The aim of the project was to improve the competitiveness of coal production by improving the quality of the mine water raised and monitoring the substances it contains, making the cost effectiveness of different methods of dam construction calculable, increasing the safety of mining by determining the flow paths and optimising the construction of dams between areas that are still being worked and those that have been closed down and minimising the costs incurred for draining the mines while taking the measures necessary for environmental protection into account.

The different objectives have in general been reached. The box model, integrating a geochemical reaction model, has proved to be a very appropriate tool in simulating mine water rebound effects in large coal mine fields. Empirical analytical solutions can easily and for a number of applications adequately describe the development of mine water quality after flooding. Equipment and methods for monitoring mine water flows and compositions have been successfully tested and applied. Data transmission units have been developed as well. Several coal mine areas have been monitored and investigated. All results led to improved quality of modelling as well as to improved parameters for mine water management. In order to optimise mine closure and subsequent effects the results of the study have highlighted several key points linked to rebound of both the aquifer and the mine water and the type of hydraulic connections between the aquifer and the mine workings. The optimisation of dam construction has been achieved.

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Optimisation of mine water discharge by monitoring and modelling of geochemical processes and development of measures to protect aquifers and active mining areas from mine water contamination

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1. Final summary

1.1. WP 1 Optimization of mine water discharge

Mine water contains a variety of substances which could potentially have an adverse effect on the environment.

The available literature on quality development during flooding and quality prognosis tools was investigated extensively and a comprehensive picture of the actual state of mine water situation in European and international coal mining areas was determined.

The spectrum of possible coal strata deriving pollutants was completely checked for environmental relevance. The sources were analysed with respect to methods to control or limit the discharge with mine water.

The mine water constituents focused on were selected in terms of their environmental impact. The mobilised substances make a different impact to the environment depending partly on the receiving water and on the local critical concentration values.

A method to consider all relevant chemical processes influencing mine water quality was developed combining the thermodynamic calculation tool PHREEQC with new features of the DMT BoxModel.

Mines recently flooded or planned for flooding in the Ruhr Area and following the criteria for an intense monitoring and calibration of the geochemical model within the runtime of the project were selected.

For the relevant mine water substances suitable monitoring parameters and appropriate measuring processes and techniques were needed Because of there was almost no existing equipment specific to mine water in-situ monitoring, concepts and equipment were developed and constructed to meet the site criteria. Finally, the equipment constructed was comprehensive, intrinsically safe and therefore universally applicable in coal mining which accomplished the task objectives.

The Haltern coalfield, in which the measuring equipment was successfully installed, started flooding in the end of 2006. This has resulted in a period without generation of data. However, this gap could be closed via extended collection of monitoring data from other sites in the Ruhr area and other European mining districts. At the end of this project the initial flush of mine water at the deep control unit was still being awaited. Activities will continue beyond the project period.

The fundamental site specific data considered are the floodable void volume, the rate of recharge and the composition of the inflowing water. Numerous international data sets for concentration developments in mine water discharge have been compiled and normalised for statistical investigations. This has resulted in empirical exponential functions which are widely used for mine water quality prognosis and have proven their applicability at numerous sites.

Data for mine water recovery and discharge mine water chemistry for several mining areas has been provided for use in DSK/DMT modelling of the chemical processes during mine water recovery. Up to this date, only the Grodziec mine can be used to calibrate the model calculations for filling against the actual mine water level measurements and the development of the water quality by means of mine water quality analyses. In the same way the flooding of the Siersza Mine was also recalculated. For an advanced understanding of mine water sources the inflow rates in the recent years before flooding were analysed. These correlations support the thesis of head-dependent dominated inflows into the Grodziec mine, which influences both the box model hydraulic setup and the calculation of the flushing process.

A development of a fully operational BoxModel was realised at four sites (Ruhr Area (Germany), Lorraine Basin (France-Germany), Grodziec mine (Poland) and Durham Coalfield (England). In complying with water management requirements, such as the pumping strategy, flooding control and scheduling of mine water treatment plants, the work accomplished exceeded the objectives initially planed.

The work undertaken has resulted in the calibration and enhancement of a BoxModel covering major parts of the Ruhr coal district. The BoxModel, including the geochemical reaction programme, was employed to simulate the quality development during the flooding process to obtain reasonable initial conditions and to describe the ongoing flushing process.

