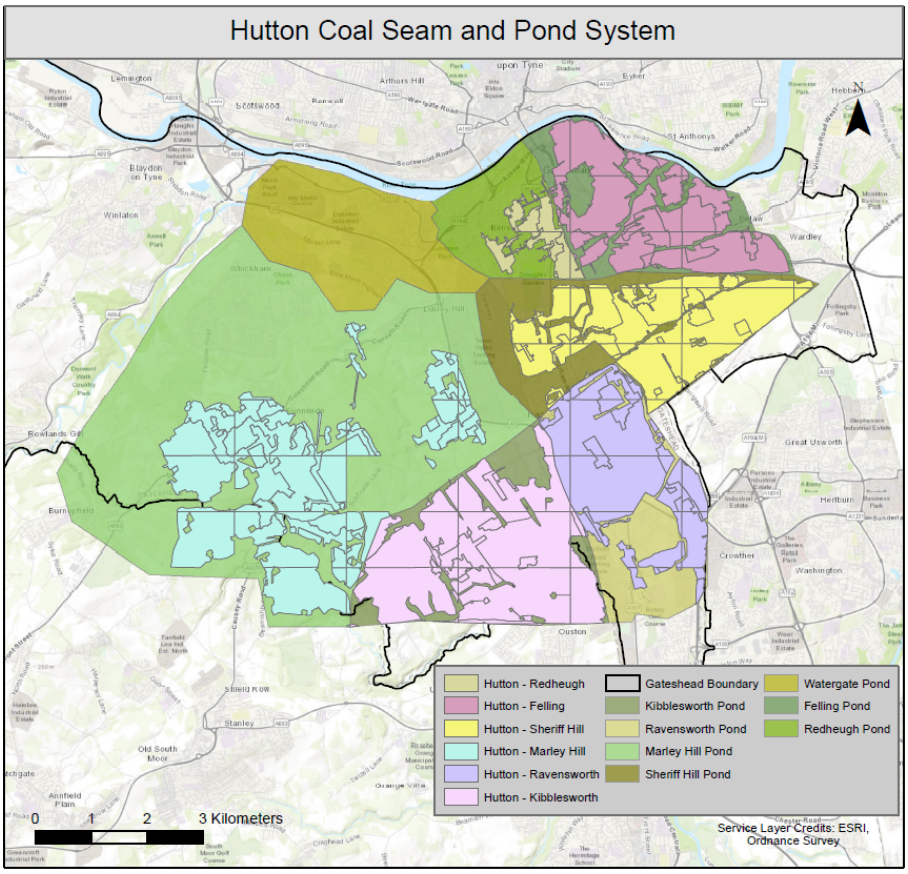

Figure 46 – spatial representation of the Hutton coal seam across seven ponds.

