Department of Mechanical Engineering

A review of the potential thermal resource in Glasgow's abandoned coal mine workings:

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Abstract

The consumption of energy for heating and hot water requirements contributes to around half of the world's energy usage. The introduction of the Renewable Heat Incentive (RHI) is part of a move towards encouraging the implementation of renewable energy sources for thermal energy production. Heat pumps are expected to contribute to some of this demand for renewable heat energy and finding a constant and reliable resource of thermal energy is paramount to the use of a heat pump. Mine-water stored in abandoned coal mine-workings is being seen as a potential thermal resource for the city of Glasgow. The research approach adopted in this dissertation includes a review of all aspects of the drilling activities and the development of a spreadsheet based numerical model. The model which will look at thermal feedback times and geothermal output for a simplified aquifer will be used alongside the drilling review to assess the potential of two case study sites in Glasgow. The findings from this report indicate that both the drilling and design of a re-injection well need to be carefully considered when designing the heating system. The main conclusions drawn are that if not properly designed the re-injection of cooled water can drastically reduce the life of a well doublet. An increase in the size of the aquifer between the two wells increases feedback times. Increasing the pumping rate decreases the breakthrough time and the re-injection into the same horizon level as abstraction will increase the chances of feedback. The dissertation also concludes that the drilling of coal horizons contains a number of potential hazards that can be mitigated with a thorough site survey and detailed planning. The dissertation recommends that this resource has a potential to meet a significant amount of the cities heating requirements if the installations are properly designed and controlled.

Keywords: Mine-water, re-injection, drilling, doublet, Glasgow

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1. Introduction:

The World's dependence on the depleting oil and gas resources, fear surrounding nuclear energy and an awareness of how our actions impact the environment have seen a shift in thinking towards energy production. Developed and developing countries are now expected to try and reduce their 'Carbon Footprint' by reducing their reliance on traditional forms of energy production. The Scottish government plans to move towards a "low carbon economy" www.scotland.gov.uk. The main focus of the government's objectives is set to tackle the issue of electricity generation with targets of a 42% reduction in carbon emissions by 2020 and 80% by 2050. They also hope to be generating 100% of Scotland's gross annual electricity consumption by 2020. However, heat energy accounts for around half of the country's consumed energy and half of its carbon emissions. The target for heat energy production from renewables isn't as optimistic due to the infrastructure and reliance surrounding the use of gas. They are targeting renewables to provide the equivalent of 11% of the countries heating demand by 2020. This 11% relies on the use of a few technologies, solar thermal, biomass and ground/air source heat pumps. To promote this uptake in renewable energy for heating the government have introduced the Renewable Heat Incentive (RHI). The RHI looks to financially reward the producers of renewably produced heat energy. It is being realised in 2 phases with the first phase announced on the 10th March 2011. The first phase of the RHI deals with non-domestic installations and opens for applications in September 2011. There is a section for the domestic market called the Renewable Heat Premium Payment Scheme which supplies grants for domestic installations. These financial incentives should encourage the uptake of heat energy production from renewable technologies. Ground source heat pumps are expected to take a partial responsibility in helping with this uptake. In particular interest to the first phase of the RHI is the use of 'open source heat pumps' as they tend to produce large amount of heat, useful in larger buildings. They remove the heat from groundwater by abstracting the water from the ground, passing it across a heat exchanger and then disposing of the cooled water. Open source systems require a steady supply of water at a constant temperature and at as high a temperature as possible.

Old mine workings have the potential to supply this resource and in particular relevance for Scotland and Glasgow abandoned coal mine workings. Due to the extraction of the coal from the subsurface the permeability and void space has been increased improving the potential for water movement through the rock. The use of mine-water is not a new idea and there are a number of installations currently operating throughout the world including Glasgow with some degree of success. It is a large resource and it is also being used in parts of Europe to help re-generate old dilapidated mining areas. This too could be said for Glasgow where the majority of the old workings are in the east of the city, a part that is seeing a great deal of re-generation in line with the forthcoming Commonwealth Games. The location of Scotland's coalfields also makes them an ideal candidate for exploitation. The coalfields are situated in the most densely populated areas in the Central belt, Ayrshire and Fife and are therefore in an ideal position to contribute to the country's heating demand.

There are a number of factors that require consideration during the design of an open source heat pump system. If the resource is going to be used on a large scale then one of the most important factors is the re-injection of the groundwater once it has passed through the heat pump. The re-injection of the cooled or heated water is necessary in certain circumstances to avoid pollution of waterways and to recharge the ground to maintain the sustainability of the system. Re-injection becomes a critical factor when it is required to control the chemical composition of the groundwater. Thermal breakthrough is a common issue related to open source systems. This happens when the cooled water being re-injected interferes with the thermal reservoir or aestifier cooling it and reducing the sustainability of the installation. Another important factor is the drilling operations involved in accessing this resource. Drilling into worked coal seams has a number of potential risks which can be mitigated with good drilling practice. This thesis will look at the use of minewater as a potential resource for heating and in particular the drilling operations and re-injection of the used water.

2. Literary Review

The use of abandoned coal mines as a source of cooling or heating is not a new one and projects have been carried out around the world to varying levels of success. This project draws on work already done on the subject of ground source heating/cooling and the use of flooded mine workings as the heat store. In this literary review heat pumps and thermogeology will be discussed along with a review of previous work done in Scotland. The first part of this is to understand what this source of energy is and the characteristics that control it. After which this section will look at how this technology is being used and will also highlight some of the ways that people are trying to improve the systems by the better understanding of how re-injected water influences the system. The literary review will also cover the legislative material that must be adhered to when considering the installation of a ground source heating system.

2.1 Thermogeology

A lot of the literature discussing ground source heating has been written by Banks and his associates and in turn they have introduced the term Thermogeology into the mainstream. The term is discussed at length in a book by Banks (2008), "Thermogeology is the study of so-called ground source heat" [3]. What this means is that it is not looking at geothermal energy which concerns the heat generated by the Earth's molten core. Thermogeology is the study of low-enthalpy heat within the first couple hundred metres of the Earth's crust, predominately supplied by solar energy.

Thermogeology draws on a lot of the science involved in hydrogeology and thermodynamics, its basic principles are derived from both of these topics. The formula used to quantify the flow of water through a section of material is Darcy's law (fig 2.1.1) and has similarities to Fourier's law (fig 2.2.2) describing heat flow through a block of material. These two formulas are based around the same principles of flow through a block of material, the only difference being that one is concerned with the flow of heat and one with the flow of fluid.

$$Q = -KA\frac{dh}{dx}$$

Fig 2.1.1 Darcy's Law

- Q = flow of water in $m^3 s^{-1}$
- K = Hydraulic conductivity or permeability in $m\ s^{-1}$
- A = cross sectional area of the block in m^2
- h = head in m
- x = distance or length of water travel in m
- $\frac{dh}{dx}$ = hydraulic gradient

$$Q = -\lambda A\frac{d\theta}{dx}$$

Fig 2.2.2 Fourier's Law

- Q = flow of heat in $J\ S^{-1}$ or Watts
- $-\lambda$ = thermal conductivity in $W\ m^{-1}\ K^{-1}$
- A = cross sectional area in m
- Θ = temperature in °C or Kelvin
- x = distance in m
- $\frac{d\theta}{dx}$ = temperature gradient in $K\ m^{-1}$

The term Thermogeology covers all aspects of Ground Source Heat Pump (GSHP) systems, from the drilling of the wells to the design of system in accordance with estimated resource potentials. When designing an open source system a lot depends on the pumping rate of the abstraction well. In his book Banks 2008, dedicates a chapter to the design of a well doublet system (abstraction and re-injection).

One of the priorities when designing an open loop system is to ensure its longevity and therefore efficiency. If an abstraction well is removing water at around 12°C and re-injecting it at about 5-7°C then there is the potential to cool the aquifer. The design of the system has to ensure that there is enough space and material between the doublet to mitigate this risk. In the book by Banks (2008) he describes how by understanding the gradient of the aquifer and the type of rock the time for thermal feedback in the doublet can be estimated. In a paper by Banks (2010) , he discusses the topic at greater length. In the paper he offers possible equations that are used to estimate the dimensions and properties of the thermal plume in a re-injection well.

There are a number of terms that are going to be used throughout this thesis that are common language in thermogeology. This next section will explain what some of these terms are and what properties of the rock and aquifer they relate to.

Ground Flow (Q): this is the movement of the water through the rock usually measured in m^3 day^{-1} or l s^{-1}.
Pumping rate (Z): this is very similar to flow rate (Q) and is used to separate the flow rate from the pumping rate. The flow rate dictates the maximum pumping rate but not the minimum. Measured in m^3 day^{-1} or l s^{-1}
Hydraulic conductivity/Permeability (K): this is an intrinsic property of the rock and describes how good the material is at letting water flow through it.
Porosity (η): Unlike permeability which can be affected by faults and gaps between the rock, porosity only deals with the inter-granular space. The amount of space that is between each grain or rock forming crystal. It is the volume fraction of the material occupied by open spaces.
Transmissivity (T): Transmissivity is defined as an extrinsic property that describes the ability of the aquifer to transmit water.
Darcy velocity (U): is defined as "flow rate per unit cross-sectional area of aquifer" Banks (2008).
Drawdown (Sw): Drawdown is the cone of depression of the groundwater that occurs around the abstraction well (fig 2.1.3). Upconing is the opposite effect seen in re-injection wells.
Doublet: Open source well system consisting of an abstraction and re-injection well.
mbgl: Metres below ground level

2.2 Ground Source Heat pumps

In this part the basic functions of a ground source heat pump (GSHP) will be explained and in particular an open source system. It is important to understand that heat pumps can be used to provide heat but they can also be run in reverse to provide cooling. Ground source heat pumps (GSHP) when used in heating mode operate by removing heat from the ground and passing it over a refrigerant in a heat exchanger. A heat pump consists of 4 parts which come together to perform the operation of removing heat from one fluid to another (fig 2.2.1).

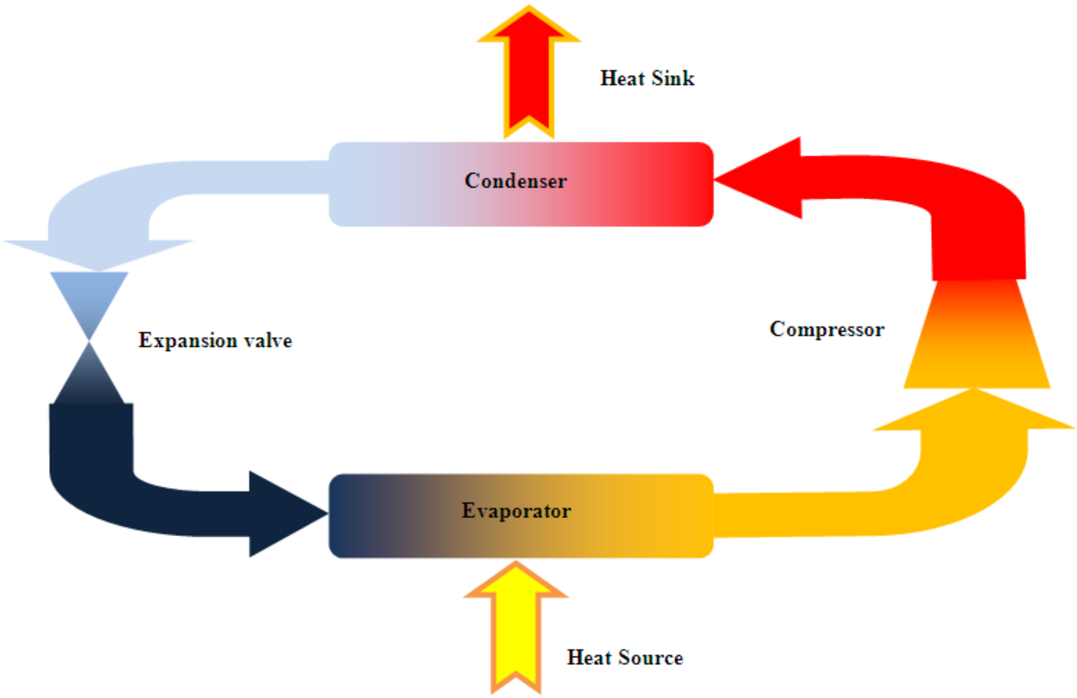

Fig 2.2.1. Components of a heat pump

1. **Evaporator (**in essence a heat exchanger)
2. **Compressor**
3. **Condenser (**the other heat exchanger)
4. **Expansion valve**

The heat is removed from the ground either via groundwater pumped up a well or a carrier fluid pumped along PVC pipes within the ground. This initial carrier fluid passes across a refrigerant in the Evaporator via a heat exchanger. The heated refrigerant then passes through the heat pump to the compressor where it is squashed to increase its pressure and temperature. After the refrigerant has been raised to a high temp/pressure it passes across another heat exchanger in the condenser. At this point heat is rejected from the refrigerant usually to water that feeds the domestic hot water tank. The refrigerant has a final pass through an expansion valve to restore it to the starting temperature and pressure and the cycles begins again (fig 2.2.1).

The term GSHP refers to a number of techniques used to extract trapped solar energy from the Earth. PVC pipes can either be laid flat out along trenches a couple of metres down in the subsurface geology or boreholes can be drilled down into the rock. The extraction of heat from mine workings will obviously use the borehole method but again there are a number of ways in which this can be done. For residential properties a closed loop system is the most popular option. This involves drilling a borehole usually around 110 mm in diameter down into the rock. A PVC pipe with a U-bend is then lowered down into the borehole and connected to a heat pump at the top via a manifold. A carrier fluid is then pumped around the closed PVC circuit extracting heat from the rock as it travels down and back up the borehole. For a system that wishes to generate a large volume of energy there is another option known as an Open loop system. Open loop systems remove water from the ground and pass it across a heat exchanger and then onto the heat pump itself. Once this water has passed through the heat exchanger and cooled it is either re-injected back into the rock or disposed of in other ways. The groundwater doesn't come into contact with the refrigerant in the heat pump to prevent the build-up of ice in the heat pump due to the low temperatures of the refrigerant. Open loop systems are a preferred option when it comes to larger buildings with high heat load. The use of pumps to abstract, move the groundwater through the system and then re-inject it uses a considerable amount of energy. This use of electricity can drastically reduce the coefficient of performance (COP) of a small system that is only being used in a small residential capacity. In the system that is being discussed in this paper the proposal is to remove water trapped in one coal seam and re-inject it into another (fig 2.2.2).

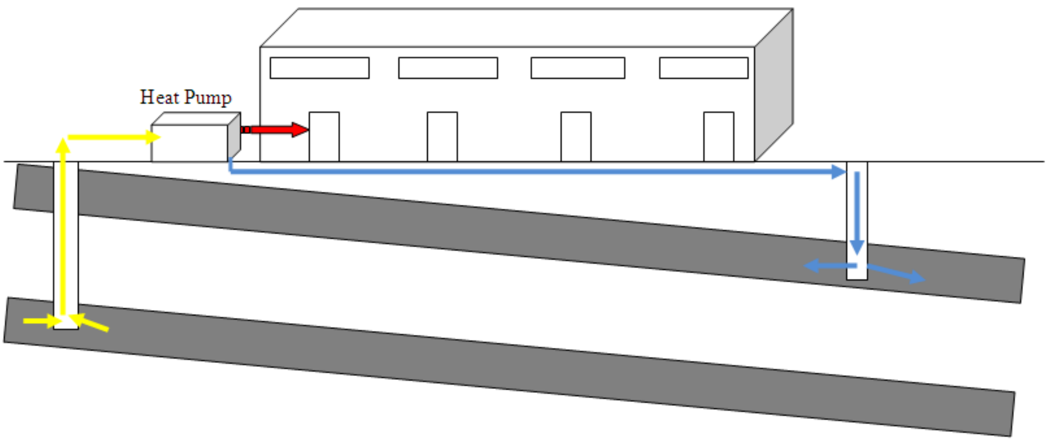

Fig 2.2.2 Open source system for a block of flats

The diagram (fig 2.2.2) illustrates how warm water is removed from a coal seam and passed through a heat exchanger which feeds a heat pump. The reason for the existence of the groundwater in the coal seams is discussed later in the paper. Once the groundwater has been cooled it is pumped along and down either one or many re-injection boreholes. The number of re-injection boreholes is determined by how easily the other coal seam can accept the water. The Dip of the coal seams would allow the designer to assume that the hydraulic gradient is moving from left to right. To reduce the potential for hydraulic/thermal feedback it is best practice to situate the abstraction well up-gradient form the re-injection well.

2.3 Glasgow's Geology & Mining

Glasgow has a rich and deep history connected to coal mining stretching over centuries, the traces of which can still be seen around the city. There is currently no deep mining for Coal in Glasgow or Scotland with the last deep mine Longannet in Fife closing in 2002 due to flooding. Glasgow owes its extensive mining history to the geology that the city was built on. The city lies on the Sandstones and Limestones of the Carboniferous period which stretched from 299 to 360 million years ago. During the Carboniferous period Scotland was moving northwards crossing the equator, (Trewin et al, 2002). The different stratigraphic layers of limestone, sandstone and coal measures indicate a time when the land was moving between shallow marine and deltaic environments. The building blocks for the coal measures were laid down during these deltaic periods when the area would have been rich in fauna, swamps and other organic material. Sea level fluctuations at this time are the reason for the environment moving between shallow marine and deltaic. The periods of high sea levels brought the sediment and shell material that would eventually form the limestone that lie between each coal in the lower coal measures. The sandstones of the Upper and Middle Coal Measures were formed during the deltaic periods. Geological activity throughout time has faulted and moved these layers of different rocks so that in some areas of Glasgow the coal seams outcrop at the top of the rock-head. This means that the coal is close to the surface, sometimes under quite thin levels of sediment and overburden. For this reason, Coal has been worked in Glasgow throughout a number of centuries resulting in the vast majority of the city being positioned over old mine workings.

There are two common techniques used in the extraction of coal for the mines around the Glasgow area, Stoop & Room and Longwall. It is these mining techniques that have increased the permeability of the coal measures. The increased permeability opens up the opportunity to use these channels of water for open source heat pumps.

Stoop & Room

This method involves the coal being extracted in a grid like pattern. The miners dig straight tunnels into the seam extracting the coal as they move forward. To prevent the collapse of the roof of the mine pillars of coal were left in-situ creating the grid like pattern (fig 2.3.1). These pillars created avenues and roadways that could either be left open once the coal had been fully worked from the seam. In some instances once the mining works had reached the end of the seam they would work backwards removing the pillars of coal as they moved out of the mine. Removal of the pillars would almost always allow the roof of the mine to collapse and infill the void space that was initially created by the roads and paths.

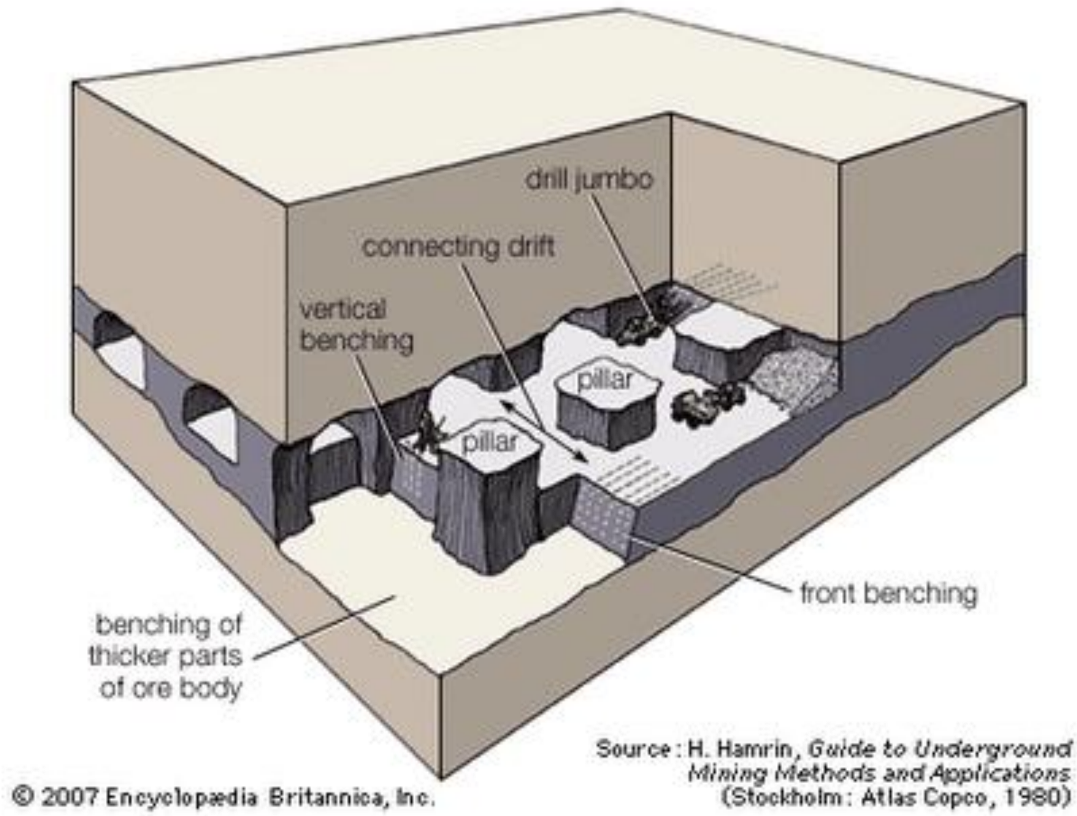

Fig 2.3.1 Stoop & Room. (taken from http://prudhoeseams.blogspot.com)

Due to the extraction of the coal from the ground the aquifer has an increased permeability. Increasing the potential for the through-flow of groundwater also increases the potential thermal resource of the aquifer. The collapse of the roof in the seam partially fills the opened spaces reducing the permeability of the worked seam.