The geochemical tools developed during the period of this project were used for the first time in a flooding water prognosis started 2003 in the Lorraine Basin using the enhanced BoxModel. The challenge was to forecast the mine water rebound when flooding the French Lorraine coalfield and stopping pumping at the German Warndt colliery. The calculations were made for two alternatives for the development of mine water quality (parameters selected are iron, sulphate and chloride) at expected points of overflow resp. points of discharge.

The BoxModel calibrated during this project as described in task 1.7 was utilised to demonstrate the practical application of the geochemical reaction model for the prognosis of mine water quality in two more European mining areas. As a prerequisite the future mine water flow had to be calculated for the North-East field of the Upper Silesian Coal Basin to be combined in a subsequent step with the geochemical reactions. The calculated sulphate concentration of the discharge reflects very precisely the concentration development monitored. Other samples taken from different levels in the shaft during the flooding also correspond well with the model.

The specific properties of the Durham coalfield BoxModel consist of extensive interconnections of mine workings and interactions between the Permo-Triassic aquifer and the workings below this aquifer. The first preliminary box model calculations performed during the research work considered the heterogeneous water inflow chemistry only. Data on the influence of discharge level and pumping rate on salinity and the flushing process were available for future use.

The results of the DSK/DMT box model calculations have been presented and published in a number of conferences.

1.2. WP 2 Developments in surface environment monitoring and control

The review of data obtained from the surface hazard response work in the UK indicated that, in general terms, most of the shafts and workings that had become exposed were shallow in depth, with obscure or unknown information associated with them. Evaluation of the existing data from the lignite districts of PPC and examination of the literature indicated the main sources of pollution of mine waters at the open cast or underground mines.

A diverse range of monitoring equipment and sensors for environmental monitoring were already commercially available at the start of the project. However, it was unclear whether these could offer long unattended operating life, whether sensors for different parameters could easily be connected to the same data-logging and data transmission facilities and how suitable they were for situations where there was a requirement to employ intrinsically safe devices.

In general, it was concluded that rugged, self-powered sensors were already widely used for environmental monitoring and where possible commercially available equipment could be used. However, intrinsically safe equipment for water sampling in deep boreholes and shafts was not available commercially and had to be tailor-made for the purpose of the project.

To further assist the industry and enable comparative reviews of currently available equipment, the findings from this task were also used to support the development of a state of the art demonstration system that also has a data transmission capability between remotely monitored sites and a ‘base station’.

A review and assessment of the methods available for the transmission of data from surface facilities, possibly from several points, to a central base station was undertaken. Ranges of disadvantage associated with the use of radio modem based systems were identified. However, further analysis led to the conclusion that HTTP was a more appropriate protocol. A demonstration web site was developed and implemented for use by project partners. This site included an embedded TCP/IP Internet gateway to provide secure remote access capability, and demonstrated the development of integrated data logging analysis and alarm signal.

Laptop PCs with GPS facilities were configured to allow detailed mapping data of the users’ current position, or a position held in a database to be displayed. A range of commercially available map packages were evaluated. Mapping software solutions that enable higher resolution map polygons to be stored and accessed directly from a database were examined. These were found to be less economically attractive. Collaboration between project partners revealed that this was the case for PPC. As a result

PPC developed its own mapping system based on the maps of the mining areas, which they already held.

A specialised piece of equipment for water sampling in deep boreholes and shafts was developed and constructed. The sampler is certified as “intrinsically safe” by the mining authority for use underground in a degassing atmosphere. This type of equipment was not available commercially and had to be tailor-made for the purpose of this project.

The intrinsically safe equipment produced for water sampling in deep boreholes and shafts was used in the two shafts of Camphausen in the Saar area and Ewald 5 in the Emschermulde. After some problems the system worked satisfactorily and 6 samples from different depths were obtained, with the samples showing a clear stratification with salinity and sulphate concentration increasing with depth.

A state of the art demonstration system that allowed the transmission of data via a GSM/GPRS modem to a web server was also constructed. This system was then compared with the typical systems currently in use by the industry with a view to identifying the potential for improvements and refinements in the light of any shortcomings identified. The typical systems in use were found to be relatively power-hungry. The systems in use presented a good argument for using standard ‘off-the-shelf’ equipment as they were found to be both practical and relatively reliable.