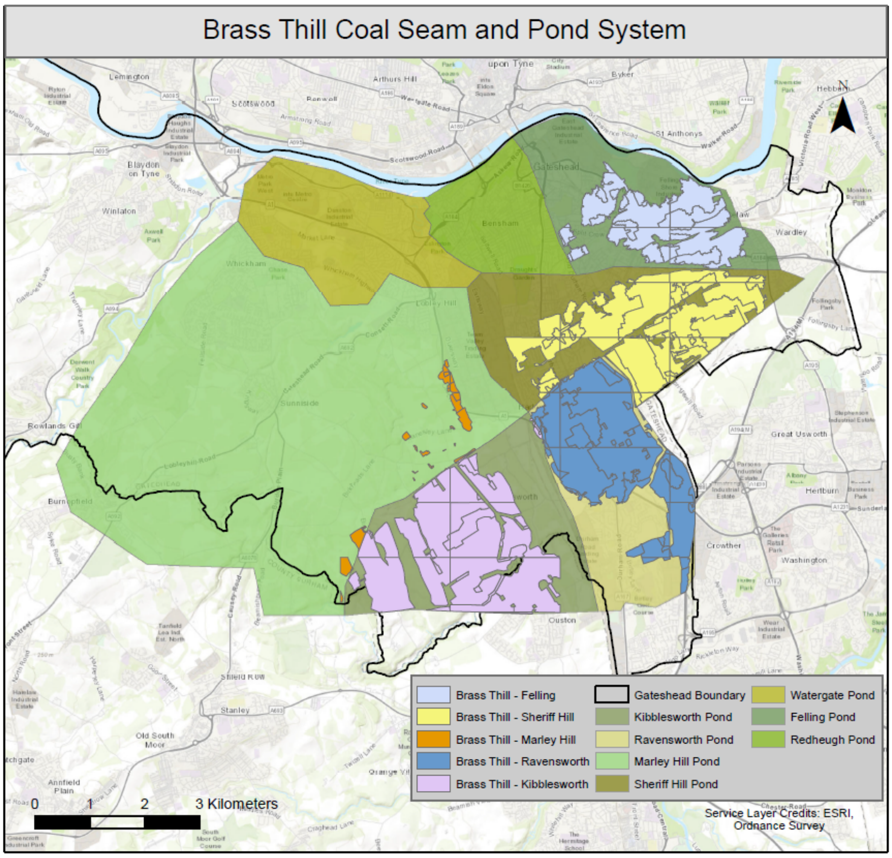

Figure 47 – spatial representation of the Brass Thill coal seam across seven ponds.

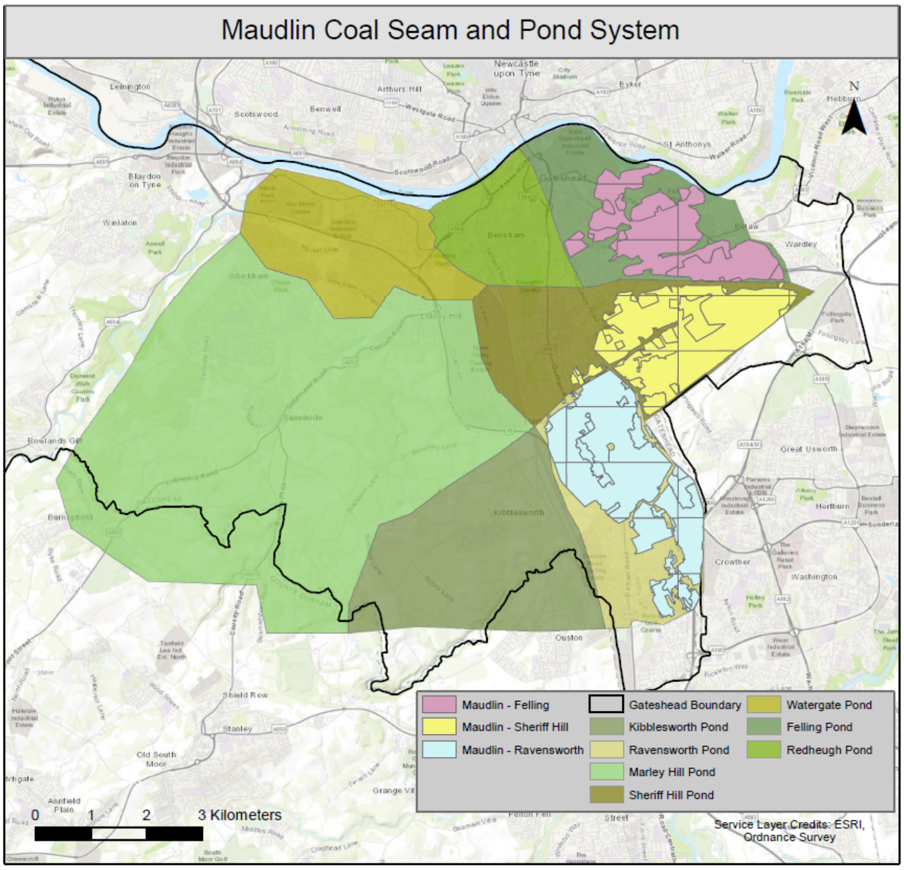

Figure 48 - spatial representation of the Maudlin coal seam across seven ponds.