In doing this it also increases the permeability of the surrounding rock. As the overlying rock collapses it creates a zone of fracturing in the rock above (Crane et al, in progress). The worked coal seams and the fractured rock above are likely to have created sub-horizontal zones of increased permeability.

Abandoned mines in which the Pillar & Stoop method has been used may still contain open roadways stretching deep into the seam. Open roadways and workings would obviously create a large increase in the permeability of the aquifer. In reality these roadways will probably only exist around the areas closest to the shaft where the importance of avoiding the collapse of the roof has been at its highest. Subsidence of the overlying rock and the removal the Pillars for their coal will have filled the void space left by the mining. In the instances where the pillars were left intact the abandoned workings could still contain open roadways within the stratigraphy.

<u>Longwall</u>

Longwall mining which was a much more commonly practiced technique within the Glasgow region involves the complete removal of the coal, allowing the roof of the workings to collapse behind the miners as they move forward into the seam (fig, 2.3.2). With this method, the coal is mined downwards from the outcrop or nearest point on the surface to the base following the dip of the strata.

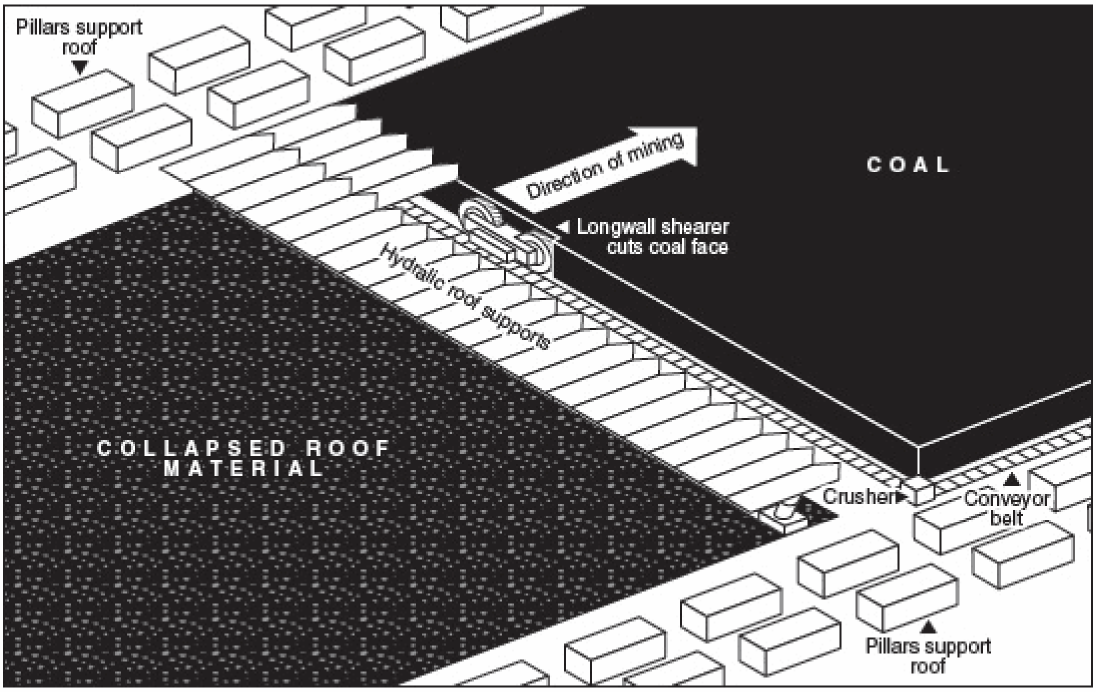

Fig 2.3.2. Longwall mining (taken from http://rajikorba.blogspot.com/2011/06/long-wall-technology-in-coal-mines.html)

The compete removal of the coal and surrounding rocks creates a large void space that is filled in as the work moves further into the seam. The void is not completely filled as subsidence will never fill more than 90% of the space left meaning that a minimum of 10% increase in permeability is achievable. This theory also applies to the Stoop & Room method where the pillars have been removed and the roof collapses into the void left by the worked coal.

It is this increased permeability that has increased the focus on the abandoned mines and their potential as a possible clean source of heat energy. The majority of the mining in Glasgow used the Longwall method so it can be predicted that there are not many areas within the city that contain large void spaces. The most likely places to find open roadways and void spaces would be around the pit entrances near the shafts.

Groundwater movement within the carboniferous coal measures of Glasgow is predominantly by lateral fracture flow with some inter-granular (Crane et al, in progress). Water movement doesn't generally move vertically through the strata but there is a possibility that faulting and/or shafts and roadways between seams could act as a possible pathway for the water. Groundwater levels in the bedrock for Glasgow are reasonably variable, borehole data suggests that it can be anywhere between 5 metres below ground level (mbgl) to 39mbgl. The Glasgow basin receives most of its water from the high areas to the North and South of the city. There is a reduced amount of recharge through the subsurface in Glasgow due to impermeable manmade structures and the majority of the groundwater discharge from the coalfields occurs within Glasgow. The groundwater is likely to be flowing through the Carboniferous down gradient towards the west in the direction of the sea.

2.4 Shettleston installation

The practice of using abandoned mine workings as a source of hot water for a GSHP heating system has already been used with a level of success in Glasgow. In 1998 John Gilbert Architects won a (HAG) Housing Association Grant sponsored competition to design sustainable housing within the Shettleston area of Glasgow. (fig2.3.1).

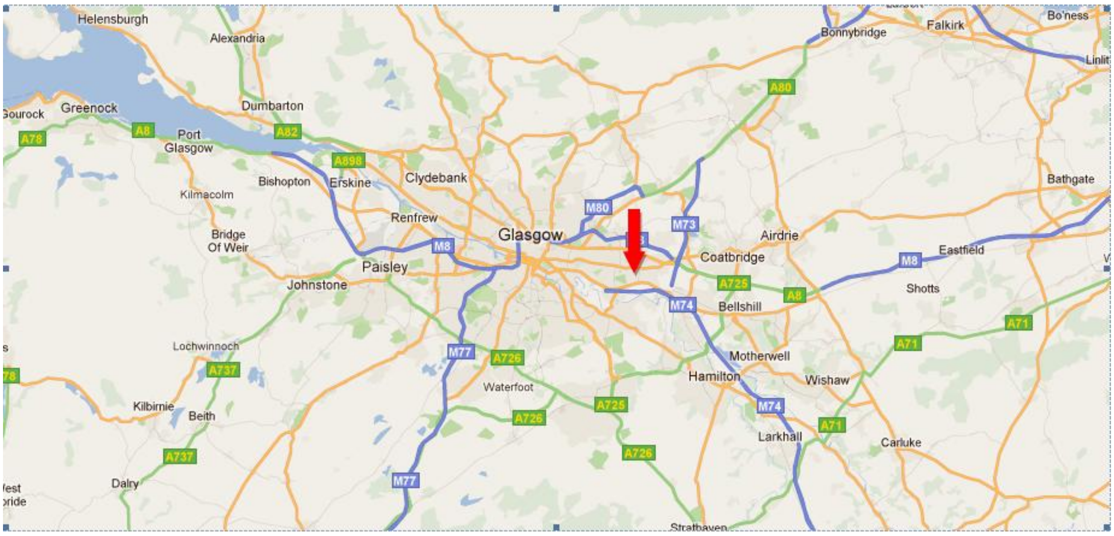

Fig 2.4.1 Shettleston, Glasgow. (taken from http://maps.google.co.uk/maps)

John Gilbert Architects recruited the services of engineering consultants EnConsult form Dunfermline to assist in the design of the system. The project involved the construction of 16 homes over an area of 1,600m^2 that would use the water stored in abandoned coal mines below the site as a source of heat for their hot water requirements. The site chosen was on Glenalmond St (fig 2.3.2) and was close to the Westmuir Pit (Pumar A, F, 2007).

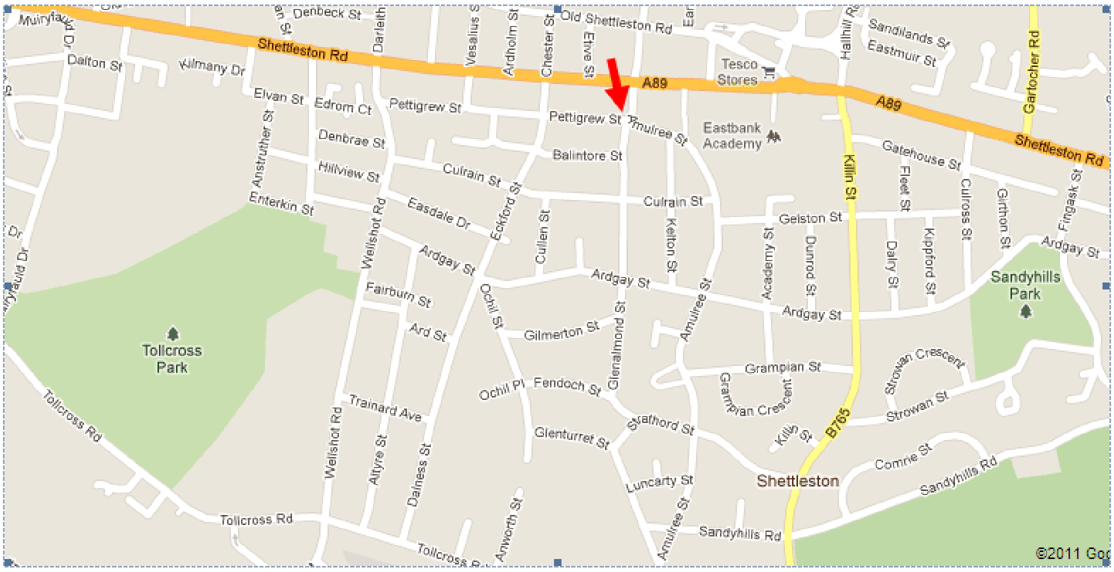

Fig 2.4.2. Glenalmond Street, Shettleston (taken from http://maps.google.co.uk/maps)

The development uses an abstraction well drilled down to 100 metres below ground level (mbgl) into what is estimated to be the worked Ell seam from the Westmuir Colliery (Pumar A, F, 2007). Water is pumped from the well at a rate of around 5-10 l

s^{-1} at a temperature of around 12°C. The system uses a water to water heat pump with an output of around 55°C. This heated water is then stored in water tanks on site and supported by an additional 36m^2 of solar panels. In the initial design for the system the cooled water was used in the black water systems in the houses for toilets. This was abandoned after the cooled minewater started to leave unsightly staining on the toilets. The cooled water at around 3°C is now re-injected back into the rock at a depth of around 55mbgl approximately 20m away from the abstraction borehole.

In over ten years since its installation the heating system continued to supply the residents within the development with heating and hot water. The only upkeep is a change of filter on the pump every 3 months due to clogging from particulates in the mine-water. The annual costs are around £90 - £100 per household for heating and domestic hot water but this is presumed to be possible with additional subsidies from the housing association (Pumar A, F, 2007).

2.5 Minewater project

The Minewater project was a European body set up in the Dutch town of Herleen in 2004 to investigate the potential for using groundwater within abandoned mines as a source of energy (Minewater project report). They were awarded funding by the EU's Interreg IIIB NEW program to carry out studies into the potential for these systems. Part of the project included involving other local authorities throughout Europe who also had ambitions to tap into this underground energy source. In the interest of this thesis, Midlothian council was looking at using the technology for a new development on the outskirts of Edinburgh. Subsequently other partners joined the project from France and Germany all of them producing studies into their particular area. This gave the minewater project a greater bank of knowledge about the different potentials for these systems. The studies included potential and feasibility studies looking at all the aspects of such installations. The economic, environmental and strategic considerations along with the design and estimation of the systems to see if they could supply the load required. Part of the appeal for these different for all of these different countries also lay in the re-generation of mining areas.

2.5.1 Shawfair

As mentioned previously in this chapter one of the partners of the Minewater project was Midlothian council who had plans for a development south of Edinburgh. Shawfair was to be a new town that would supply much needed housing for Edinburgh city and Midlothian council. A number of partners were initially involved in the potential study for this development area known as the South East Wedge, Shawfair Developments Ltd, Miller Homes and Midlothian council. The plan was to build a new town over 15 years that would contain approximately 4,000 homes with schools, offices and local amenities. Along with the initial partners PB power were invited to undertake a study into the potential resource for the area and Scotland as a whole. PB power produced a report that detailed not only the potential resource in the proposed Shawfair site but a potential Geothermal resource for all of Scotland's coal mining areas. For Shawfair in particular they looked at a potential system using both a heat pump and CHP unit (Fig 2.5.1). The initial estimate at the potential load for the new town was in the region of $25MW_{th}$ but this would be much less come installation due to building regulations improving (PB Power, 2004).

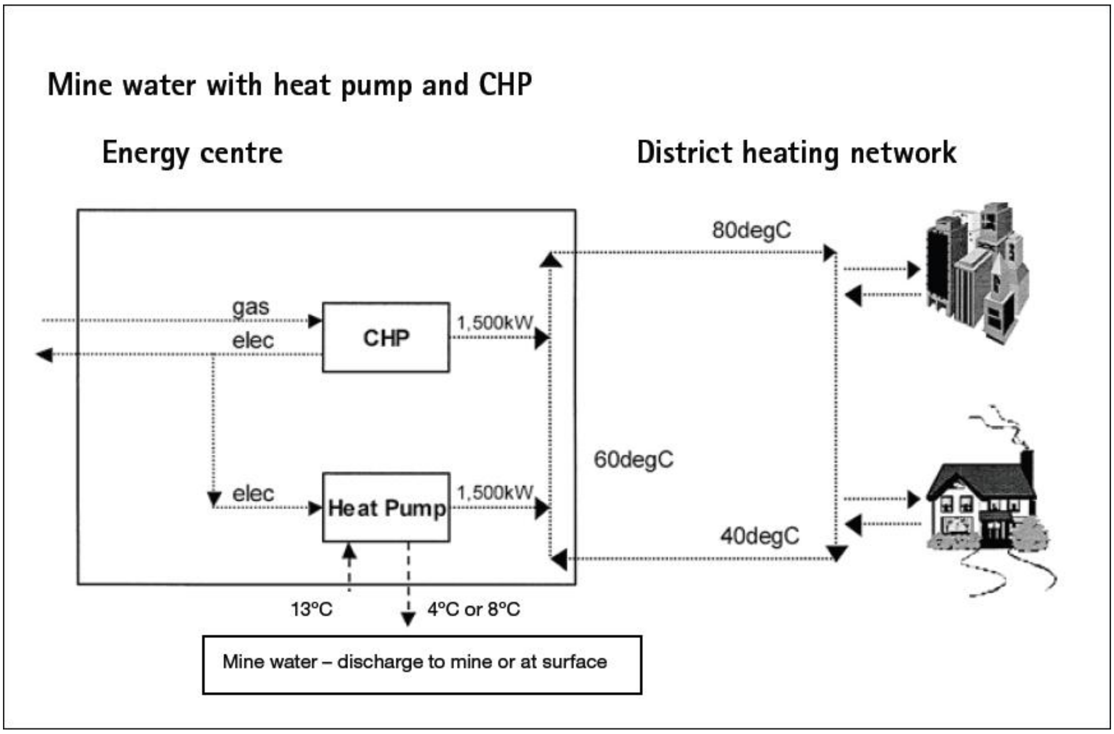

Fig 2.5.1. Heat pump and CHP heating system (taken from minewater project paper)

The system is designed to take groundwater from the worked coal measures underneath the development site. Shawfair lies directly over the Monktonhall colliery which has been pumping groundwater at a rate of 100 l s^{-1} since closure. Monktonhall is also one of the UK's deepest mines at around 900 mbgl with the potential to extract water at a temperature of 37^{o}C. It was decided that a temperature of 37^{o}C would be hard to sustain but a water temperature of 13^{o}C and a pumping rate of 100 l s^{-1} could be easily maintained. The first part of the Shawfair development was going to see the building of 555 dwellings, 12,000 m^2 of office space and 15,000 m^2 of school. This would have a thermal energy demand of around 3,000 kW_{th}. PB Power estimated that a pumping rate of 30 l s^{-1}, extracting water at 13^{o}C could be used to heat returning domestic hot water. The heat pump and CHP unit would be used in a district heating scheme where the returning water would be heated by the heat pump from 40 – 60^{o}C. This water would then be raised up to 80^{o}C via the CHP and then passed back through the buildings heating systems. A heat pump with COP 4.5-5 and a 450 kW compressor with a CHP unit running at a high efficiency around 92% were proposed for this system.

A lot of study and work was put into this project but it unfortunately never took off. This wasn't because the feasibility study had indicated that it couldn't work but down to a lack of funding.

2.6 Work done by the BGS

A considerable amount of work relating to the use of the abandoned mines around Glasgow has already been done by the British Geological Society or BGS. They have been working in conjunction with the city council and sustainable Glasgow to better understand how this resource can be most efficiently used. The BGS have concentrated their initial work on grid square NS66SW, compiling a large amount of data into a GIS map (fig 5.1) of the City and a 3-D geological map (figs 5.2/5.3). They have produced a number of internal reports looking at estimates for water volumes and heat resource for the city. An internal report by McLean (n.d) suggests that there could be over 10.3 billion litres of water within the worked seams of the NS66SW block of Glasgow. McLean (n.d) produced a spreadsheet and accompanying report to estimate this figure of 10.3 billion litres. He brought together all of the digitised records for mine workings and took the average thickness for each of the worked seams in grid square NS66SW. From the abandonment plans he was able to estimate 5% of stoop and room workings were still open. Within the Stoop & room 50% would be the pillars or stoops leaving a void space of 50%. By estimating that 5% of the mine workings still lay intact meant that 95% had been subject to complete abstraction. In the report it states that it is widely been recognised by mining engineers that subsidence at the surface is only 90% of the void space. This would mean that there is an additional 10 % void space in the worked seams. These figures for the known worked areas were then applied to the un-known sites, picked out by borehole records or by estimating areas that probably would have been worked at some point. From these assumptions and data in the abandonment plans he was able to come up with his figure of 10.3 billion litres. Following on from this the BGS started to look at the thermal potential of the mine workings across all of Glasgow. A report by Abesser (2011) digitally represented the mine workings and the thermal properties of the superficial deposits and bedrock of the city (figs 2.6.1/2.6.2). Other work by the Crane et al (in progress) estimates a geothermal resource potential for the whole of Glasgow. This report looks at the geology and hydrogeology of Glasgow and in what way the extraction of the coal has altered the permeability and therefore potential yield. It takes the work of Bill McLean (above) for grid square NS66SW and extrapolates this across Glasgow to help estimate city-wide thermal potential. The report looks at a number of ways of calculating the geothermal resource/km^2 with quite varying results. The report finishes by highlighting the areas that require further investigation including the aspects of re-injection and thermal feedback.