Within PPC’s lignite fields extensive pumping is required to achieve sufficient drawdown of the aquifers, which are influencing the mines. Consequently the major problem is the water table level and how it affects the mining works, the surface environment, slopes stability and the quality of water. PPC installed a number of water level sensors, which were cheap, commercially available, compact and suitable for difficult mining conditions.

In Ptolemais, PPC installed a telemetry system, which consisted of one main computer, an RS-232 connection, a modem, a GSM modem, and four remote stations. The stations were placed in 2 wells and 2 pumping stations. Every station consisted of a data logger, a GSM modem for the transmission of data to the main computer and a sensor.

The mine water and ground water quality data obtained was used in both the input data and control data for the PHREEQC modelling. Water quality, water level and the temperature and conductivity monitoring was used in the risk assessment undertaken with regard to the overlying and interconnected aquifers and to determine mine water flow paths both within the workings and to the Permian aquifer in the case of the previously contaminated aquifer.

Changes in fluid conductivity and temperature with the increasing mine water pumping rate in Horden shaft, including temperature inversion, clearly demonstrated the principal flow paths in the mine workings resulting from the stepped pumping test. Changes in mine water chemistry also helped to confirm the flow paths.

The deep mine water level monitoring at Silksworth and Sunderland showed that there was no immediate risk of aquifer contamination. In the Megalopolis lignite district, water level sensors were used to provide daily measurements of the groundwater table. Daily rainfall was also monitored.

In all the lignite fields of PPC the major problem is the water table level and how it affects the mine workings, the surface environment, slopes stability and the quality of water. PPC installed and operated a number of water level sensors. Several piezometric maps of aquifers were created.

The measurements of the piezometric surface were taken once a day and finally a continuous picture of the fluctuation of the water table due to the rainfall measurements was obtained. By knowing the water level, the direction of water movement was ensured, and by comparison with the results of chemical analysis conclusions could be drawn.

Surface hazards arising from historic mining liabilities in the UK were investigated. Many of these incidents result in old mine shafts being detected, due to shaft collapse, infill settlement, capping disturbance and shallow working collapse, leading to surface cone depressions and ground fracture. This element of the research was used to assist in investigating the reasons for these incidents and to determine if there is a relationship with any changes or movement in ground water.

Immersion tests using simulated acid mine water and concrete cores were undertaken, with the aim of identifying and quantifying the physical and chemical effects. Concrete samples were immersed in tap water, de-ionised water, dilute sulphuric acid pH 5, actual acid mine water pH 4 and compared with un-soaked samples. Similar tests on grit and coal measure material were also conducted. The results showed that shaft linings with any form of cement are subject to corrosive attack and chemical reactions are numerous and complex.

An integrated database system, which combines information on the type of surface hazards, liability, stratigraphy, geology and water regime and analysis, was developed. This database can also be linked to integrated GPS and mapping systems developed for use by the first response surface hazard teams.

Further statistical analysis of the data was undertaken to determine if correlations could be established that would assist in predicting the risk of surface hazards occurring. The statistical results obtained positively identify hazard incidences clusters, based on geographical location, that could be related directly to areas of coal mining activity. However, although the results obtained in task 2.7 suggest that there may also be correlations with mine water variables; these could not be established from the available data. It is postulated that such correlations may still exist but are likely to be completely masked as a result of limitations in the historical data currently available and the currently unknown time scale of any mine water degradation effects.

The central part of the Emschermulde (Ruhr Area, DSK) is subject to an ongoing flooding process until mine water decants towards the central Zollverein underground pumping station. In several shafts level measurements were taken on a regular basis by DSK. The water level measurements from these shafts were used to calibrate and verify the modelling of the mine water rebound. These measurements were run by conventional logging technique, but initial trials to use pressure probes, installed at the bottom of the shaft before flooding, performed well.

1.3. WP 3 Mine water contamination of aquifers

All the historic UK data still available were brought together on one database that could be used for the research into mine water contamination of aquifers. The data required for the various tasks included seam chemistry, mine water and aquifer chemistry, mine water inflow and pumping data and water level data for aquifers and mine water. To aid in the assessment of risks and the selection of sites for investigation detailed mine plan and mine entry data was required and this was converted to digital format for use in other work packages.