11.0 Appendix C

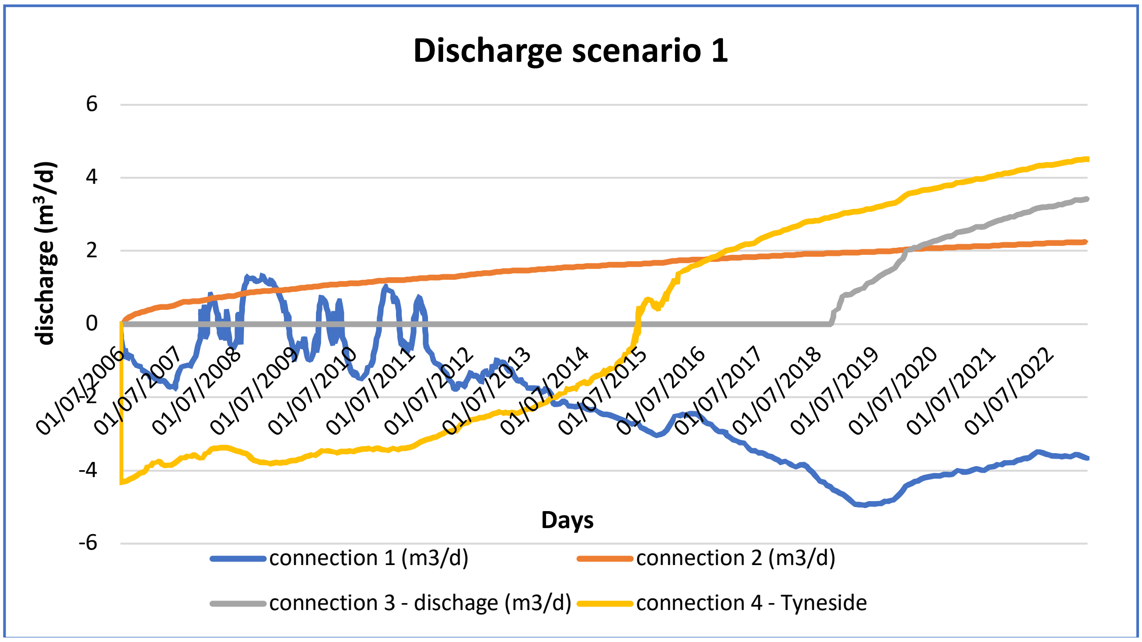

Figure 49 - Discharge output under scenario 1

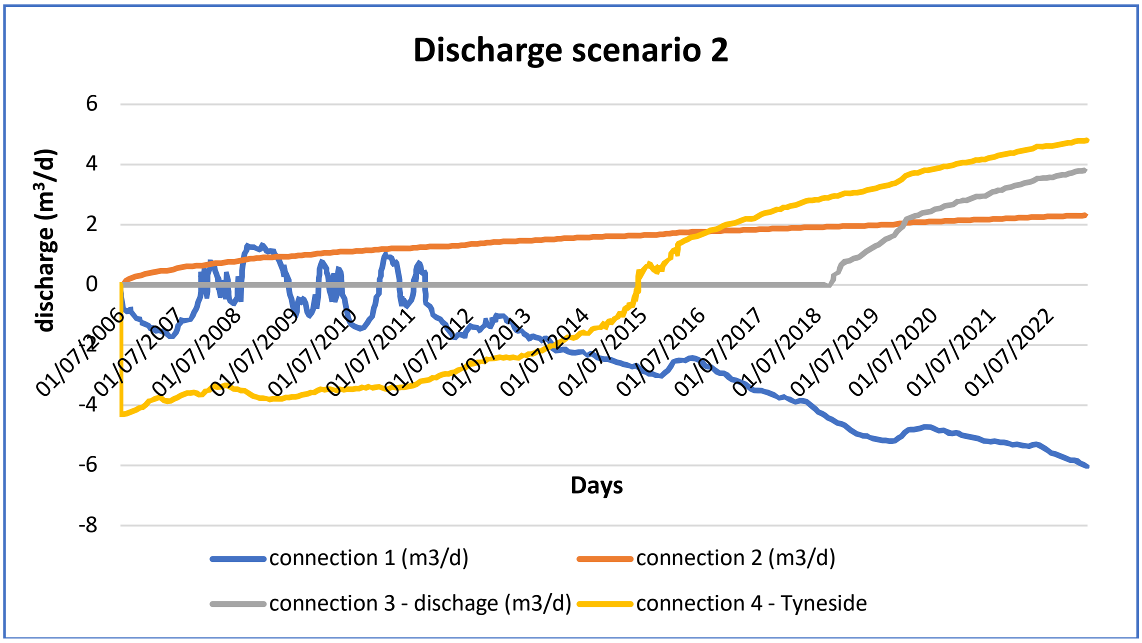

Figure 50 - Discharge output for scenario 2