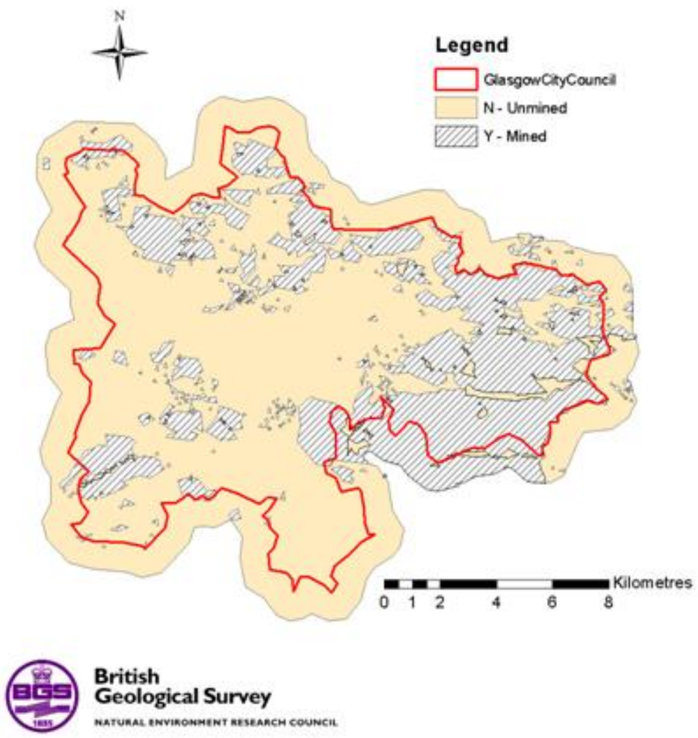

Fig 2.6.1 Map of the mined areas of Glasgow (Supplied by the BGS)

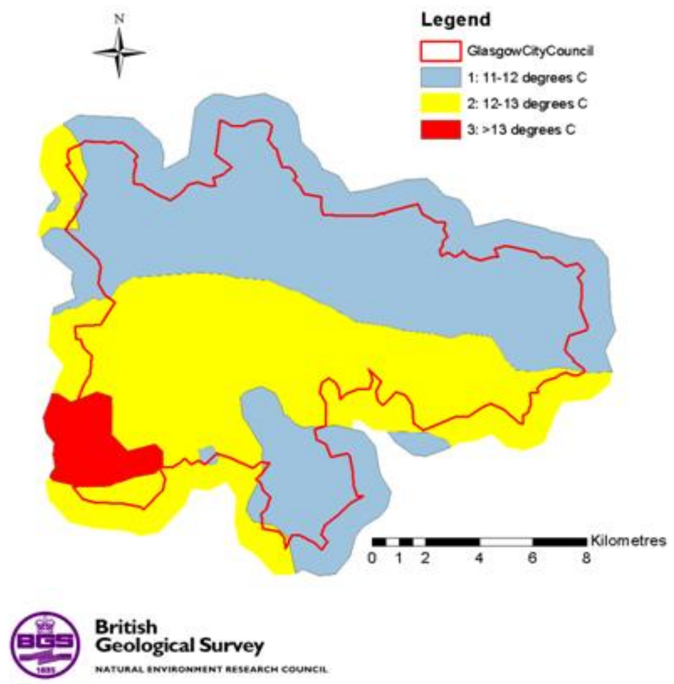

Fig 2.6.2. Map of the thermal properties of the bedrock in Glasgow (Supplied by the BGS)

3. Drilling

This part of the thesis will cover all aspects involved in the drilling of open source systems and in particular drilling through coal seams, worked or un-worked. Before any drilling takes place it is imperative that a full and detailed site investigation is undertaken and all members are aware of the legislative obligations that they must adhere to. Before any contract can be awarded for the work a thorough check should be made to ensure that all legislative obligations have been addressed. The legislative material and governing bodies that require consultation are covered in the next sub-chapter. There will be a number of terms used in this chapter when describing the different processes involved in the drilling of a borehole. The following section will describe some of these terms.

- Drill string – These are the rods that connect the drill head to the drilling rig and transfer the power from the rig to the drill head. In Geotechnical borehole drilling rigs they will typically comprise of 3m lengths of toughened steel that screw together on the rig.

- Casing – Casing is used to support the structure of the well through any overburden or soft or granular geological layers. It is also used to seal the borehole from ground surface pollutants and to prevent any uncontrolled movement of fluid back up the borehole. The casing usually consists of 3m lengths of tubular steel that are welded together in-situ at the top of the borehole. At the base of the first casing length a casing shoe is welded on, this is a thicker piece of steel with drill bits in it. It helps with the drilling and installation and protects the bottom impacted area of the casing.

- Rotary drilling - This is a drilling method that relies on the continuous rotation of the drill bit to break the rock at the base of the borehole. The cuttings are removed via a fluid that circulates down through the drill string, out the end of the bit and back up the borehole.

- DTH – DTH stands for down the hole hammer. It operates by similar principles to rotary drilling but with an added mechanism. The drill rig rotates the drill string and bit at a high revolution in much the same way as rotary drilling. Along with the rotation of the bit the DTH method uses compressed air to drive a small jack-hammer behind the bit. This hammer works like a piston with the compressed air applying a vertical knocking force to the base of the borehole. The knocking effect fractures the rock making it easier to break with the rotation of the bit. The compressed air and water is then used to flush the debris form the borehole. DTH is one of the fastest ways of drilling a borehole. There are applications that can use water as the driving fluid behind the hammer. The noise emitted from the rig is a loud rattle as the air drives the hammer up and down while the drill steels turn at high speed.

- Bentonite – There are a number of different types of bentonite that are used in a variety of different industries. Sodium bentonite is used within the construction industry for

3.1 Legislative material concerning abstraction of water from coal seams

There is legislative material issued by different bodies that governs drilling, intersection of coal seams and the abstraction and re-injection of ground water. The British Drilling Association (BDA) issues guidance on all of the legislative material surrounding the use of the drill rigs. The Coal Authority (CA) requires the completion of a licence application for drilling and intersecting coal seams for the abstraction of water. SEPA govern the abstraction and re-injection of groundwater in Scotland and set out guidelines to control these activities.

3.1.1 Drilling

The BDA is the UK's trade association set up for the ground drilling industry. It is a membership association that promotes best drilling practices along with H&S and Environmental support for any party interested in drilling (www.britishdrillingassociation.co.uk). Within their website they set out the European (EN) and British (BS) standards that are designed for the drilling of boreholes on land. These standards primarily concern themselves with the H&S involved in the operation of drilling rigs. The standard title is BS EN 791:1996 Drill rigs, Safety. A final draft on this European standard for drilling is expected to be ready by January 2013 and it is expected that any drilling operations in the EU should adhere to these standards. Most drilling contractors will have their own standards like ISO that they will follow; these will be based around this European standard.

3.1.2 Coal Authority

The Coal Authority is a UK wide government funded organisation that controls any construction or activity around or involving coal seams, worked or un-worked. There are a number of hazards involved with the extraction of coal form underground mines. The Coal Authority licence and control any activities that could disturb coal seams to mitigate the release of dangerous mine gases or polluted water.

The CA website (coal.decc.gov.uk) sets out the different forms of approval that are required for different types of work involving the coal seams. Drilling through coal seams or intercepting a seam for the abstraction of groundwater in Glasgow would require a licence from the Coal Authority. This licence can be applied for online and requires the contractor that will undertake the work to provide all the details of their proposed work. The application for a licence to intercept the coal and abstract water requires the following information:

- A method statement for the works intended, setting out the technical details of the borehole and a vertical section highlighting the strata and the target horizon. The depth of superficial deposits and details of any geological structures like faults that could provide pathways for gas.

- It also requires details of the drilling method (Rotary or DTH), the flushing media (air, water, mud or polymer), and information on the casing.

- It asks for proposed method of sealing the borehole and full MS and Risk assessments in all the possible hazards that could occur. Plans for abandoning the borehole.

- On completion all log data and geological information must be made available to the CA.

3.1.3 SEPA

The Scottish Environment Protection Agency (SEPA) is Scotland's environmental regulator for land and water. Their role is to protect the environment and to assist in enabling customers to comply with the environmental regulations concerning their line of work. The abstraction and reinjection from and to the water environment are controlled activities and therefore require the permission of SEPA before any works can commence. SEPA follow the guidelines set out in the Controlled Activities Regulations (CAR) 20011 which draw on the Water & Environment Services Act (Scotland) (WEWS) 2003.

CAR outlines three levels of control:

- General Binding Rule (GBR)
- Registrations
- Licences

The system that is being discussed within this project will be removing potentially polluted groundwater at > $10m^3day^{-1}$ and will therefore require the application for a licence. Application for a licence requires that declaration of a 'responsible person' normally a company that can ensure compliance with the conditions of the licence. SEPA allows 40 days for the application of a licence to be assessed. During this time they will assess the impact of the designed system on the water environment and define strict rules by which the licence will be formed. They can draw form any part of the regulations to ensure the protection of the water environment during and after installation of the system. A discharge licence will also be required for the re-injection of the groundwater. A large number of guidelines for water abstraction and re-injection can be found on SEPA's web-site (www.sepa.org.uk).

3.2 Hazards

Part of the reason for all of the legislation surrounding the extraction of mine-water is because it potentially contains a large number of risks to humans and the environment. The worked seams can contain large amounts of Mine-Gas and pollutants in the water. The water itself neglecting the impact of pollutants or dissolved gases can present a potential hazard. If the borehole hits an aquifer under pressure artesian water can be produced this can have detrimental effects on the environment.

3.2.1 Mine Gas

Mine gas predominantly consists of methane, CO_2 and oxygen depleted air which is usually rich in nitrogen. Mine gas is a product of coal extraction and its abundance and location are dependent on number of factors including age of coal, hydrogeology, and interconnectivity within the rock horizons. All coal seams have traces of these gases within their pore structure and untouched present no danger as the gas is trapped within the coal. The extraction of the coal through blasting or digging releases these gases and they can accumulate to dangerous levels in parts of the mine.

Methane is a product of firedamp which is released from the coal during degassing. As firedamp decays it releases methane which in certain quantities can become unstable and highly combustible. The methane becomes combustible when confined and diluted with air to the concentration of 5%-15% volume of methane (Dept of Environment report, 1996). The mix of CO_2 and Nitrogen is known as Blackdamp and is a result of atmospheric air oxidizing in the open seams. It is an asphyxiate that accumulates at the floor of the worked seam due to its high density. Another product of decay within the coal seams is Carbon monoxide and in strong enough concentrations can be lethal. The displacement of groundwater during mining operations left large open voids for these gases to accumulate in. Since the end of mining and the pumping the groundwater has started to re-fill these voids pushing these gases up towards the surface. A high groundwater level can either mean that there is no mine gas or concentrated volumes near the surface. Any drilling into coal or mine workings must include the use of mine-gas monitoring equipment.

3.2.2 Chemistry of mine-water

The chemical composition of the rocks and water at depth can be very different to the conditions on the surface. This creates the potential for an abstracted groundwater with a distinctive chemical composition to pollute cleaner surface water or other clean aquifers. The potential hazards associated with the chemical properties of the minewater arise when it is extracted from its environment and comes into contact with the surface environment. Banks (1997), indicates that minewater chemistry can fall into one of three categories.

- Water that has a high salinity from the natural minerals of the rocks that comprise the aquifer.
- Acidic heavy metal containing waters usually occurring from the oxidization of Pyrite an Iron Sulphide crystal common in coal, better known as Fools Gold.
- Alkaline waters containing hydrogen sulphide formed from the reduction of sulphate.

Abstracting these waters can result in de-gassing of gases trapped within the water and precipitation of calcite, iron deposits or biofilms. In a paper by Banks (2009), he looks at the example in Lumphinans, Fife, Scotland. The system in Lumphinans was another installation designed by John Gilbert Architects and was using minewater from 170mbgl as a heat resource. This system was performing well until vandals broke the recharge well exposing the groundwater to the oxygen rich atmosphere resulting in clogging up of the recharge well. He performs a number of laboratory tests on the water from Lumphinans and comes to a number of conclusions. Pressure reductions in the system and exposure to atmospheric CO_2 resulted in degassing of the water. A rise in pH and an accumulation of CO_2 resulted in the precipitation of calcite and Iron Hydroxide. Heating schemes where there is a reduction in the temperature of the groundwater reduce the rate of biofilm precipitation. Cooling schemes have the opposite effect and encourage biotic and abiotic reduction. Precipitation of substances is a bi-product of the chemistry of the water, the pH of the water can also have detrimental effects on the equipment used to extract it. Acidic conditions within minewater are usually produced because of the action of bacteria. The bacteria generate energy through the oxidization of Ferrous Iron Fe^{2+} to Fe^{3+} Ferric Iron using oxygen. The Ferric Iron then attacks the Pyrite within the coal seam to produce more Ferric Acid.

$$4Fe^{2+} + O_2 + 4H^+ = 4Fe^{3+} + 2H_2O$$

The acidic and ferrous water will attack any metal components of the heat pump system. The possible solutions for many of these potential hazards posed by the chemical composition of minewater may be technical and costly but they are necessary if the sustainability of the system is to be maintained. One solution is to ensure that the water never comes into contact with the atmosphere. In the paper by Banks 2009, he offers a solution. The pumping rate must be controlled so as to ensure it doesn't de-water the mine leaving space for gas to fill and initiating a chemical reaction. This is a potential risk when removing water from a confined aquifer as might be the case with the coal seams. De-watering creates space for air which can promote oxidation of sulphide minerals, precipitation of iron and bacterial growth. It is therefore important to understand the characteristics of the aquifer so the calculations can be made to decrease the risk of de-watering. The pipework and heat exchanger should be sealed units; the heat exchanger connects to the heat pump so the water doesn't come into contact with the heat pump. Recharge should take place below the waterline to try and balance the pressures. Pressure can also be maintained via regulation valves on the discharge main in the re-injection well, this will decrease the possibility of the de-gassing of the water. The use of plastic components should be used where possible to prevent corrosion; a prophylactic heat exchanger is one example of such a device.

3.2.3 Artesian Water

For a borehole to encounter an artesian water source it must penetrate a confined aquifer where the potentiometric surface (water level) is above ground level (fig 3.2.3.1). The water is trying to find its natural level above the ground surface. This water can reach the surface at a high velocity and controlling it can be difficult. Some artesian pressures can be so high that removal by water tankers isn't even an option and the only course is to try and seal the borehole and abandon it. It is therefore best practice to ensure casing is securely grouted into the horizon above the suspected aquifer to prevent water escaping up the outside of the casing and up the borehole. During drilling it is possible that a confined aquifer is encountered before the target horizon has been reached. If the potentiometric surface is lower than ground level then it should not present any problems but if it is above then the borehole may have to be abandoned.

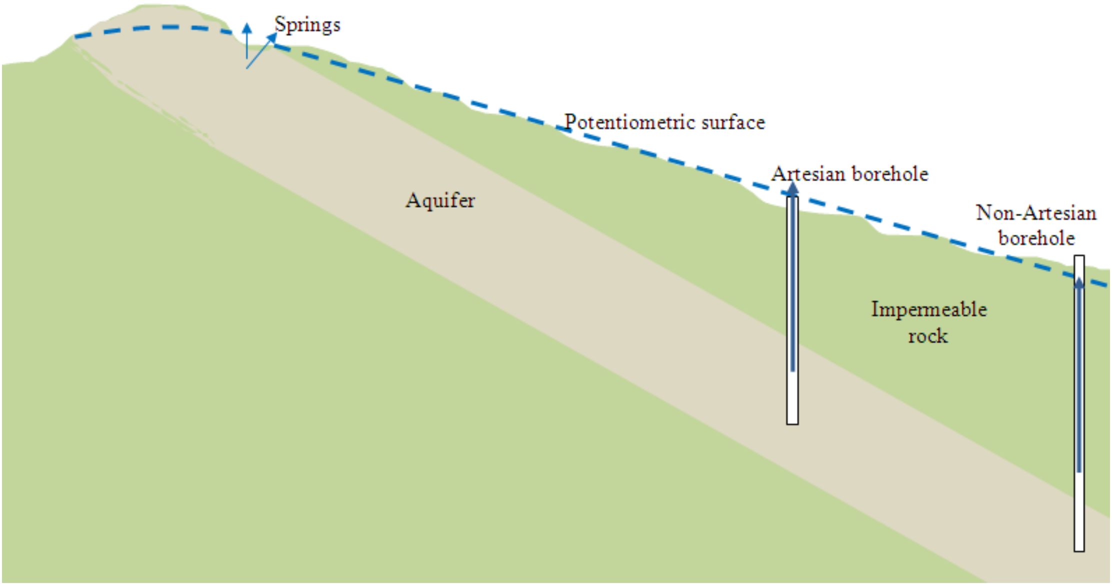

Fig 3.2.3.1 Artesian borehole

The water table in the bedrock aquifers in Glasgow can be reasonably high and lie in the superficial deposits in some areas of the city. It is possible that in some areas of Glasgow the potentiometric surface for groundwater in the bedrock aquifers could easily be above the ground surface level. A study of local borehole information would indicate if this is likely. Care must be taken during drilling operations because the potentiometric surface can rise above or below ground level in a matter of a couple of metres meaning previous boreholes may not have encountered artesian conditions.

The risk is an environmental one as it concerns the uncontrolled movement of groundwater onto the surface where it can reach open waterways if not controlled in time.

3.3 Drilling Operations

Assuming that all the legal requirements have been checked and the location of the boreholes has been selected after a thorough site investigation then the drilling can proceed. When drilling in an area with known coal seams whether they have been worked or not a gas monitor must be at the site of the borehole at all times. Depending on the proximity of other buildings monitoring may be required in a number of places in case of seepage. The main focus of this project is looking at the exploitation of mine-water in the worked coal seams of Glasgow. It is expected that the best flow rates for groundwater will be found in the open roadways and workings left behind in the old mines. It is therefore critical that the surface location of the borehole is as accurate as possible to the position of the known open areas of the mine. The condition of the mine workings cannot be completely certified and it is not really known what drilling will encounter until it starts. A good site investigation will supply the driller with information on the superficial material and rock horizons that are likely to be encountered.

3.3.1 Drilling technique

There are a number of different drilling techniques used in the excavation of boreholes. The two most common methods used for the drilling of geothermal boreholes are Rotary and DTH, discussed previously at the start of the chapter. As mentioned previously the DTH method pounds the rock into a dust which is then flushed back up the borehole by a combination of high pressure air and water. The water acts as a lubricant and a coolant for the hammer. Mains tap water can be added to the borehole if there is insufficient groundwater. Due to the use of compressed air this method isn't favoured in areas of worked coal seams. If there is a lack of water in the ground and mine gases are released the compressed air can push these gases through the strata. This means that they could appear at the surface far away from the drilling operations and be undetected. Using a rotary rig set up for a water flush system would be preferable. Mud-flush using rotary drilling is an option and requires a rig designed to circulate and clean the drilling mud as it drills the borehole. The mud is pumped down the drill strings and out of the bit and then re-circulated round the borehole. It is intended to act as a lubricant and help strengthen the walls of the borehole as it is drilled. A polymer can be added to the water flush system and it acts in a similar way to the mud. The Coal Authority will assess the location and the drilling method and suggest which one they would prefer so as to secure the licence for the works. If the drilling contractor can prove that there is sufficient groundwater then the use of compressed air can sometimes be allowed.

3.3.2 Casing the borehole

No matter the drilling technique required by the CA the first part of the drilling operations is to case through the overburden or superficial deposits overlying the rockhead. In a normal borehole the casing will be driven approximately 2m into the top of the rock formations and sealed in using a grout. The rest of the borehole is then drilled "open hole" meaning that there is no protection from borehole collapse and once the drill string is removed it is just the stability of the rock that holds it open. A good geological site survey will determine the likelihood of the borehole staying open. Boreholes through compact, solid rock are more likely to stay open than those through fissile or granular material. In the situation that this project is looking at, the intersection of worked coal seams the casing may be required to be drilled down into the desired horizon. This would impact on the cost and time but ensure the stability and sustainability of the borehole for the system. It will also assist in the prevention of cross horizon contamination via the borehole. The coal seam may contain polluted, contaminated water and it may be a requirement to ensure that this does not enter any overlying clean aquifers. Drilling the casing down into the horizon above the intended terminal depth and then grouting the end of the casing should ensure against any cross contamination. The best practice is to grout the end of the casing securely into the ground to prevent any potential pathways for the ground water. Once the casing has reached its intended depth it is raised a few metres above the terminal depth. The casing is held at the surface while a pre-mixed grout is placed at the bottom of the borehole via a tremmie. The grout can be a mix of sand, bentonite and Portland cement (OPC). The specifications may be given in the granting of the licence form the CA. Before the grout has set the casing is lowered back into the borehole forming a tight seal between the rock and the casing. Once the grout has hardened the drill string is re-deployed to the base of the casing and drilling of the rest of the borehole commences. It is very difficult to case through voids within the strata. The casing tends to twist and bend under its own weight through the space and eventually the welds will snap under the strain. It is therefore imperative that any site survey before drilling should try and avoid locations where voids could be encountered. If the drilling is intended to directly hit an open roadway any slight deviation in the angle of the drill string through a void could result in metres of deviation further down the borehole. The casing of the borehole is a very important aspect of the drilling, get it wrong and it can have a disastrous impact on the environment of the surface or other parts of the geology. The following set of diagrams (Fig 3.3.1) highlight a number of possible hazards involved with the drilling of a borehole into an aquifer.