For the deep mined hard coal areas of the UK the work carried out required digitised plans at a scale of 1/50,000 of each seams worked, the base of the aquifer, and the hydraulic gradients in the mine workings and the aquifer. A detailed study was then made of all the mine shafts and mine abandonment plans to abstract the mine water inflow data that was then transferred to the overview plan. Based on the original rates of inflow, the type of connection and the current relative piezometric heads between the aquifer and the mine workings the flow into or from the mine workings was estimated.

In the lignite mining areas the work concentrated on those aquifers potentially at risk of contamination from mine water. The areas of potential danger mine have been determined from the existing data collected and plotted on mine plans using of conventional surveying methods. In addition to the existing 38 sample points at Ptolemais the risk assessment identified a additional 29 where regular water chemistry were required.

In the lignite mining areas in Greece seven sites were instrumented. The equipment installed was for monitoring of the aquifers in the Megalopolis mine area (task 2.4). In addition 4 instruments were installed in Ptolemais, 2 in pumping stations and 2 in water wells. These instruments are recording Q, pH, E.C., T^{o} C and additionally to water level.

Three sets of TROLL 9000 equipment were installed in the areas of study in the UK.

A concept for installation of monitoring equipment adjusted to mining requirements and demands of the mining authorities was developed for the Ruhr Area. Specification to be regarded for intrinsic safety affects the beginning of the measurements and sampling depending on the flooding process. In order to simplify the electronic control system and to minimize the standards for intrinsic safety the power supply for the pumps was separated from the power supply and data transfer to and from the probes.

The modelling using PHREEQC of mine water mixing with aquifer water and comparison of the results with real data from an area of contaminated aquifer has shown that the modelling can accurately predict the contaminants and the levels of contamination if the flow rate of the contaminating mine water mine water is known.

Where the flow is not known the risks to the aquifer can be determined as in the case of the high iron and chloride mine waters in the East of Durham area which predicts high chloride levels even when small percentages of mine water are mixed with aquifer water.

In the lignite mining areas of Greece the PHREEQC modelling of mine waters mixed with aquifers in Megalopolis led to the general conclusion that there are no significant affects from the mine waters of the ponds on the aquatic system of the area. In the Ptolomais area is no significant effect in the surface water of Soulou stream from the mine water. The main problem of elevated concentrations of NO^-_3, NO^-_2 and NH4+ in the river result from the agricultural activities in the area not.

In the lignite mining areas of Megalopolis and Ptolemais additional lagoons were constructed (150m x 80m x 5m) and tests were undertaken to show that extended retention time (5 to 24 hours) lowered the total dissolved solids (TDS) in the mine water as well as suspended solids

In general the surveys confirmed that there were no problems with the stability of the mine shafts. No problems were encountered in the shaft sections passing through aquifers. Several shafts, both open and filled, reportedly had flows of water through the shaft linings at points below the base of aquifers. It is believed that these flows are the source of the Permian water observed in the upper mine water layers.

In the German Ruhr coal district many centuries of intensive mining left a legacy of risks associated with close to surface mining voids, adits and shafts. Collapses and damage to housing and infrastructure continue to occur in abandoned mining areas and are expected to increase in frequency and intensity when the mine water rebounds closer to the surface.

There is still need to catalogue and evaluate the actual risk situation. For the time being characteristics like geometry, filling, age, geology, groundwater situation and use of land are applied to separate into very simple risk classifications.

To minimise risks of aquifer contamination the shallow pumping of mine water at varying rates while monitoring and assessing the impacts on mine water quality layering was started in June 2004 in the East of Wear area of Durham and continued through to the end of the project. The initial results showed that even at low flows the chloride levels of the mine water would pose a significant risk to the aquifer and given the type and number of connections between the aquifer and the mine workings sealing of all connections was not an option.

In the Butterknowle area none of the mine to aquifer connections identified are suitable for sealing and pumping has been identified as the best option for control of mine water flow into the aquifer. A borehole is planned into the area of connection that is believed from the monitoring and modelling to have the highest flow to check on the chemistry of the mine water and determine the feasibility of pumping.