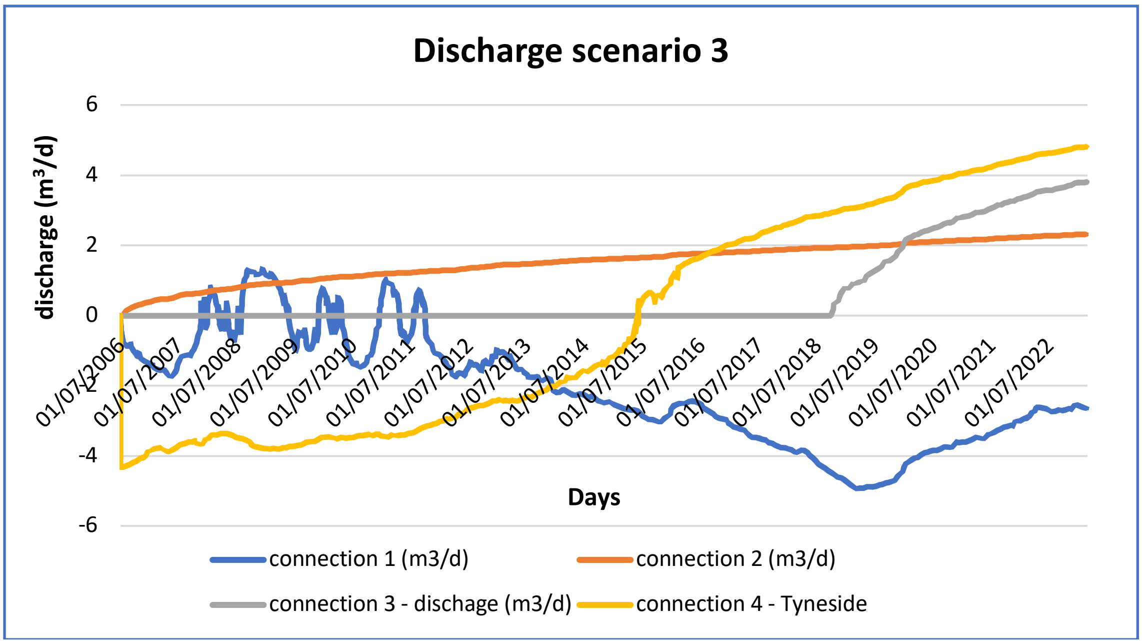

Figure 51 - Discharge output for scenario 3

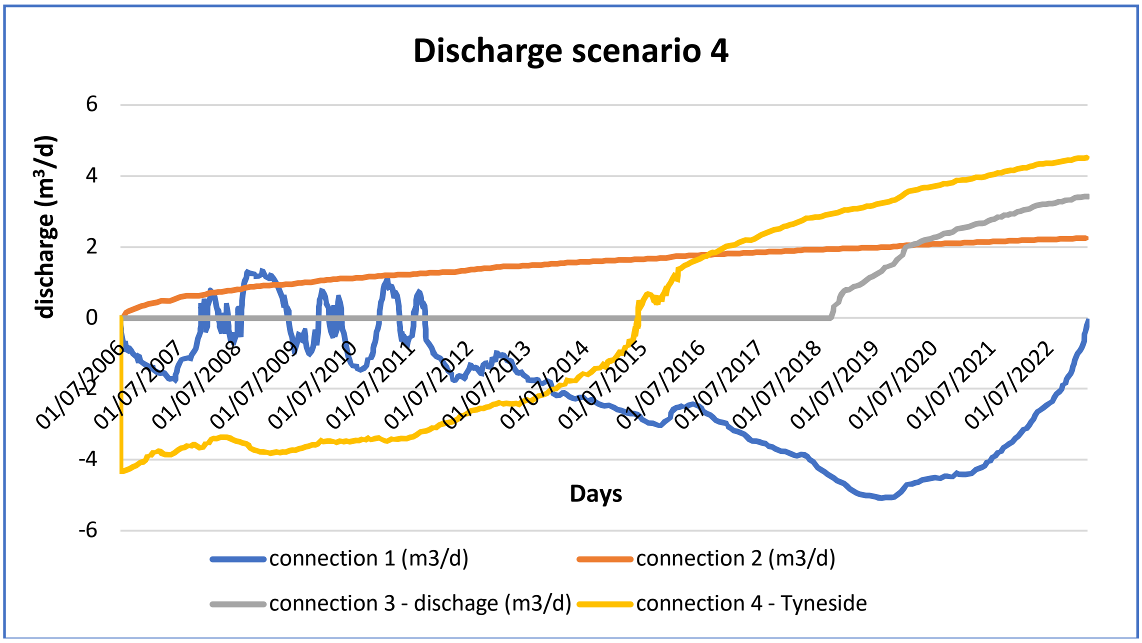

Figure 52 - Discharge output for scenario 4