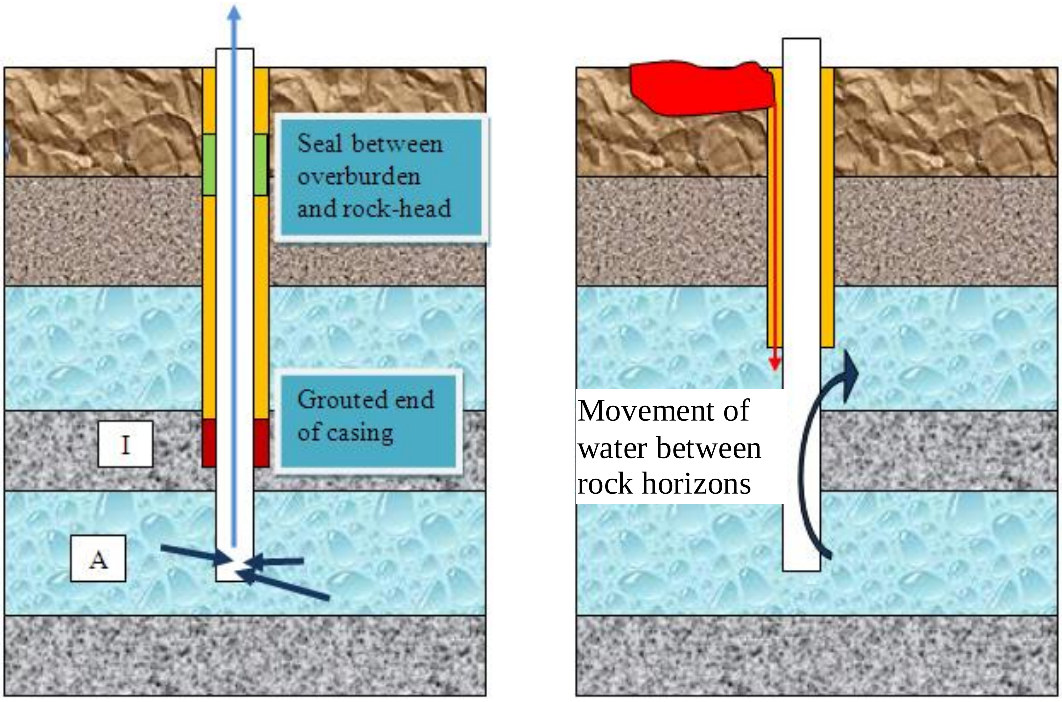

Fig 3.3.1, Two scenarios showing the potential hazards involved in the casing of a borehole.

The first diagram represents the correct installation of the casing if a particular stratigraphic layer is the intended target. The second shows some of the possible flow paths that can result if the casing isn't properly installed. The blue arrow represents inter-horizon contamination between the two aquifers (A) either side of an impermeable layer (I). If the aquifers were separated before drilling and there was no mixing of the water between them it can be seen that the drilling of a borehole can link these two. This is fine if the chemistry of both aquifers is the same but if they aren't and one is being used for drinking water at some other point this is a potential hazard. The grouting in of the casing at the bottom prevents this but a further seal at the top must be designed in to stop surface pollutants reaching the aquifer below.

3.3.3 Installation of the well liner

Once the casing has been installed and sealed then the drilling can continue and the well liner and pump installed. The casing will be designed to have a larger inside diameter (Ø) than the outside diameter of the well liner. Typical casing diameters will be around 140mm inside and around 168mm outside. Typical well lining will be around 110mm thick and the space around the well liner will be packed with a gravel filter if the borehole is open hole after the overburden has been cased. The diameter of the well will be designed around the pump that will be used and the pump used will be determined by the yield of the well. The exact yield of the well may be an unknown until drilling has finished and the well can be tested. It is therefore sensible to design the well and pump around the yield that is required for the desired energy output. The well liner will normally comprise of 3m lengths of plastic tubing. There will be plain sections and slotted sections with vertical or horizontal slots. Due to the possibility of corrosive materials within the water plastic well screen should be used. It is also cheaper and lighter to use. There are products on the market that are non-rigid flexible synthetic tubes that can be paced down the borehole. At the moment the most common method is to use the rigid PVC pipes. Testing of the chemical composition of the water in the coal seam would allow the designer to know what type of wellscreen they can use.

The well liner is screwed together on the surface as it is lowered into the borehole. The first/bottom sections should be plain/un-slotted to keep the well free of any sediment that can build up at the base. The slotted sections fit together and are designed to be within the aquifer. This is the part of the liner that the water for the pump is drawn through. The slots on the plastic tubing are designed as a primary filter for the well. Once the wellscreen is in place then the borehole can be packed with a gravel filter and the top sealed to prevent ingress of surface water and pollutants.

Depending on the pressure of the groundwater and the horizon that it is being re-injected into the cooled water may require pumping into one or more boreholes for re-injection. All re-injection boreholes should be constructed using the same method as used for the abstraction well.

3.4 Environmental aspects

The drilling of these boreholes is for a renewable technology and this makes it even more important to ensure that there is as little environmental impact on the area from the drilling operations as possible. It would be counterproductive to install such a technology to the detriment of the environment it is trying to protect. During the drilling process it is of paramount importance to keep the works as clean as possible. During drilling there may be an abundance of rock chippings and water leaving the borehole in the flushed fluid. Using the rotary drilling method this fluid will pass through a series of filters to remove as much debris as possible before being re-circulated back down the drill. Although this method uses water or mud as a flushing agent it is relatively clean due to the necessity to retain as much of the flushing fluid as possible. DTH drilling can be a little messier as it uses compressed air along with water to blow the hole clean. It used to be common practice to blow the rock chippings and water straight out of the borehole onto the surrounding area. Environmental legislation has all but stopped this method in the majority of situations. One method of containing the water and rock debris is by the use of a 'clean drilling system'. This uses tubing connected to the drill rig and top of the casing that re-directs any blown water/debris along the hose ad into a baffled skip. The skip can be designed to partially separate the water from the rock. Depending on the depth of the borehole and amount of debris/water this skip can be emptied by tankers throughout the work or taken away and be disposed of in landfill. A 'clean system' set up can be seen in the following picture (fig 3.4.2).

Fig 3.4.2 Clean drilling system (supplied by Rocklift Ltd)

This rig is drilling boreholes for a closed loop heat pump and the coils for this can be seen on the right hand side of the picture. This rig is using a DTH and can be used for the drilling of waterwells. It can also be customised to use a water flush or mud flush rotary drilling technique. The skip on the left collects the debris/water from the borehole and is emptied periodically or replaced with an empty skip once it is full. SEPA do not allow the disposal of any groundwater or water used in industry into any waterway, whether it is a drain, sewer or open waterway. Some groundwater lies within horizons under pressure and when intercepted can flow to the surface in great volumes. This is known as Artesian water and occurs when the potentiometric surface of the water is above ground level. If artesian water is encountered the borehole may need to be abandoned if the water cannot be controlled. If the pressure and flow are not too great the artesian water could potentially save on pumping costs. When drilling into the groundwater all surface activities must be controlled to mitigate the potential for pollutants reaching the groundwater. Any fuel or oils must be securely stowed in containers and bunded.

4. Re-injection

An open source heating system taking groundwater from the coal seams will inevitably have to re-inject the cooled water. The re-injection of the water mitigates a number of risks involved with the abstraction of the water from the mine workings but it can also negatively impact the system if not properly designed. The two following diagrams illustrate two scenarios for a well doublet (Banks 2008). The first (fig 4.1) illustrates a well doublet where feedback between the wells isn't occurring and the second (fig 4.2) where feedback is occurring.

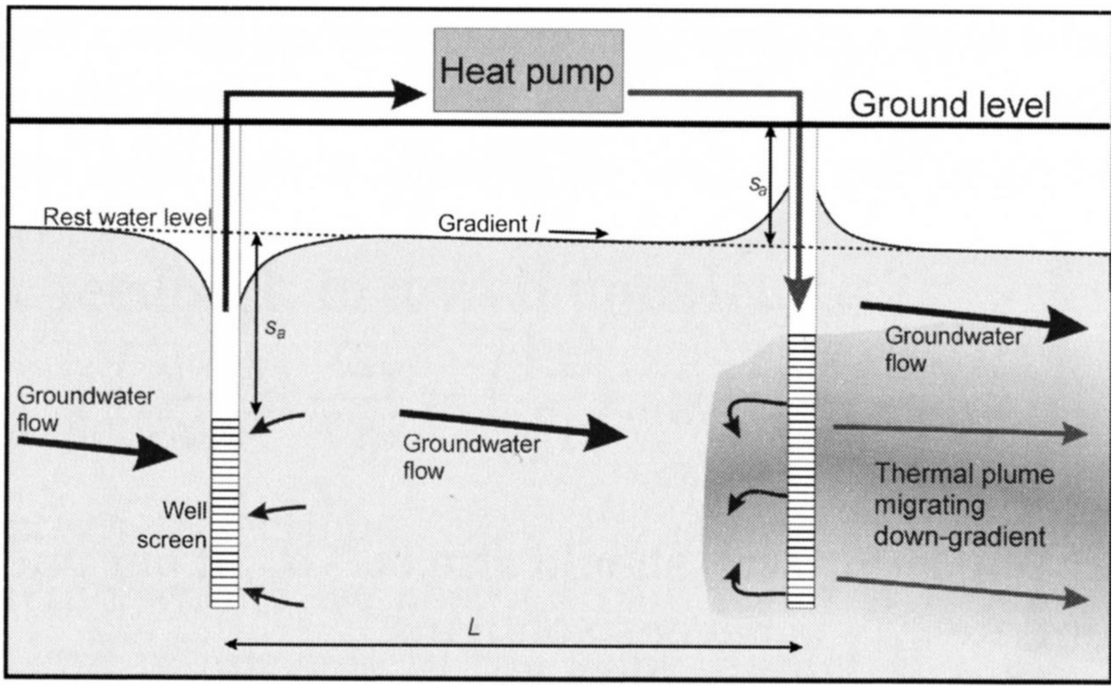

Fig 4.1. Well doublet with no thermal feedback (Banks 2008, p167)

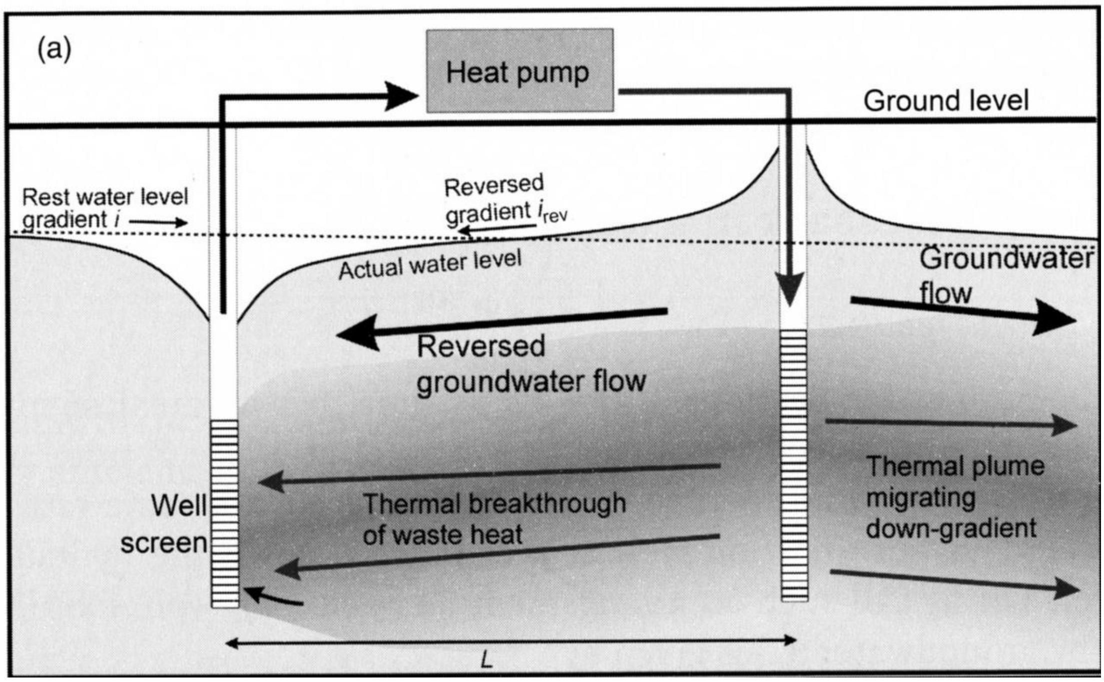

Fig 4.2. Well doublet experiencing thermal feedback (Banks 2008, p170)

A paper by Banks (2010) presents a number of calculations that can be used to numerically model the thermal plume for a homogeneous aquifer. The equations used allow the user to produce a mathematical 2-D model of the aquifer and its properties. It doesn't offer a conclusive answer as to how the aquifer will respond to the installation of a well doublet. It does however; allow the user to see if there is a risk of thermal feedback and the dimensions of the resulting thermal plume from a re-injection borehole. Banks (2008) makes clear that this isn't a solution to the complex modelling required to understand the characteristics of a reservoir. There is no input for 3-D transfer of heat to overlying or underlying strata. It also assumes that the thermal equilibrium between the matrix and the water is instantaneous. What it does offer is a conservative estimation of the properties of the thermal plume and breakthrough times. A number of these equations have been used in the model for this project and are described in detail later in the paper.

Further work by Shook (2001a) looks at the movement of water and thermal plume through a porous (non-fractured), permeable, heterogeneous aquifer using tracer tests. Tracer tests are the industry's standard way of testing the flow and thermal breakthrough times for geothermal reservoirs. A pre-determined volume of tracer is injected into the reservoir via the re-injection well followed by clean water. They are injected at the equivalent temperature and flow rate of the groundwater during normal running procedures for the installation. The tracer moves at the same velocity as the bulk fluid through the media. A retardation factor can then be applied to the tracer breakthrough time in the knowledge that the thermal front lags the fluid front at a constant rate. Using this method Shooks (2001a) predicts reasonably accurate breakthrough times for a heterogeneous media where the prominent flow is through pore space. The calculations do not take into account the change in viscosity of the fluid as it cools meaning the paths between the wells that it takes will change and the velocity of the fluid will also decrease. This method assumes a constant retardation rate between the movement of fluid and thermal fronts through a media. It does this by neglecting conduction and dispersion effects. Although this method does make a number of assumptions it is a hands on approach that uses the actual aquifer as a testing ground and therefore supplies reasonably accurate results.

Almost all of the work done on re-injection has been forced to make some assumptions about the reservoir and the water movement through it. This is because effectively predicting the sub-surface geology and the way in which groundwater travels through the rocks is incredibly difficult. Water moves through rocks via pore spaces and fractures and accurately calculating these properties is difficult, even in un-mined rocks. In mined areas, the estimation of these properties is even more difficult. There are some programmes available that can offer a comparatively accurate estimation of groundwater and heat movement through an aquifer, Banks (2008):

- SHEMAT: A German software used for the simulation of water flow, heat transport and contaminant transport.
- HST3D: A similar software package to SHEMAT produced by the US geological survey.
- FEFLOW: A commercial software package that can simulate "variable density groundwater flow, coupled with heat or solute transport" Banks 2008.

5. Modelling

The modelling section of this project is designed to estimate what the potential resource could be for a particular doublet system. A simple numerical modelling of groundwater and heat flow through idealised aquifer systems has been done. It is the intention to use this to investigate the potential thermal resource in a case study of a doublet (abstraction/re-injection) GSHP system in abandoned mine-workings in Glasgow. A spreadsheet model has allowed observations to be made with regards to geothermal output from the abstraction well. It also estimates what the final output would be once the water has been passed through a heat pump with known COP. As mentioned in the introduction one of the aspects that this project looks at is the re-injection of the cooled groundwater. The model will estimate the hydraulic and thermal breakthrough times for a single well doublet.

At this point it should be made clear that there have been a number of assumptions made during the making of the model. To simplify the model it has been assumed that the reservoir (i.e. the mined bedrock aquifer beneath Glasgow) is homogeneous. In reality it will contain a number of different stratigraphic layers with varying natural values for porosity, permeability, thickness etc. The aquifer will also contain a large number of faults and igneous intrusions that will either impede or enhance the flow through the aquifer. It is difficult to know about every single fault and intrusion within the sub-surface. With stratigraphic horizons that contain worked coal measures the effects of mining and post-mining collapse will have a major significance on the hydraulic properties of the aquifer. This will be both due to the location and permeability of high permeability zones formed by variously mined and collapsed coal seams (e.g. still open / partially collapsed / fully collapsed / fractured in the overlying rock), and the presence of engineered pathways between the different layers of rock. These engineered pathways could consist of shafts that may connect worked (and now abandoned) coal seams at different levels. This will further increase the permeability of the aquifer, a property which can't be guaranteed until the aquifer has been tested. It is also difficult to definitively predict the properties of the aquifer i.e. permeability, porosity etc without drilling into the rock and testing it. Sandstone from one area will have completely different properties to another and this applies to all rock types. The BGS has a large amount of borehole data but it tends to be rock type and there is comparatively very little data on the rock properties. Treating the aquifer as homogeneous required taking average values for each of the properties and using these within the spreadhseet. For the temperature of the reservoir a value of 12.5^{o}C was used as this appears to be the average value recorded in a number of texts and in the opinion of Brighid O'Dochartaigh from BGS would be the most likely temperature. In the first couple hundred metres of rock. Variables within the model that can be changed are length between the doublet, thickness of the aquifer and temperature difference between the doublet. These equations assume intergranular flow with the extraction and injection of the water along the same horizon. IN reality this will not be the case.

One of the most important variables that must be considered is the pumping rate (Z). For a heating or cooling system the flow rate along with the (ΔΘ) change in temp of the groundwater allow the Geothermal output to be estimated.

$$G = \Delta\Theta \, . \, \mathrm{Svcwat} \, . \, \mathrm{Z}$$

(5.1)

Knowing the geothermal output can then help with calculating the energy output from the heat pump. If a COP of 3.5 is assumed for the heat pump then the energy out can be calculated by.

$$H = \frac{\Delta\Theta \, . \, \mathrm{Svcwat} \, . \, \mathrm{Z}}{1 - (1/3.5)}$$

(5.2)

For cooling the equation reads:

$$C = \frac{\Delta\Theta \,.\, \text{Svcwat} \,.\, \text{Z}}{1 + (1/3.5)}$$

(5.3)

In all three of the above equations the value for Svcwat is 4180 J $kg^{-1}K^{-1}$ and the value for Z will be in ls^{-1}.

The only way to really find out what Z is likely to be for a site is by drilling down and pump testing the well. What we do know from previous work is that the carboniferous rocks of Glasgow tend to produce a Z of around 5 – 10 L S^{-1} and from the BGS borehole data we can see that the range is from 0.3 L S^{-1} to 32 L S^{-1} or 25 – 2750m^3 day^{-1}. Z is a product of Transmissivity, aquifer width and hydraulic gradient using the equation:

$$Z = -T.w.\frac{dh}{dx}$$

(5.4)

Where w = width, T = Transmissivity and $\frac{dh}{dx}$ = hydraulic gradient. The maximum pumping rate is determined by this equation but it can be lower than this depending on what the requirement of the installation is. This model is choosing to ignore this relationship and offer values depending on a varying (Z) pumping rate.

If Q is known along with values for (L) length between the well doublet and well radius (rw) then the drawdown (Sw) for the well can be estimated. Knowing Sw then allows for an estimation of (Δh) or head difference, then by dividing the Δh by L you can get the hydraulic gradient for the aquifer between the wells.

$$Sw = \frac{Z}{2.\pi.T} \,.\, \ln\left(\frac{L}{rw}\right)$$

$$\Delta \text{h} = 2\text{Sw}$$

(5.5)

This is assuming the upconing from the injection well is 100% of the drawdown on the abstraction, in reality it won't.

$$i = \frac{\Delta \text{h}}{L}$$

(5.6)

In the equation for Sw there is a requirement to know a value for T or transmissivity which is the ability of the aquifer to transmit groundwater flow.

$$T = K \, . D$$

(5.7)

Where D equals the aquifer thickness and K is the hydraulic conductivity or permeability. These two values will be constants in the model of the homogeneous aquifer along with L, rw, ΔΘ and T by comparison with K and D.

The spreadsheet model has been used to calculate the minimal distance required between the doublet to ensure against thermal breakthrough.

$$d < \frac{2Z}{T.\pi.i}$$

(5.8)

For the two equations above Z will be in m^3 day^{-1}.

Where U is the Regional Darcy Velocity which is the flow rate per unit through cross sectional area of the aquifer.

$$U = \frac{K.\Delta \mathrm{h}}{L}$$

(5.9)

What is now known is.

- D
- K
- U
- T
- Z
- i
- L
- rw

At this point a couple more assumptions are required about the porosity (ηe) and the volumetric heat capacity of the aquifer (Svcaq). Svcwat is known to be 4.18 MJ m^{-3} K^{-1}.

I can now estimate the (t_{hyd}) hydraulic breakthrough time and the (t_{the}) thermal breakthrough time for each doublet length L in relation to the other properties using equations proposed by Lippman & Tsang (1980) and Clyde & Madabhushi (1983).

$$\text{thyd} = \frac{L.\eta e}{K.i}\left[1 + \frac{4\alpha}{\sqrt{-1-4\alpha}}\tan^{-1}\left(\frac{1}{\sqrt{-1-4\alpha}}\right)\right]$$

(5.10)

and

$$\text{tthe} = \frac{Svcaq.L}{Svcwat.K.i}\left[1 + \frac{4\alpha}{\sqrt{-1-4\alpha}}\tan^{-1}\left(\frac{1}{\sqrt{-1-4\alpha}}\right)\right]$$

(5.11)

where α is calculated by the equation below and Svwat and Svcaq are in MJ m^{-3} K^{-1}.

$$\alpha = \frac{Z}{2.\pi.K.D.i.L} = \frac{Z}{2.\pi.T.i.L}$$

(5.12)

It is these two values t_{hyd} and more importantly t_{the} that I will compare against changing values for L, K and D to give a picture of how the doublet will function depending on what the properties are once the well has been drilled.

A lot of these calculations can’t be done until an abstraction well has been drilled. The equations and the model used have been tested against work and calculations carried out in other pieces of work on the topic. In a paper by Banks (2010), he takes a look at the chalk aquifer of London. He uses similar equations to produce a 2-D view of a homogenous chalk aquifer. In his book (2008), Banks devotes a chapter to the methods used in the design of an open source heat pump. A number of the equations used have been taken from this work. Examples within the book and the paper (Banks 2008, Banks 2010) were used to verify the work done in the model for this project. To really understand how a doublet will perform and how it may influence the reservoir beyond the abstraction and re-injection wells either 3-D modelling or tracer testing should be used. In a paper by Shook (2001), he describes the use of tracer testing to predict the thermal breakthrough in a heterogeneous media.

The model/spreadsheet that was produced for this project used equations taken form a couple of pieces of literature. The equations for the model were taken from between the paper by Banks 2010 looking at breakthrough times and his book on thermogeology, Banks 2008. During and after the completion of the spreadsheet it was tested against the example for thermal feedback times and geothermal output in the literature. When the figures used in the literature examples are put into the model for this project the exact same answers were recorded.

6. Case studies

The project involved the study of two particular areas in the 66SW area of Glasgow to illustrate the estimation of thermal potential form mined areas and the issues involved in designing a GSHP system. One area was chosen through consultation with Sustainable Glasgow and looked at a possible development opportunity in the Tollcross region near the Mutton Pit. The other site picked an area on the south side of the river in Rutherglen. The site in Rutherglen is located near the Govan Pit # 5 and will present an area with more challenging drilling concerns due to the depths involved. Both sites are located in the NS66SW block of Glasgow around the Commonwealth village, an area that is expecting a lot of re-generation over the coming years. Both of the study sites are in extensively mined areas and in an area (grid square NS66SW) in which the BGS have collated and interpreted a large amount of data on the location and characteristics of mine workings. This means that there is a lot more valuable information for these areas compared to other areas of Glasgow. The geology of the block NS66SW is roughly the same throughout the entire area. The area consists of the Scottish Coal Measures of which there are three, the Lower, Middle and Upper in decreasing order of age. Each of the Coal Measures Group subdivisions contains uniquely identifiable coal seams. The coal measures in this area have been faulted on their northern and southern limits (fig 6.1).

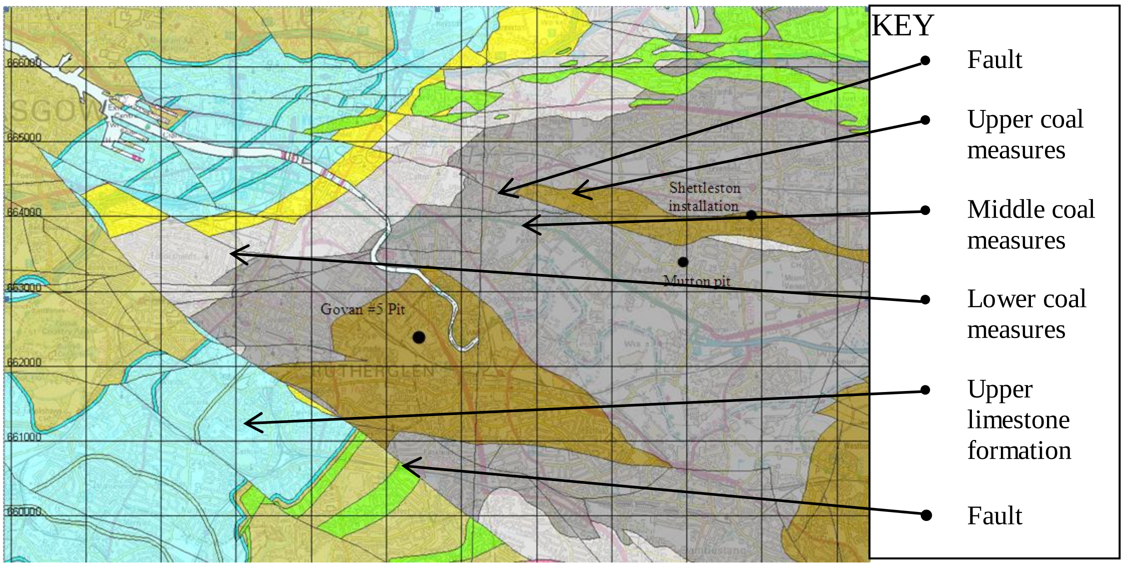

Fig 6.1. Bedrock Geology of Glasgow at 1:50 000 scale (Supplied by the BGS)

Within the diagram above the oldest rocks are the Upper Limestone Formation, not part of the Coal Measures Group; this is overlain by the lower then the middle then the upper coal measures. A large fault is visible running NW-SE along the western edge of the map. This has thrust the limestone formation up above the coal measures. There are many other faults throughout the map but none have altered the strata as much as the one on the south western side. As mentioned before these faults can either be pathways for water increasing the hydraulic conductivity or they can be full of impermeable clay material and reduce permeability. The faulting around the coal measures has resulted in a depressed structure known as a syncline centred round the Govan #5 pit. This bowl like depression round Govan #5 can be better visualised in the BGS 3-D stratigraphic map (fig 6.2). This is a W-E cross section through the NS66 block. Not all of the stratigraphic layers are represented but only 4 of the coal seams. The coal seams that are represented are the Glasgow Upper (yellow), Ell (green), Splint (blue) and the Kiltongue (purple). These are listed in order of youngest to oldest with the first three existing in the middle coal measures and the last in the lower coal measures.

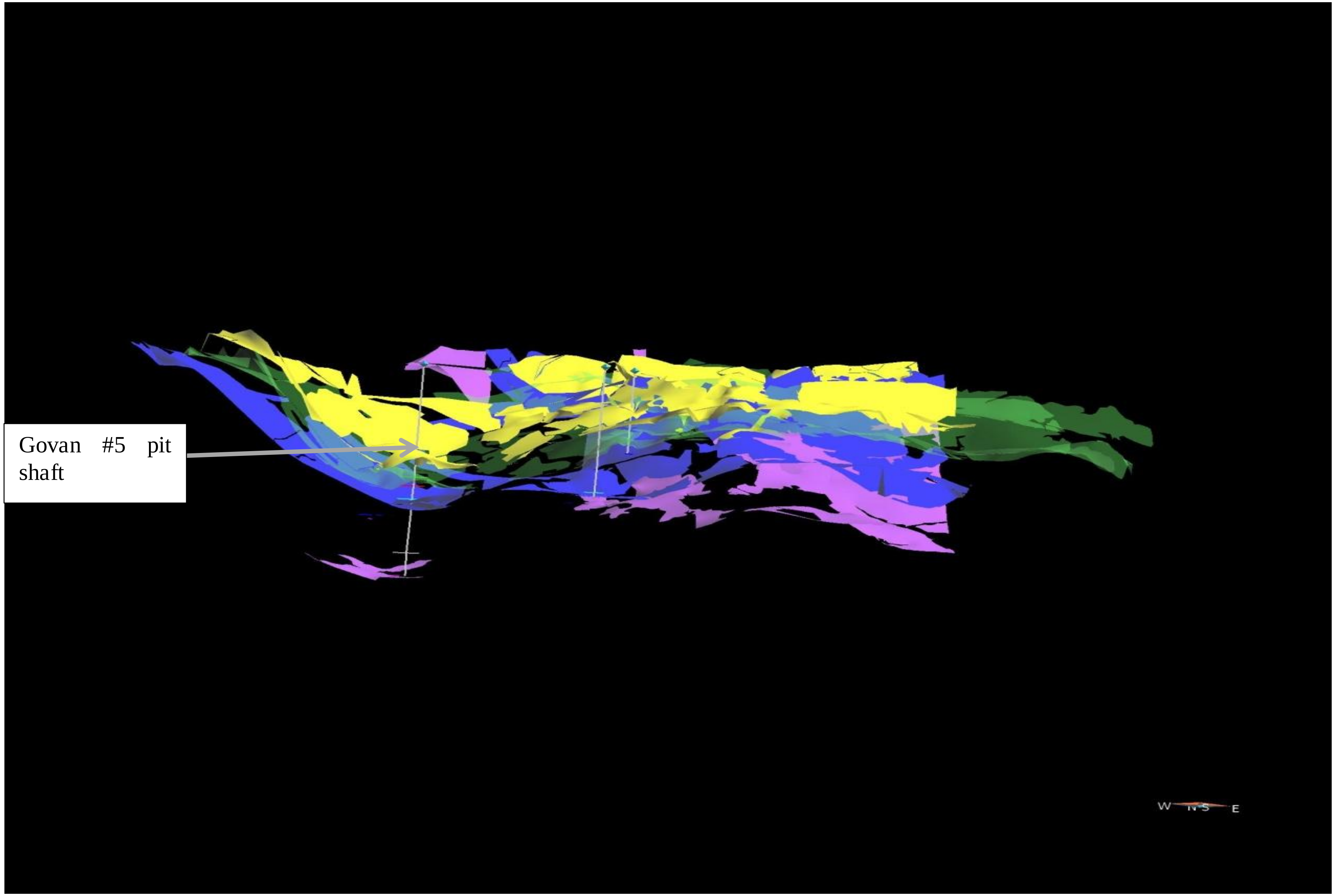

Fig 6.2. 3-D geological cross section of the coal measures in block 66SW. (supplied by the BGS)

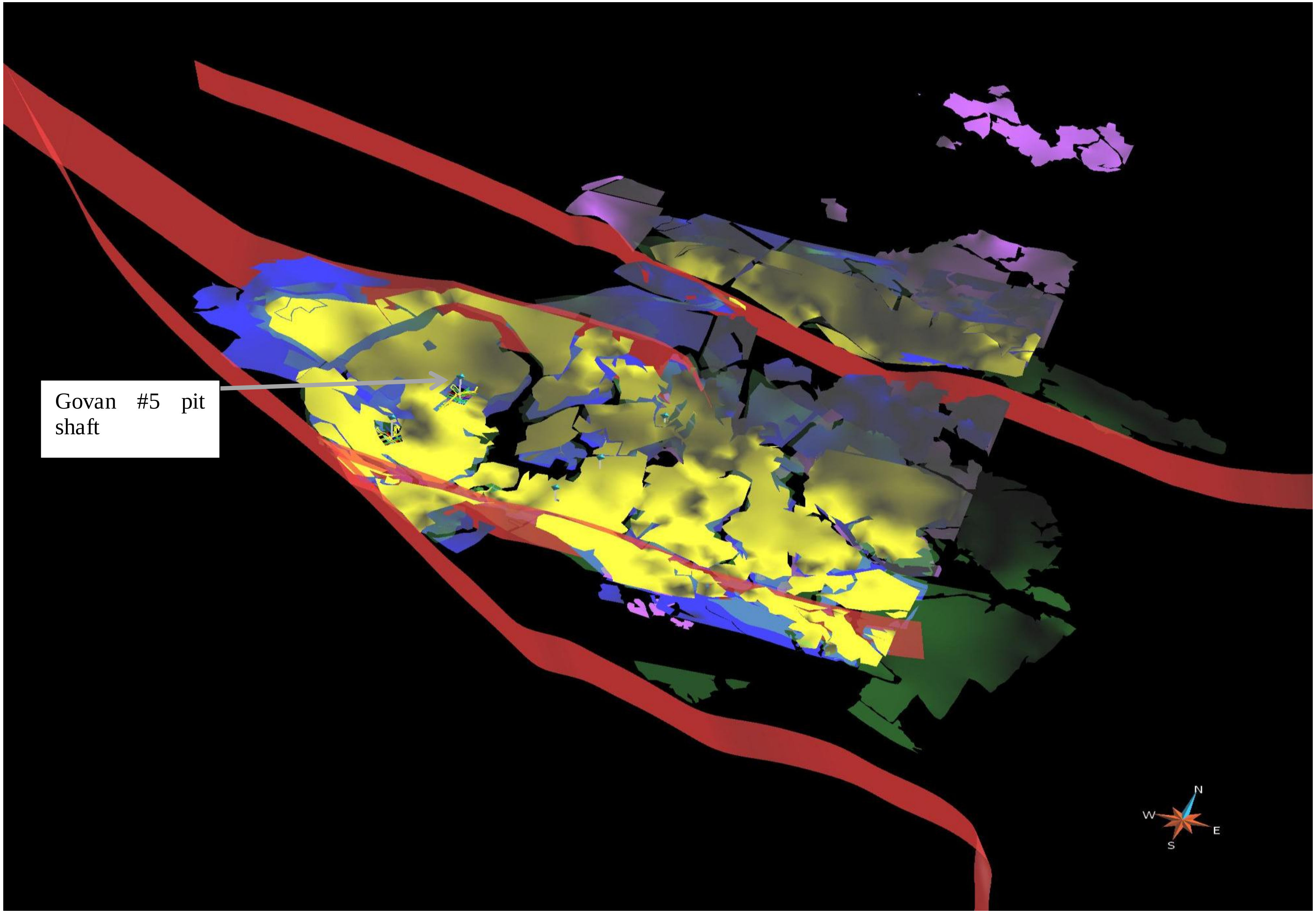

Fig 6.3 Tilted plan view of the 3-D section showing major faults. (supplied by the BGS)

From the diagram (fig 6.2) it can be seen how the stratigraphic layers form a bowl like depression in the West and then again but less pronounced in the East. This structure forms in geology when the rocks are put under pressure and buckle changing the order of how the different stratigraphic horizons appear on the surface. The next set of diagrams (fig 6.4) explains how the rocks are laid down and then faulted to appear that older rocks lie on top of younger ones.

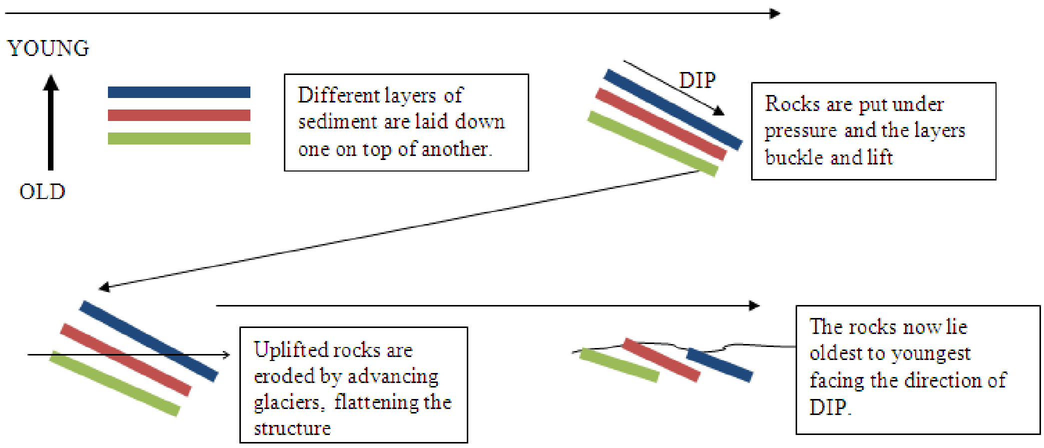

Fig 6.4 Sketch showing the folding of the rock horizons.

The basin like structure can be seen again in figure 6.3, where the fault lines are picked out in bright red. Only the major faults within the strata have been included within the BGS 3-D model because putting in all of these structures would be very time consuming. What can be seen by the inclusion of these four main fault zones is that they appear to cut off the coal measures creating an enclosed bowl. This gives a fairly detailed view of the overall geology of the area but to design an open source system within this each site must be looked at individually. The four coal seams represented in the two 3-D sections are not the only coal bands in the coal measures of Glasgow. The Middle Coal Measure alone has a number of other coal seams between the layers of sandstone and limestone.

In descending order they are:

- The Glasgow Upper Coal
- The Glasgow Ell Coal
- Glasgow Main Coal
- Glasgow Humph Coal
- The Glasgow Splint Coal
- The Glasgow Virgin Coal

Middle Coal Measures

- The Kiltongue Coal
- The Upper Drumgray Coal
- The Mid Drumgray Coal
- Scottish Gas Coal
- Mill Coal

Lower Coal Measures

The Virgin is the deepest of the coal seams in the Scottish Middle Coal Measures after which the coal seams of the Scottish Lower Measures take over, the first being the Kiltongue Coal represented in the 3-D sections. With respect to this project the coal seams below the Kiltongue will not be considered during this project due to their existence at great depths in the majority of the area.

6.1 Tollcross site

The location at Tollcross was selected after consultation with Sustainable Glasgow and BGS where the decision was made to match a future housing development site with an abandoned pit. Sustainable Glasgow is interested in the potential of thermal heating/cooling resource of mine-water for future developments within the city. This case study looks at the potential and the issues connected for one particular site. The site that has been chosen is a proposed development of new housing along Wellshot Road in the Tollcross area of Glasgow, grid reference 26389 66338 (fig 5.1.1).

Fig 6.1.1 Location of Mutton Pit and proposed area for development

This location offers the chance to look at the site of a proposed development close to an abandoned mine-shaft. The shaft closest to this site is the Mutton Pit of the Tollcross Colliery abandoned in October 1897. The development area lies within the circled zone on the map in figure 6.1.1. This location is also very close to the Shettleston installation discussed within the literary review.

The Mutton pit was part of the Tollcross colliery and initially worked the Virgin coal seam. The abandonment plans for the Mutton pit indicate that the ceiling of the Virgin seam is at 18 fathoms (fig 6.1.2). Taking the British Fathom to be 1 fathom to 1.85m the ceiling of the virgin should be at about 33-34m below ground level. These are reasonably shallow mine workings and because of this the existence of groundwater cannot be guaranteed. Groundwater in Glasgow is fairly variable, borehole records from around the Tollcross site vary between 5mbgl to 39mbgl. There is a risk that these mine workings may not contain any groundwater and there is the potential risk of de-watering the mine during pumping. This could allow dangerous mine-gas to build up in the void spaces left by the pumped water. Water levels could only be proves by local testing and a deeper level may have to be looked at for the installation. At the moment it will be assumed that the mine-workings contain enough water to support the system. The hashed areas in the abandoned mine plan (fig 6.1.2) are parts of the mine where the roof has been allowed to collapse in after the coal has been extracted. The solid blue lines and white coloured blocks represent the roadways to each of the worked areas. Some of these roadways may not be still be open as these plans date back 1898. The areas that are most likely to still contain open roadways are those around the pit entrance as they received the highest degree of support when the mine was being worked. From the abandonment plans it can be seen that both the Air pit and the Mutton pit are located close to the proposed development site.

From the geological maps in the BGS GIS systems the position of the Mutton Pit can be viewed between the Splint and Main outcrops (fig 6.1.3). This means that the outcropping bedrock that underlies the sediment in this area is the sandstones and other sedimentary horizons between these two coal seams, probably close to the Humph coal.

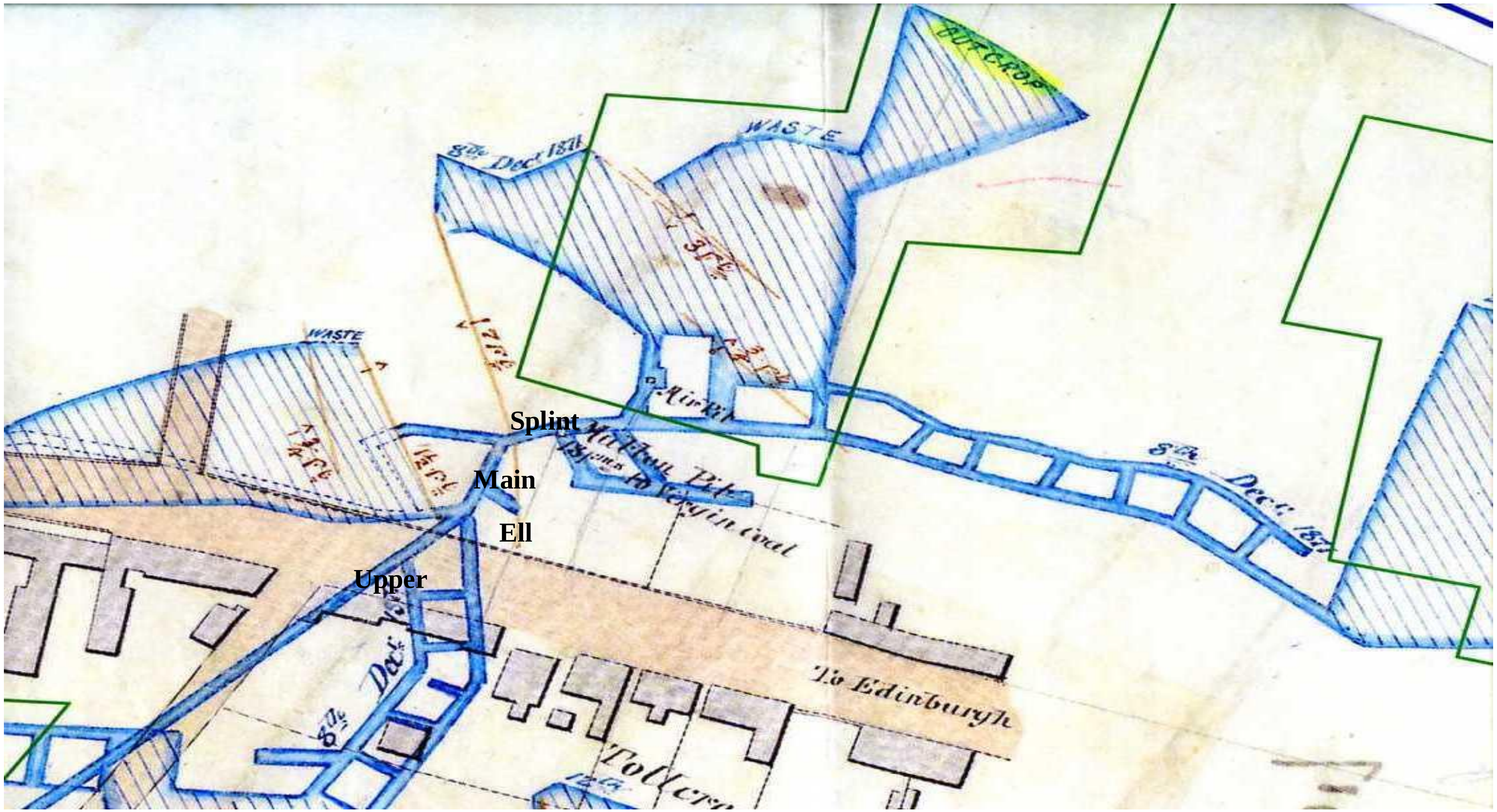

Fig 6.1.2, Abandonment plan for the Mutton pit Shaft, Tollcross colliery (Supplied by the BGS)

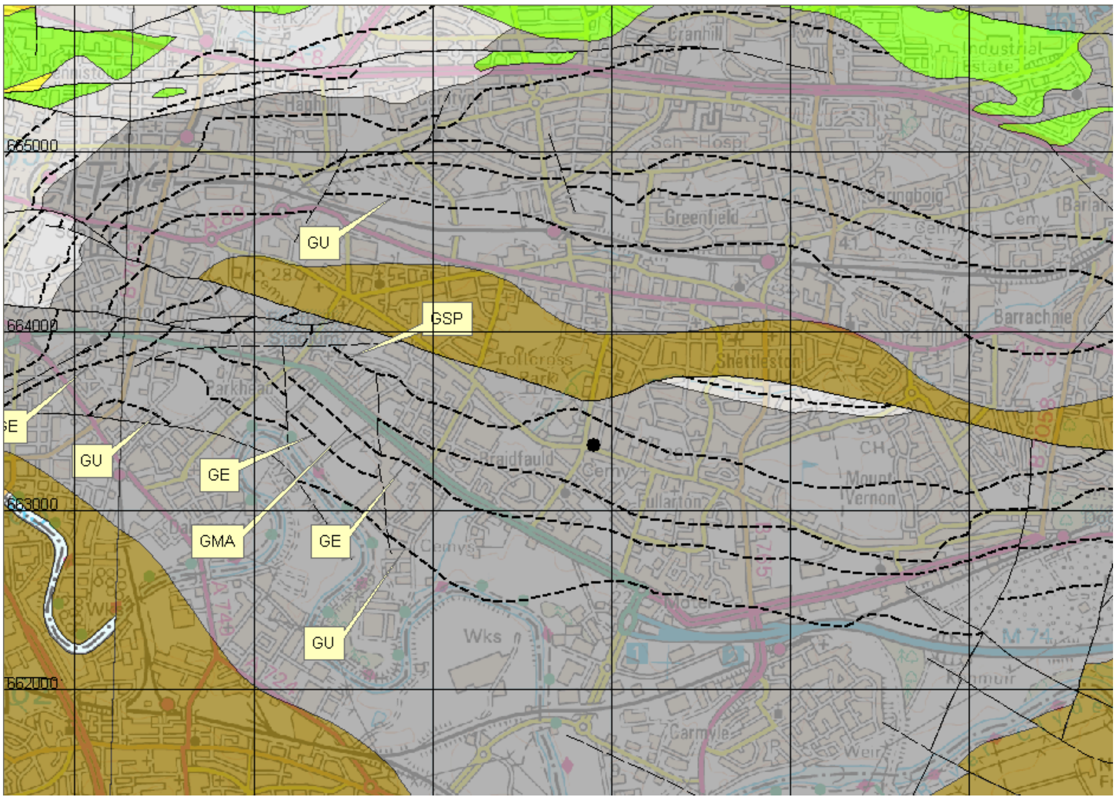

Fig 6.1.3 Location of Mutton pit in relation to coal outcrops. (Supplied by the BGS)

The black dot represents the Mutton pit while the dotted lines indicate where each of the coal seams outcrop. The map shows that it is lying in between the Main and Splint seams which mean that it has been drilled into older rock than the Main seam and younger than the Splint, see fig 6.4 for reference. This means that the coal seams available at this site will be the Splint and the Virgin of the Middle Coal Measures and any worked seams from the Lower Coal Measures.

The abandonment plans give a good visual representation of what the mine workings look like and the possible areas of increased permeability. Along with having access to the abandonment plans for old mine workings and geological maps the BGS have a large collection of borehole data. This can be accessed through their internal GIS systems or via their website (www.bgs.ac.uk), following the links towards the GeoIndex. The borehole logs allow a more detailed picture of the depth of geology for a particular site. Within their records the BGS have the borehole log (fig 6.1.4) from the Mutton Pit and from this it can be concluded that the Virgin seam was not the only one worked from this Shaft.

MUTTON PIT,TOLLCROSS U/G BH			
Non-confidential (Code : 1)			
NS66SW BJ 160.	(BNG E / N)	**263890 0663380**	
Surface Level (m):			
Drilled Length (m):	62		
Entered by:	E_EPS	31-Oct-88	
Updated by:	KAH	27-Sep-07	
Interval Details (Interpreter : AAMI)	**Base Bed**	**Thickness**	**Depth (m)**
Sediment & Overburden		18	0-18.00
(MCMS) Sandstone		5	18.00-23.00
Undefined sedimentary		0.8	23.00-23.80
(HUC) Humph Coal		1.3	23.80-25.20
(MCMS) Sandstone/mudstone/breccia		6.5	25.20-31.70
(GSP) : Splint coal		0.03	31.70- 31.725
(MCMS) : sedimentary rock (undifferentiated)		2.44	31.725 - 34.165
(VI) : Virgin coal		0.91	34.165-35.075
(MCMS) : sedimentary rock (undifferentiated)		0.10	35.075-35.175
(MCMS) : coal		0.05	35.175-35.225
(MCMS) : mudstone		0.08	35.225-35.305
(MCMS) : sandstone (undifferentiated)		3.86	35.305-39.165
(MCMS) : sedimentary rock (undifferentiated)		1.35	39.165-40.515
(COMC) : Coatbridge musselband coal		0.33	40.515-40.845
(MCMS) : sedimentary rock (undifferentiated)		2.26	40.845-43.105
(MCMS) : sandstone (undifferentiated)		5.10	43.105-48.205
(MCMS) : claystone, seat-earth		1.14	48.205-49.345
(ABBC) : coal		0.20	49.345-49.545
(MCMS) : claystone, seat-earth		1.09	49.545-50.635
(MCMS) : sandstone (undifferentiated)		3.43	50.635-54.065
(VDMB) : mudstone		3.50	54.065-57.565
(LCMS) : limestone		0.56	57.565-58.125
(LCMS) : sandstone (undifferentiated)		1.14	58.125-59.265
(AV) : coal		0.25	59.515-59.765
(AV) : claystone, seat-earth		0.58	59.765-60.345
(AV) : coal		0.23	60.345-60.575
(LCMS) : sedimentary rock (undifferentiated)		3.81	60.575-64.385
(BELC) : coal		0.25	64.385-64.635
(LCMS) : sandstone (undifferentiated)		2.29	64.635-66.925
(LCMS) : mudstone		2.82	66.925-69.745
(LCMS) : ironstone		0.10	69.745-69.845
(LCMS) : sedimentary rock (undifferentiated)		1.93	69.845-71.775
(LCMS) : mudstone, carbonaceous		0.23	71.775-72.005
(LCMS) : mudstone		2.08	72.005-74.085
(LCMS) : mudstone, carbonaceous		0.33	74.085-74.415
(LCMS) : sedimentary rock (undifferentiated)		3.73	74.415-78.145
(KMUB) : ironstone		0.13	78.145-78.275
(LCMS) : claystone, seat-earth		1.24	78.275-79.515
(LCMS) : sandstone (undifferentiated)		8.68	79.515-88.195
(LCMS) : sedimentary rock (undifferentiated)		3.25	88.195-91.445
(KILC) : Kiltongue coal		0.81	91.445-92.255
(LCMS) : sedimentary rock (undifferentiated)	TERMINAL DEPTH	1.24	92.225-93.495

Fig 6.1.4 Borehole log for the Mutton Pit (supplied by the BGS)

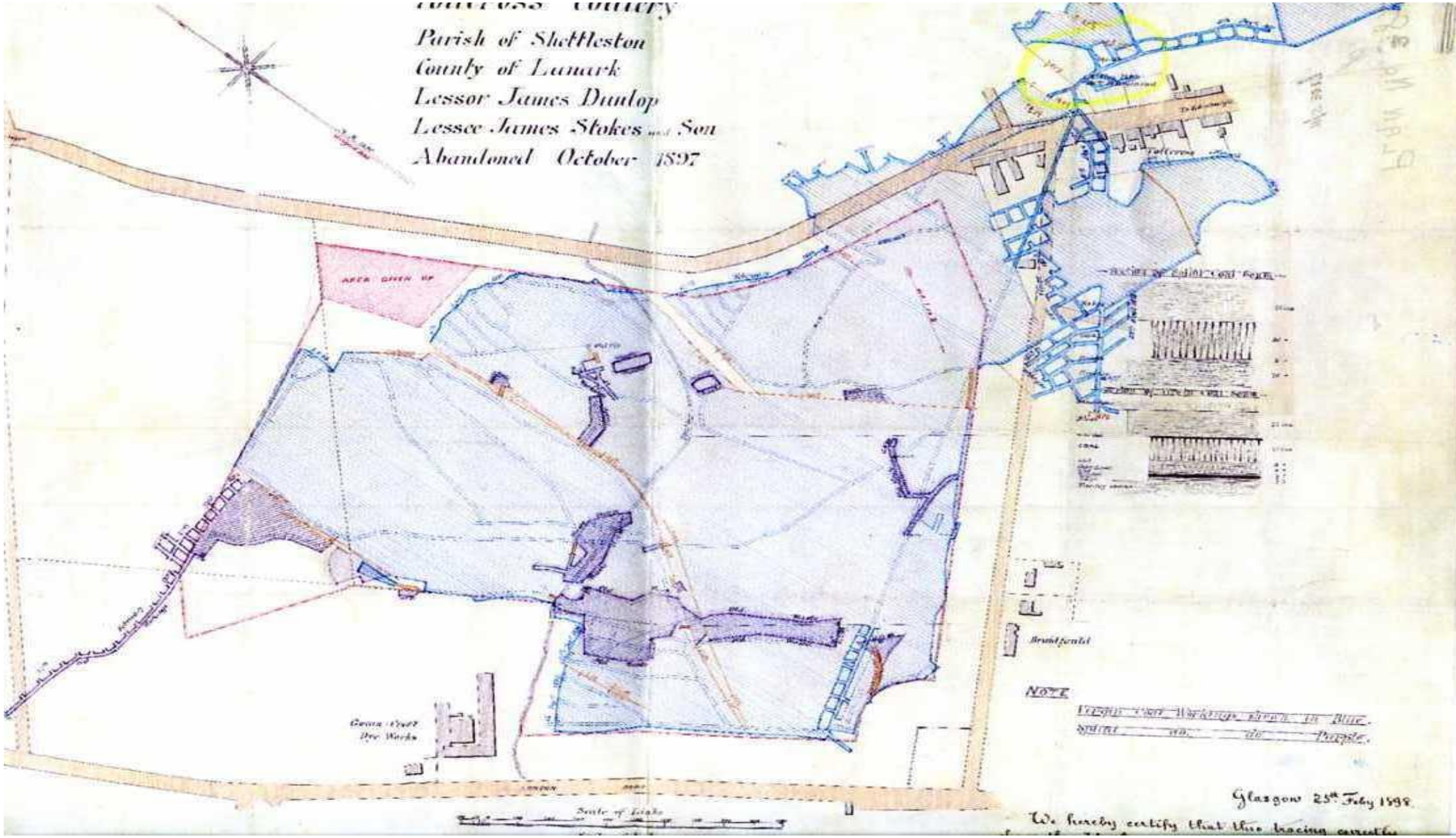

Fig 6.1.5, Large abandonment plan showing the connection between the Mutton pit and the rest of the worked Virgin seam in this area (Supplied by the BGS)

The original borehole log for the Mutton pit dates from 1827 and is recorded in fathoms from the pavement of the Splint seam. The BGS have taken this original log and changed the depths into metres. One fathom is equivalent to around 1.85m. In the original log there is some confusion over the depth of the Splint pavement and the Virgin seam, both appear to be around 18 fthms. The borehole log (fig 5.1.4) is an interpretation of both logs and other borehole data from around the Mutton pit. From the original 1827 log and the 1898 abandonment plan the Virgin is interpreted as being at about 18 fthms/ 34m. The borehole log is a direct copy of the one taken from the BGS system but the rock overlying the Splint estimated from other borehole logs in the area. The second of the abandonment plans (fig 6.1.5) indicates how large an area this pit connects to. One issue of concern is that the development site is located in the North end of the worked Virgin seam. The rocks in this part of Glasgow dip to the south. This could mean that a borehole drilled in this area would be up gradient of any old workings in the Virgin seam, this may impact on the water movement towards the well. There is a large fault running along the top of this site (fig 5.3) throwing the rocks to the north up. This fault may act as a potential path for water between the stratigraphic layers or it may contain clay-like material and act as an impermeable barrier. Data for mines in the area adjacent to the fault should contain details of the material in the fault line. One other possible concern is that Glasgow City Council's records indicate that there has been some grouting carried out on the Splint and Virgin seams on Wellshot road (fig 6.1.6). The work was carried out between 19/01/1987 and 16/04/1987. During this period 914 tonnes of grout was pumped into the Splint seam and 808 tonnes into the Virgin seam. Grouting is used in coal mining areas to fill the voids left by the mining activities, helping to prevent subsidence once the property has been built. Comparing the grouting plan (fig 5.2.3) and the abandonment plan (fig 5.2.1) it is easy to see what part of the workings has been grouted. Unfortunately the answer to whether or not the aquifer has been affected by the fault and/or the grouting can't be determined until the borehole has been drilled and pumping of groundwater has commenced.

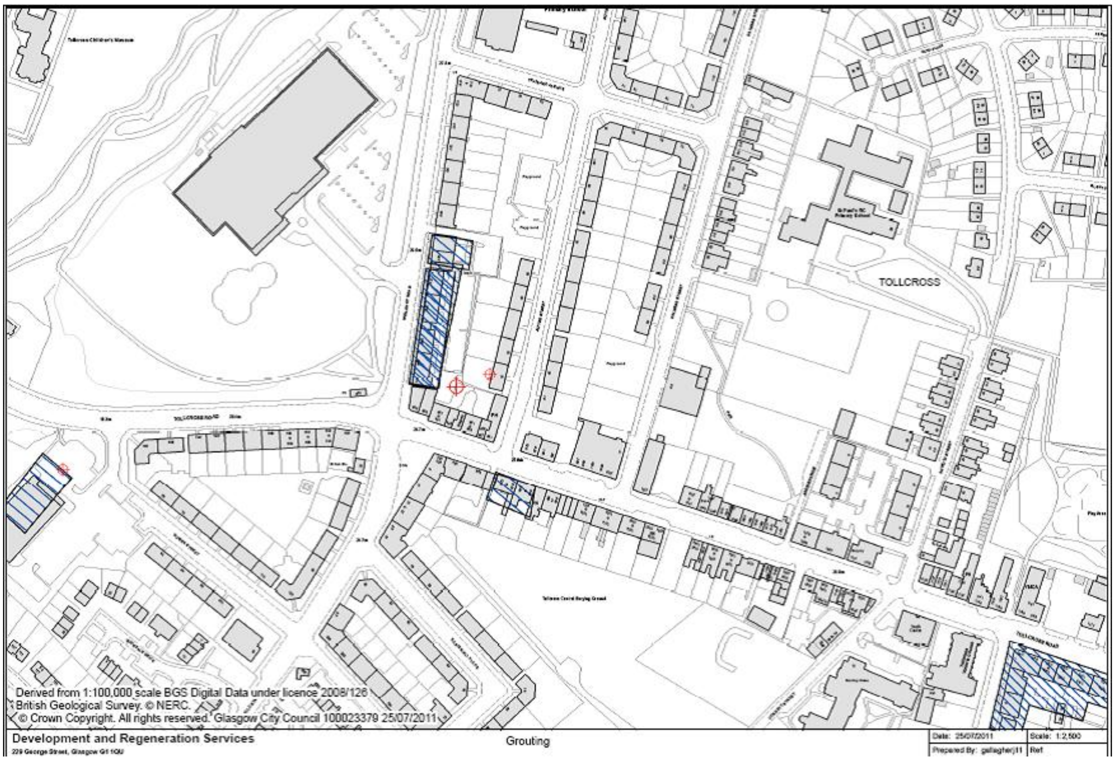

Fig 6.1.6. Grouting plan for Wellshot road. (supplied by Glasgow City Council)

The dashed blue rectangle along Wellshot Road is the grouted area and the red crosshair is the location of the Mutton Pit.

Putting this location through the spreadsheet model requires a few assumptions about the properties of an aquifer at this site. The abandonment plans only indicate the area worked within the Virgin seam but looking at the borehole log there appears to be a number of coal seams at greater depth. If a well draws from above and around itself then a borehole into the Virgin at this point would only have around 17-19m of aquifer thickness to draw from provided there are no impermeable layers. At this point it must be made clear that the assumption that the 17-19m is homogeneous and doesn't contain any faulting. In reality the faulting of the rocks around the extracted coal is why these areas could potentially contain a large thermal resource. The model requires the aquifer to be considered as homogeneous and although this may seem unrealistic the model can still be used to calculate conservative results. The aquifer thickness also doesn't take into account any water within the superficial deposits because the model is using equations designed for the calculation of water movement through pore space in solid rock. It is known from the Shettleston installation that the pumping rate (Z) is between 5-10 l s^{-1}. Taking the mean value between these two as 7.5 l s^{-1} or 648 $m^3 day^{-1}$ gives a rough estimate as to the possible pumping rate. If a pumping rate of around 684$m^3 day^{-1}$ is to be assumed then this can be applied to the groundwater flow rate (Q). The volumetric heat capacity (Svcaq) is assumed to be around 2.5 MJ m^{-3} K^{-1} and 4.18MJ m^{-3} K^{-1} and 4180 J kg^{-1} K^{-1}. This is taken from a couple of borehole records in the NS66SW block. An average porosity between all of the strata can be assumed to be around 0.25 by taking the average porosity values from a number of available texts for each of the stratigraphic horizons. Estimating the permeability of the aquifer is the tricky bit. Within this location the Humph and the Virgin are of workable thickness, the Splint at only 0.03m may have not been economically efficient. During extraction the height of the Room or extracted area would have been in the region of +2m. The model will assume a height of extracted rock to be 2m for both the Humph and Virgin seam giving a total thickness of extracted rock for this area at 4m. The model will also assume that all of the worked area will have collapsed back into itself to maintain a homogeneous approach. In reality as suggested by the Bill McLean's work of the BGS, 5% of the workings will remain completely open with a very high permeability. The model will assume that 4m of worked rock representing 22% of a 17m aquifer has a 10% increase in its void space as mentioned in the literature review. The 10 % increase in void space is assumed to be negligible when considering the overall porosity of the aquifer. A 10% increase for and area representing 22% of the total aquifer would increase the porosity form 0.25 to 0.26. The permeability will be the big change and it affects the value for transmissivity which along with the hydraulic gradient determines the flow rate. A lot of this will be unknown for this aquifer until a well has been drilled and the maximum flow rate determined. Therefore for this model it is assumed that the hydraulic conductivity (K) for the whole 17m thick aquifer is 1 m day^{-1} meaning the Transmissivity is 17 m^2 day^{-1}. This is a conservative estimate for the zone of increased permeability and without data for permeability values for abandoned coal seams conservative assumptions must be made. The geothermal resource potential is determined by the pumping rate and difference in temperature of the water between the abstraction and re-injection using equation 5.1. To estimate the heat resource potential the COP of the heat pump unit must be included in the equation 5.2. For this model a COP of 3.5 will be used for the heat pump unit.

Using equation 5.2 the output for this aquifer would be 463 kW_{th} for a pumping rate of 684 m^3 day^{-1}. The graph in figure 6.1.7 indicates how this resource will change with the pumping rate.

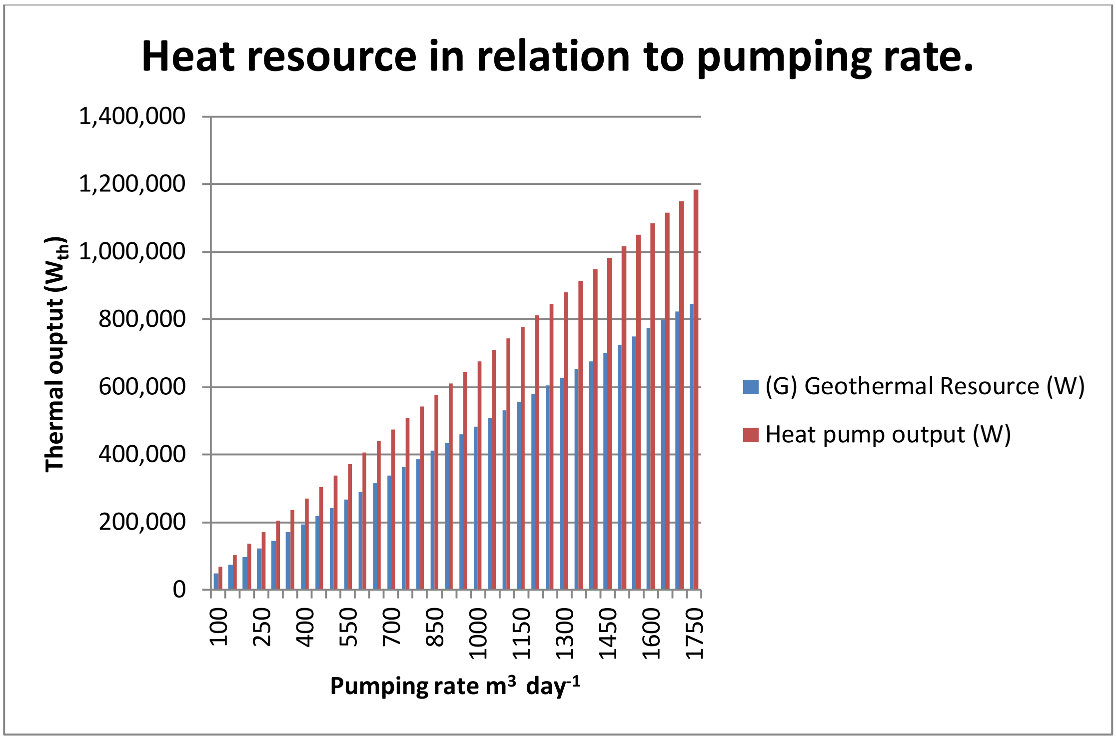

Fig 6.1.7 Heat resources in relation to pumping rate

Installing a well doublet system at this location assuming these aquifer properties will produce 463 kW_{th}. Re-injecting the water back into the ground helps with the re-charge of the groundwater and helps mitigate some environmental issues with the abstraction of groundwater. Re-injecting the water can have a negative effect on the heat resource. If the re-injection well is not carefully designed the life of the doublet system can be dramatically reduced due to thermal feedback from the cooled water entering the ground. A basic equation (5.8) can be used to estimate the minimal distance required between the boreholes to prevent thermal feedback. For this aquifer the well doublet would need to be positioned over 2.6km away assuming a hydraulic gradient of 0.01. This is not practical so a better understanding of the lifetime of the well doublet system is required. This equation requires the assumption that the abstraction and re-injection wells are located in the same horizon. The existence of impermeable layers throughout the stratigraphy means that the re-injection well could be positioned much closer to the abstraction well and above it in a different horizon. The impermeable layer would prevent the cooled water from reaching the part of the aquifer that the abstraction well was drawing from. The abstraction well at the Tollcross site would preferably be situated close to the pit shaft which is at the south end of the site. This limits the space down gradient for the installation of the re-injection well. A realistic down gradient length (L) of 50m between the doublet can be assumed and using equations 4.11 and 4.12 the time for thermal and hydraulic feedback can be estimated. For a well doublet system 50m apart, removing 10°C, in an aquifer 17m thick with a hydraulic gradient of 0.01, ground flow of 684m^3day^{-1} and Transmissivity 17.0 m^2 day^{-1} the thermal breakthrough time would be 10 days. This is assuming a homogeneous aquifer. This breakthrough time of 10 days assumes constant work by the heat pump 24 hours a day so the actual breakthrough time would be much longer. It doesn't consider re-charging of the groundwater heat in the Summer months when using the open source system to cool the building, although 10 days isn't a long enough time period for the seasons to affect the result. The following graph (fig 6.1.9) highlights the results of a simple sensitivity analysis done on the model. It shows the relationship between thermal feedback time, pumping rate and doublet length.

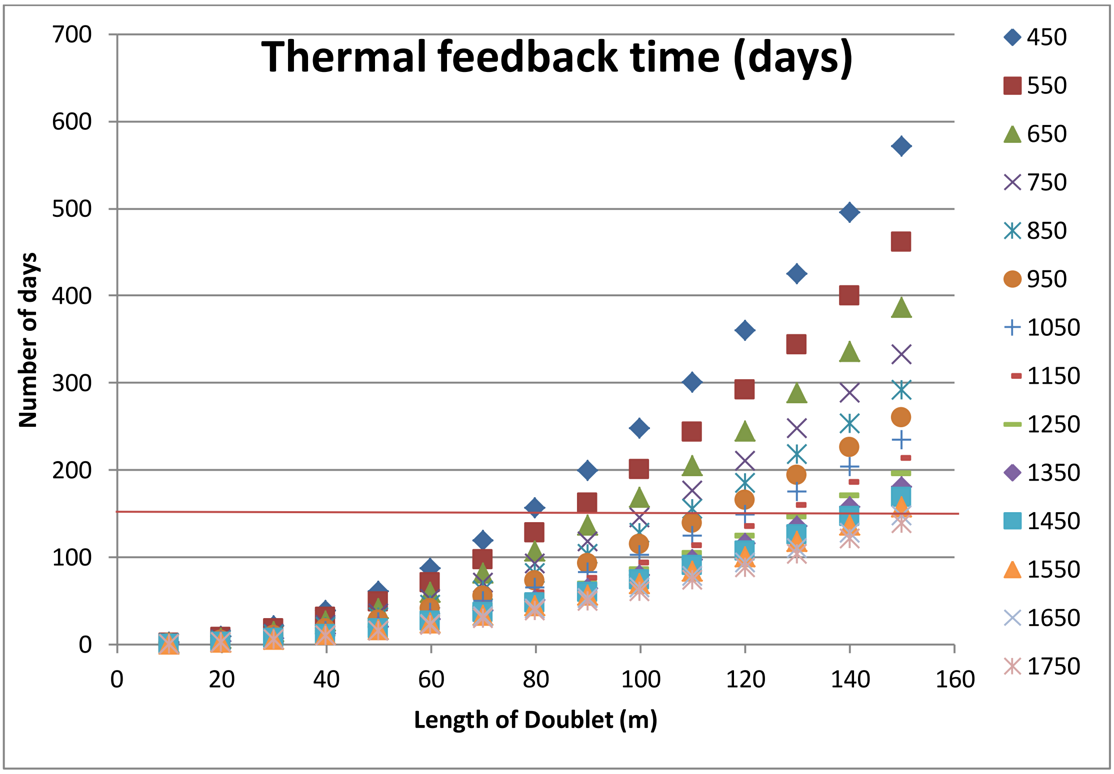

Fig 6.1.8. Legend values are pumping rate (Z) in m^3day^{-1}

The pumping rates are in the legend at the right hand side of the graph and are in m^3day^{-1}, the red line indicates 150 days. It is clear from the graph that the time for thermal feedback increases the lower the pumping rate and the further apart the well doublet are. These results are calculated assuming a fairly high estimation of the hydraulic conductivity at 1.0 m day^{-1}. The dimensions of the aquifer have a large impact on the thermal feedback times as can also be seen in the next graph (fig 6.1.10).

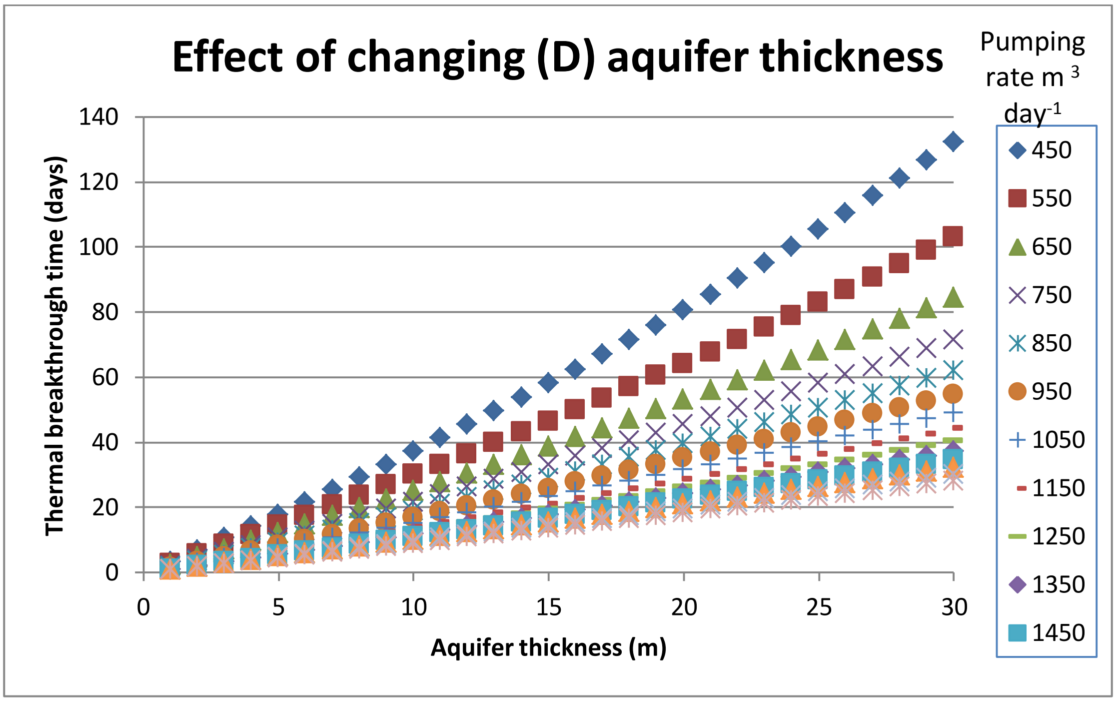

Fig 6.5.9 Thermal breakthrough time in relation to pumping rate and aquifer thickness.

The thickness of the aquifer appears to not have such a dramatic effect as the length between doublet. Thermal breakthrough times increase at a constant rate in relation to an increase in aquifer thickness.

The reason for looking at these sites is in the hope that the extraction of the coal has increased the fracture permeability of the rocks surrounding the worked seams. In consultation with Crane of BGS it was discussed that the permeability could be in the range between 0.01 – 1m day^{-1}. This is the permeability of the whole height of the aquifer that is being considered, the mined seams themselves would have much higher permeability. Increasing permeability increases the yield of the well and therefore the geothermal resource. It also has a decreasing effect on the drawdown of the well and increases the breakthrough times for a homogeneous aquifer using this model. Using all the same aquifer properties for before but changing the permeability value in relation to pumping rate a graph was produced (fig 6.1.10)

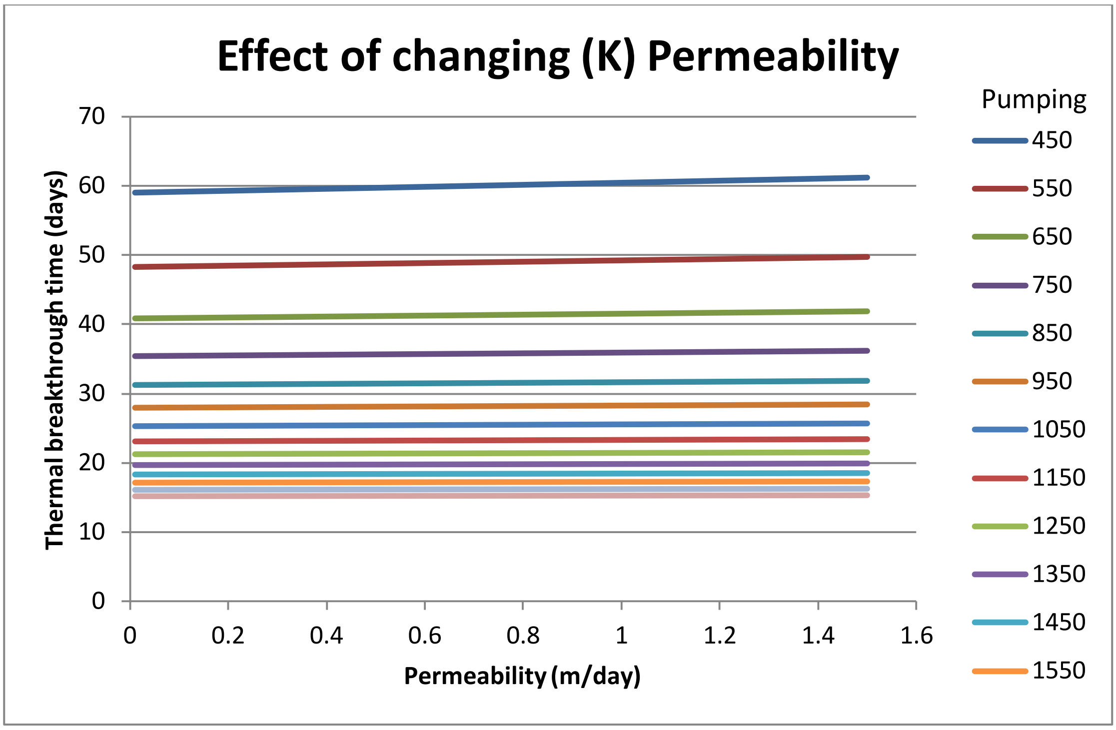

Fig 6.1.10 Effect of changing K and Z on thermal feedback times.

The graph indicates that the higher the permeability of the aquifer the higher the number of days before thermal feedback in a doublet system. The permeability doesn't appear to have a large effect over the feedback time. It is unclear if these results represent realistic estimations in the thermal breakthrough times for a doublet. There is a possibility that increased permeability would actually decrease breakthrough times as it allows the faster movement of water through the rock and therefore the faster movement of heat. This model as stated before assumes a homogeneous aquifer at a constant hydraulic gradient of 0.01 where the re-injection occurs down gradient. It therefore may assume that by increasing the permeability the flow across the doublet increases and the increased flow will inhibit movement of water up gradient against the flow. In the actual aquifer the gradient will not be solely controlled by the dip of the rock and it may be easier for water to move back up gradient towards the abstraction well. This theory is supported by the fact that the model increases the thermal breakthrough time if the hydraulic gradient is increased.

There have already been a number of assumptions made about the aquifer at this location. These assumptions have ignored the fact that there will be faulting, open roadways in the workings, impermeable layers and a host of other factors that will affect the way this aquifer operates. All of these may restrict or enhance groundwater flow. One other possible solution to the re-injection of the cooled groundwater at this site would be to re-inject it at a lower level. The shallowness of the Virgin coal seam here means that it would not be difficult to re-inject the cooled water below the Virgin seam. Re-injecting water below and down gradient would potentially prevent any feedback. There is a possible impermeable layer of Claystone at around 50mbgl which would also help with preventing hydraulic feedback. There are other deeper options in the Lower Coal Measures (LCMS) at 59mbgl which have two clay horizons between the MCMS and the LCMS. Thermal feedback in a well doublet is a product of hydraulic feedback so an impermeable layer would prevent both of these occurring. This is something that would maybe require some further investigation provided the water pressure allowed for the water to be pumped back in at this depth.

6.2 Rutherglen site

The second case study undertaken in this project is at a location in Rutherglen, South of the River Clyde but still within the NS66SW block (fig 6.2.1), it was chosen in consultation with BGS.

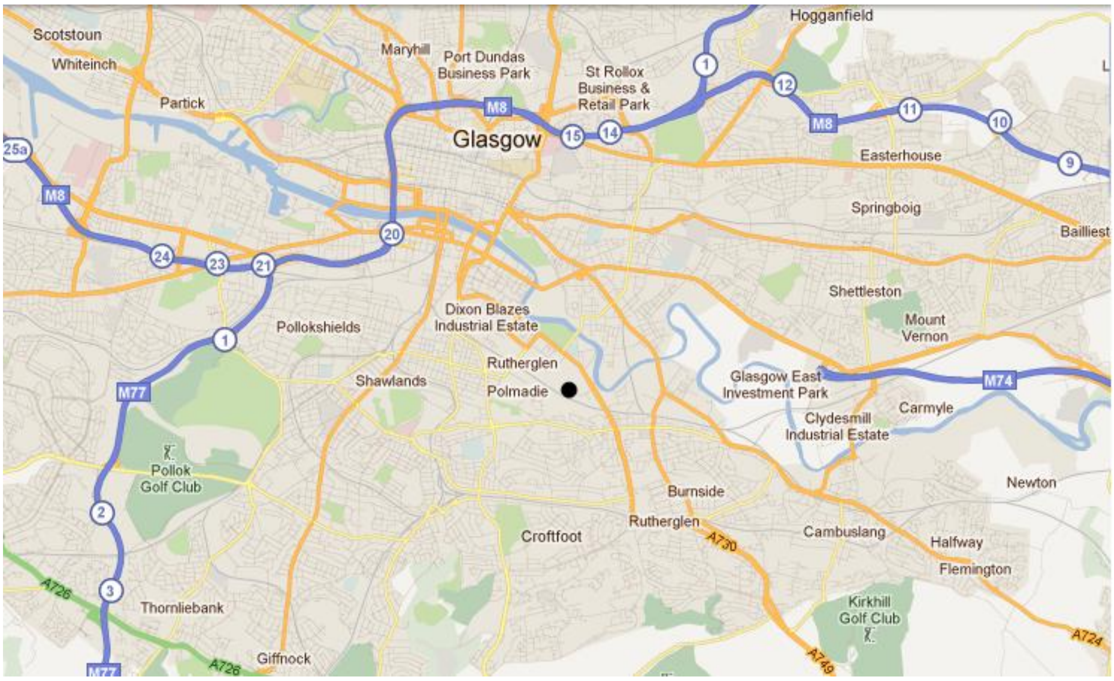

Fig 6.2.1 Location of the Govan pit #5 (taken from http://maps.google.co.uk/maps)

It was chosen because of the large amount of data that was available in the 3-D sections for this location. It also represents an area that will present a more technical approach with regards to the installation and drilling of the open source system. It will not be modelled in respect of estimating thermal breakthrough time for a well doublet. This is because the area around the Govan # 5 pit is at the base of the syncline (fig 6.3) meaning that it should potentially be at the bottom of the hydraulic gradient. Therefore any re-injection of used ground water here would have to be up gradient from the abstraction and would require a more detailed degree of analysis. Used water could potentially be re-injected at a lower horizon but this would also require some advanced modelling. The geology of this second site will be similar to that of the one up at Tollcross. It will contain the same coal horizons and Scottish Coal Measures. One of the key aspects that set this site apart from any other in Glasgow is the work done here by the BGS on the abandoned mine workings. This is the first area that they have done any mapping of the abandoned mine workings in their 3-D model (fig 6.2.2).

Fig 6.2.2, Plan view of the abandonment plans for Govan #5 pit (Supplied by the BGS)

The digitised representation of the abandonment plans was taken from the 3-D model. It shows the roadways and open sections of the different mined seams that are present in the model. It can be seen some of the roadways lie one on top of another which could restrict access to the lower roadways. If the installation required accessing one of the deeper seams the drilling may have to go through some voids which present a number of problems. Casing of the borehole down to the horizon above the target seam may be required to prevent cross contamination between the horizons. Potential requirement for this is something that the Coal Authority will indicate to the installer during the application for the licence. It is difficult to case through void spaces or heavily broken/fractures rock at depth as the deviation in the drilling bends the casing and snaps the welds. Putting these entire plans one on top of another allows the user to see where the best place to drill is so as to avoid the other void spaces in the worked seams.

One geological difference with regards to the strata that is present in this area is that it is the Upper Coal Measures that outcrop (fig 6.2.3).

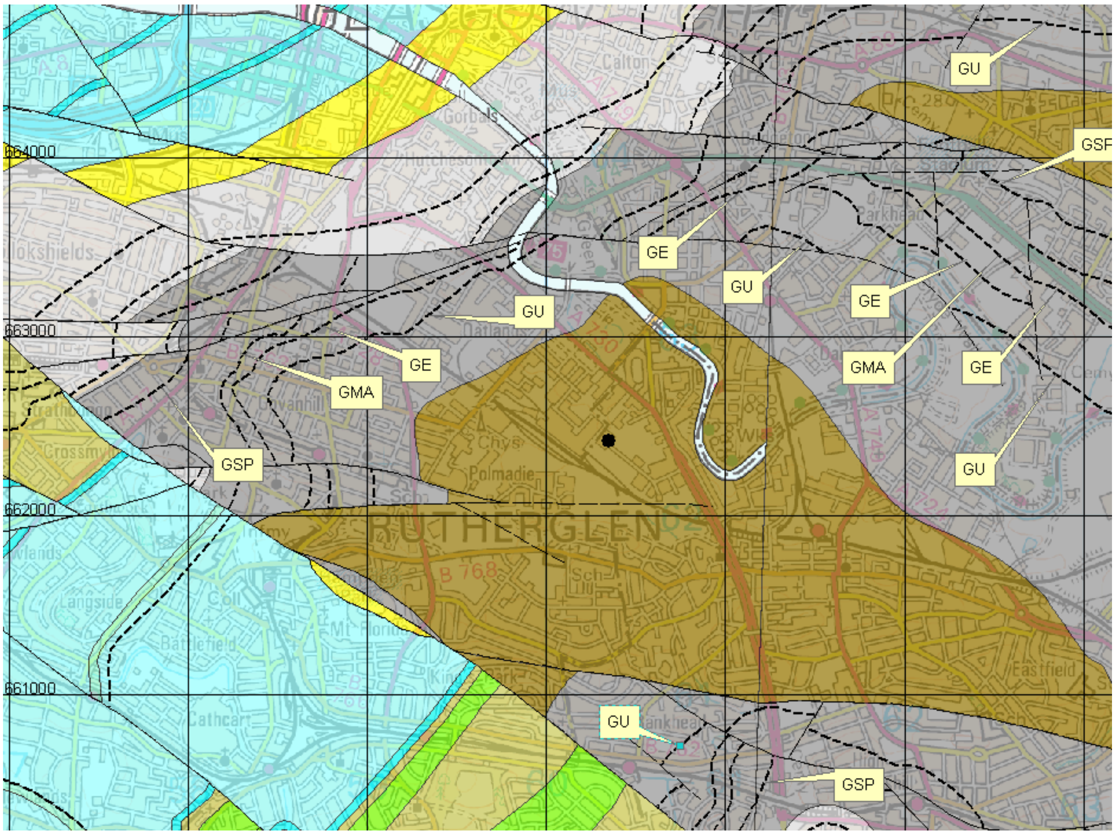

Fig 6.2.3. Geological bedrock map with coal seam outcrops (Supplied by the BGS)

Points of reference on the map (fig 6.2.3) are the black dot which represents the Govan#5 pit, the dotted black lines which indicate where each of the coal seams outcrops. The brown section of the map is the Upper Coal Measure (UCMS), the youngest of the coal measures in the carboniferous of Glasgow. The borehole log for this pit (fig 6.2.3) indicates that the UCMS is 36.41m thick and is overlain by an additional 30.47m of superficial deposits. All of the coal seams of the MCMS are present in the borehole log. The borehole terminal depth is over 200m, drilling to anything deeper would be costly and risky. What this location offers over the

Tollcross one is the possibility to intercept any one of the MCMS seams depending on their properties and potential flow rates. Being at the base of a Syncline these wells should produce a high yield.

GOVAN PIT 5			
Non-confidential (Code : 1)			
NS66SW BJ 198 .	(BNG E / N)	**260360 0662410**	
Surface Level (m):	11		
Drilled Length (m):	201.08		
Entered by:	E_EPS	31-Oct-88	
Updated by:	MSSW	29-Jun-11	
Interval Details (Interpreter : AAMI)	**Base Bed**	**Thickness**	**Depth (m)**
No strata code defined : undifferentiated superficial deposits (natural and/or artificial)	ROCKHEAD	30.47	0 - 30.470
(UCMS) : sandstone (undifferentiated)		36.41	30.470 - 66.882
(MCMS) : mudstone		1.52	66.882 - 68.405
(MCMS) : mudstone, calcareous		0.23	68.405 - 68.634
(MCMS) : seat-earth (undifferentiated)		1.47	68.634 - 70.106
(MCMS) : sedimentary rock (undifferentiated)		6.65	70.106 - 76.759
(MCMS) : coal		0.38	76.759 - 77.140
(MCMS) : sedimentary rock (undifferentiated)		14.04	77.140 - 91.182
(MCMS) : sandstone (undifferentiated)		15.01	91.182 - 106.188
(MCMS) : sedimentary rock (undifferentiated)		2.64	106.188 - 108.829
(MCMS) : coal		0.08	108.829 - 108.905
(MCMS) : sedimentary rock (undifferentiated)		10.59	108.905 - 119.493
(MCMS) : mudstone		9.65	119.493 - 129.142
(GU) : Upper coal		0.31	129.142 - 129.447
(GU) : seat-earth (undifferentiated)		0.28	129.447 - 129.726
(GU) : Upper coal		1.80	129.726 - 131.529
(MCMS) : claystone, seat-earth		0.71	131.529 - 132.240
(MCMS) : mudstone		3.43	132.240 - 135.668
(MCMS) : sedimentary rock (undifferentiated)		3.20	135.668 - 138.867
(GEI) : Ell coal		0.38	138.867 - 139.248
(MCMS) : sedimentary rock (undifferentiated)		16.50	139.248 - 155.753
(GE) : coal		0.99	155.753 - 156.743
(GE) : seat-earth (undifferentiated)		0.05	156.743 - 156.794
(GE) : coal		0.28	156.794 - 157.073
(GE) : mudstone		0.10	157.073 - 157.174
(GE) : coal		0.25	157.174 - 157.428
(MCMS) : sedimentary rock (undifferentiated)		5.26	157.428 - 162.685
(CGM) : ironstone, carbonaceous		0.20	162.685 - 162.888
(MCMS) : sedimentary rock (undifferentiated)		3.58	162.888 - 166.468
(GMA) : Main coal		1.47	166.468 - 167.941
(MCMS) : sedimentary rock (undifferentiated)		8.13	167.941 - 176.066
(MCMS) : coal		0.15	176.066 - 176.218
(MCMS) : sedimentary rock (undifferentiated)		9.17	176.218 - 185.385
(HUC) : Humph coal		0.91	185.385 - 186.299
(MCMS) : sedimentary rock (undifferentiated)		7.95	186.299 - 194.246
(GSP) :Splint coal		1.12	194.246 - 195.364
(MCMS) : sedimentary rock (undifferentiated)		1.57	195.364 - 196.938
(VI) : Virgin coal		0.81	196.938 - 197.750
(VI) : mudstone		0.69	197.750 - 198.436
(VI) : coal		0.10	198.436 - 198.537
(VI) : mudstone		0.43	198.537 - 198.969
(VI) : coal		0.20	198.969 - 199.172
(VI) : seat-earth (undifferentiated)		0.05	199.172 - 199.223
(VI) : coal		0.08	199.223 - 199.299
(MCMS) : sedimentary rock (undifferentiated)		0.43	199.299 - 199.731
(MCMS) : coal		0.46	199.731 - 200.188
(MCMS) : seat-earth (undifferentiated)	TERMINAL DEPTH	0.89	200.188 - 201.077

Fig 6.2.3. Borehole log for Govan #5 (Supplied by the BGS)

The drilling of a borehole at this second location is going to be more technical and therefore more expensive than at Tollcross where relatively shallow depths are involved. Its location is closer to the river Clyde and because of this it has a large amount of overburden, in excess of 30m. After the superficial deposits there is an additional 36m of UCMS sandstone with no coal horizons. The first coal is intercepted at 77m and it is not until 130m until the borehole reaches one of the named, recognised coal seams, the Upper Coal. The fact that this location is also at the base of the syncline would make it potentially difficult to re-inject the water without it feeding back into the abstraction well. One possible solution could be to re-inject it higher above the mudstone that lies over the Upper Coal as this could potentially be an impermeable layer. Abstracting from one of the deeper seams would also decrease the likelihood of thermal feedback. Being at the base of a syncline could have its advantages when it comes to potential yields for this location. The groundwater should flow down towards this point meaning that high yields may be possible.

The biggest challenge for this site is going to be maintaining a straight borehole during drilling due to the depths of the coal horizons. If the intention for the installation is to intersect one of the open roadways near the pit shaft the surface location will have to be very accurate. A 10^{o} deviation in the angle of drilling would result in the base of the borehole being offset by 23m for a 130m borehole. The drill string can deviate a long way off of the vertical during drilling and the deeper the borehole the higher the potential for deviation of the drill string. The deviation is caused by the drill string bending at the joins between the drill rods and not in the structure of the rods. Deviation occurs when the drill head moves through a horizon of rock into another one that is either comparatively harder or softer. The drill head is more likely to deviate when moving form a soft rock into a comparatively harder one. This change in the resistance of the drilled horizon can deviate the drilling alone but of the rocks have a steep angle of dip this can increase the potential (fig 6.2.4). Void spaces in mined horizons are an extreme example of this change in drilling resistance. If the drill head were to pass through a void it would be very difficult to ensure the bit continued to drill in the same direction after the void. This change in the resistance of the drilled material can also affect the casing. Casing to any great length will increase the potential of the welds breaking and casing through voids would inevitably result in the casing twisting and the welds breaking.

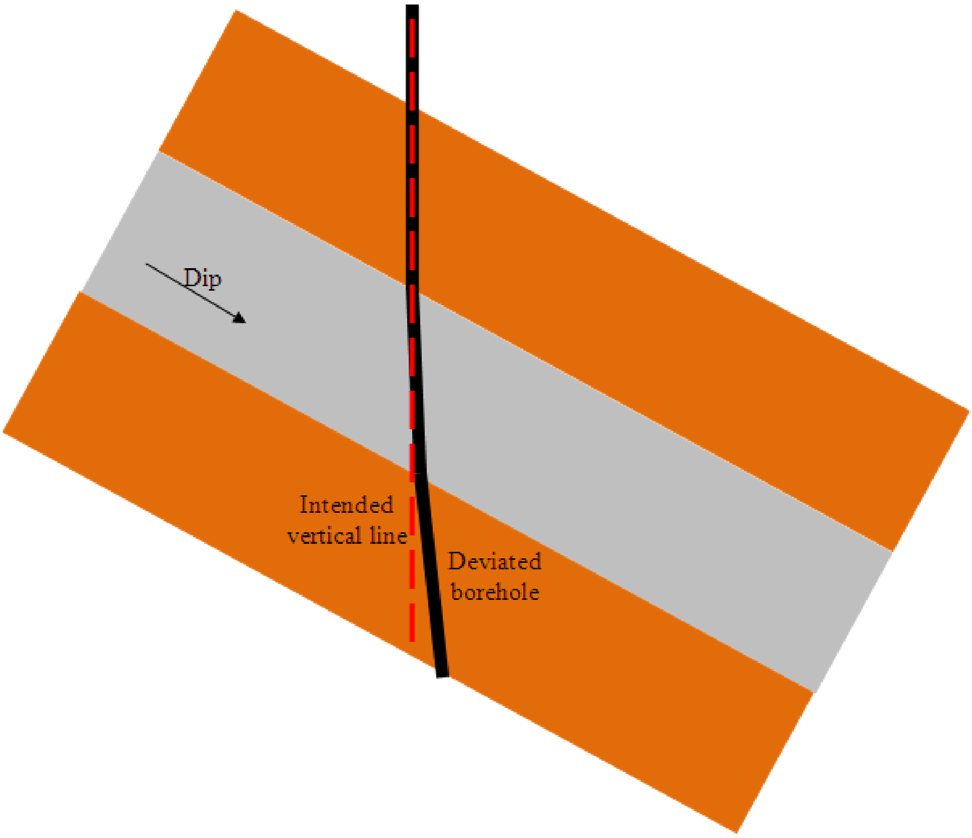

Fig 6.2.5. Red dotted line indicates the vertical borehole while the black line shows how the borehole can move each time it passes through a different horizon.

There are a number of options to try and reduce the potential of the borehole to deviate during drilling. Reducing the number of joins in the drill string would decrease the deviation by reducing the number of points along the string where bending is likely to occur. Providing as much weight behind the bit as possible will also decrease the likelihood of deviation occurring. This can be achieved through using heavier drill rods or by installing a weight in behind the bit. The oil and gas industry sometimes use eccentric weighted collars positioned behind the bit to try and correct and deviation during drilling. The collar works by using gravity to move a freely rotating weight to the lower side of the drill head and pull it back in the direction opposite to the deviation. At the moment these devices are not available for geotechnical drilling. The option of drilling directly into one of the open roadways is attractive due to the high permeability values that are likely to exist. The deeper the drilling the harder it is to guarantee a direct hit and it may therefore be more beneficial to look at another option. Intersecting one of the worked areas that has been partially filled with the collapse of the roof would be considerably easier. These areas will still contain much higher permeability then the surrounding rock and mitigate the potential problems and costs associated with trying to maintain a straight borehole. It really depends on the required yield for the heating system and then a study into what is practically achievable. This site has a large potential because of the number of available coal seams and the variable depths allow for abstraction and re-injection to happen at different levels with considerable spacing. There is the potential for abstraction at around 200mbgl and re-injection much higher from anywhere below 31mbgl. The greater the vertical gap between the doublet then the less chance for feedback.

7. Discussion/Conclusion

The object of this project was to assess the potential thermal resource stored in the abandoned coal mine-workings in Glasgow. After consulting a number of interested parties with experience in the evaluation of this resource it was decided that the project should focus on a number of key objectives. During the literature review it became clear that the issue of re-injection and thermal feedback between the wells was one of concern with regards to the sustainability of these systems Using examples from literature a spreadhseet model was produced to conservatively estimate the feedback times and geothermal output for a well doublet. Another aspect of the project would look at the drilling involved in these open loop systems. Both the drilling review and the model would be used to look at two potential locations in the NS66SW block of Glasgow.

In the case study model for the Tollcross area the thermal breakthrough time is a lowly 10 days. In reality the breakthrough period would be longer as there have been a number of assumptions made when using the model. The model is designed to be used on a homogeneous aquifer. For the aquifer present at the site in Tollcross and for every site using mine-water as the heat resource this will not be the case. The geology will be far more complicated, containing faults, open areas of old mine-workings and impermeable layers all of which will give each aquifer its unique characteristics. Taking the fact that the aquifer has been simplified into a massive block and values for each of the properties have been estimated the model allows the user to see how a generic aquifer responds to changes in these properties. The primary concern for any developer looking to use this resource is to estimate the maximum potential geothermal resource and output. Output increases along with increasing flow rate (Q) and thus pumping rate (Z). The flow rate determines the maximum potential pumping rate if de-watering of the aquifer is to be prevented. Geothermal output increases with increasing (Z) and ΔT. In the model the primary variable is pumping rate but in reality this is controlled by the hydraulic conductivity and transmissivity of the aquifer along with a number of other properties. It was decided that the model would simplify these relationships and assume a number of different pumping rates. This also made sense due to the inaccuracy of estimating the properties of the aquifer. The best way to determine the maximum potential pumping rate is to drill a borehole and carry out some pump-testing. What can be seen from the results with regards to thermal breakthrough times is that they increase with increasing doublet spacing and aquifer thickness. This means that the larger the aquifer between the doublet the longer the time taken for feedback to occur. The model suggests that an increase in permeability increases the thermal feedback time. As discussed earlier this could potentially not be the case in a real aquifer that isn't one large homogeneous block.

The use of the model in the Tollcross case study assumes a constant pumping rate of 648 m^3day^{-1} when in reality the water would only be pumped for a few hours a day if required. If the pump only operates during a 4 hour period during one day then the model is assuming an increased use up to six times the actual. The model also doesn't consider a seasonal variation in pumping rates. A thermally balanced system where the heating and cooling loads are equal throughout the year would help balance the resource. The resource would be best put to use in one of these balanced systems where the building has been designed with the heat pump technology in mind. A completely balanced system could only exist where there was no hydraulic gradient. If designed in the heating mode the abstraction of warm water would happen up gradient and the re-injection down gradient to minimise the effects of thermal feedback. Reversing this would have the system remove cold water from down gradient and pump the warmed water back up gradient of the now abstraction well. This would shorten the life of the abstraction well in cooling mode as feedback would be shorter due to the effect of the hydraulic gradient. The complexity of the geology in the Carboniferous means that there should always be some degree of hydraulic gradient. The abstraction and re-injection of water into the aquifer will create a regional hydraulic gradient. This regional hydraulic gradient is caused by drawdown at the abstraction well and up-coning at the re-injection well. Because of the costs involved in designing a system using mine-water and the technology required to implement it's safe and correct installation it would financially make more sense to use it in larger heating systems.

The case study for the Rutherglen site didn't use the model and looked instead at the drilling aspects involved in accessing this resource at a greater depth than at Tollcross. The issue of directly targeting an open roadway within the workings was one potential point of discussion. Directly hitting a particular roadway a few metres wide at any depth is tricky and would require careful planning but could still not be guaranteed. It was concluded that the design of a system that targeted the fractured worked coal seam would be a lot easier than one that targeted an open roadway. Further work looking at the potential permeability of these in-filled workings would allow for more accurate design. The permeability of these filled spaces may be sufficient to supply the required yield for a heating system. The site at Rutherglen offers the opportunity to abstract and re-inject at a number of different horizon levels. This was one of the reasons for not using the model for this case study. The option to abstract and re-inject either side of tens of metres and impermeable clay layers would decrease the potential for thermal feedback. One point of concern for this site due to the depth was the likelihood of having to drill through worked coal seams to reach the target horizon. As discussed in the chapter on drilling, intersecting a number of horizons without casing creates the potential for cross contamination between the horizons. Further studies would be required to see if this would have a detrimental effect on either of the intersected horizons.

In conclusion, the potential thermal resource that lies in the abandoned mine-workings of Glasgow could be very large. There is the potential for this resource to supply much of the cities heating load. The re-generation of the east end of the city in line with the forth-coming Commonwealth games offers an opportunity to put this resource into practice. To do this a better understanding of the impact of these systems is required. It is important to know if these systems will interact with one another if they are installed closely together. Re-injection at one well doublet may impact on the abstraction well of another. It will therefore be necessary to fully understand and control the installation of these systems. Poor control may result in the poor performance of installations which may impact on the confidence of installers and hinder the uptake of this resource.

8. Future work

There is a large potential for future work within this topic:

- The model and equations in this project could be used and tested on existing installations in Glasgow like the one at Shettleston.
- The use of more advanced forms of software as discussed earlier could be used to simulate the impact of a well doublet at both of these sites.
- There is also the potential to follow on from some of the work by BGS and look at the total thermal resource in the abandoned mine-workings for the city of Glasgow.
- A study looking at the equipment used in these types of installation.
- There is the potential to look at the energy balance within the aquifer for a well doublet. Looking at exactly how the recharge of temperature occurs in an aquifer that is having water abstracted and re-injected. This would follow on from the assumption by the model used in this project that the water is pumped 24 hours a day. How does turning the pump on/off affect the thermal resource of the aquifer?

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