The DSK/DMT BoxModel has been applied to a risk assessment to identify the preventive measures to minimise aquifer contamination of an important drinking water resource in the French German border area of Lorraine and Saarland. This trans-border model provides answers to the important hydrogeological issues arising as a result of the planned mine closures and the resultant flooding.

1.4. WP 4 Development of methods to separate flooded areas safe and fast

The objective of the work was to study and develop solutions for construction of underground plugs to protect areas of active mining from mine water inflow from abandoned areas.

Information on the construction of underground plugs has been obtained through specialised publications, in the Internet and by means of direct requests to involved professionals and companies different sealing experiences around the world, both successful and unsuccessful, types of sealing barriers, constructive technologies, composition of the concrete used, alternative used materials, monitoring strategies, etc.

HUNOSA's Figaredo mine was selected as the most adequate area for the construction of the plug from the operative and technical point of view. Some important aspects have been controlled inside and outside of the mines in order to define a hydrogeological conceptual model. Before the HUNOSA mines San José and Santiago as also the abandoned mine of Lumajo from MSP Group have been studied, but were discarded because of different problems.

Different alternatives for plug design and construction techniques, including new experiences and solutions adopted in other industrial sectors for different applications have been analysed.

A monitoring system for measuring the hydraulic and mechanical parameters of the test plug has been designed. The basic parameters to be monitored to assess the plug performance are pressures, movements and displacement, temperature, seepages, and pressure release.

Other parameters to be controlled in some cases are the air quality (environmental measures): concentration of methane, CO and CO_2 in the gallery to avoid explosive atmosphere or poisonous and asphyxiating gases.

In order to check the water quality in the area, during the field works were measured the main physic-chemical characteristics of water (electrical conductivity, Fe_{Tot} and SO_4) in several springs, discharge from abandoned mines and other water well inventory items.

Hence, the effects that the substances dissolved in the mine water will have on the plug are supposed to be negligible; anyway it is quite possible that the water quality could change in the long term because of the increase of the transit time of groundwater after the construction of the plug.

A series of tests were carried out in the Bierzo school-mine of Foundation Santa Barbara in order to check the behaviour of the formulation developed and to assure the feasibility of the plug construction operation in different working conditions with said formulation.

The site selected in the Figaredo mine for the demonstration plug was the 7th floor, close to the operation loop where the pumping station and the access pit are located. The plug constructed in this location allows the flooding of the north works up to the 6th floor. It also receives water from Barredo mine through a connection in the 5th floor.

A field campaign has been carried out in order to seek for a suitable water well where to install pressure probes in order to control the piezometric levels around Figaredo area, which has connections with Barredo and San José coalmines.

No suitable water wells were found, so finally the water discharge from three abandoned mountain type coalmines has been instrumented. This has provided indirect data about the possible fluctuation of water level in the test area. The lag-time between rainfall and discharge is around two days in some of the mountain coalmines, whilst there is no discharge fluctuation in other ones.

Water discharge from instrumented coalmines has been controlled in order to improve the hydrodynamic comprehension of the area and to complete the conceptual hydrogeological model. The infiltration of the rainfall is very fast most likely due to the existence of many abandoned mine works close to the surface in the zone.

The monitoring phase could not be started neither in the Figaredo mine nor in the Laciana school-mine plug due to the delays accumulated during the selection of site.

The first results were presented in the 9th International Mine Water Association Congress (INWA) that was held in Oviedo (Spain) from 5th to 7th September 2005. Also, a communication with the final results of the project will be prepared to be presented in the 23rd International Applied Geochemistry Symposium (IAGS) that will take place in Oviedo (Spain) from 14th to 19th June 2007. In the same way, the possibility to send other presentation to the IMWA Symposium 2007 is being considered. This congress will be held in Cagliari, Sardinia (Italy) between 27th and 31st of May.

2. Scientific and technical description of the results

2.1. WP 1 Optimisation of mine water discharge

Mine water contains a variety of substances which could potentially have an adverse effect on the environment especially when the hydrodynamic situation varies as mine levels become increasingly flooded due to modifications in mining operations, or at mine closure.

The aim of this work package was the development of methods for optimisation of mine water discharge by determination of the substances to be considered under specific mine site conditions. Processes contributing to the mine discharge have been studied in order to develop a predicting tool for mine water quality. To achieve this, two interacting main activities were planned:

- Modelling of relevant geochemical processes.
- On-line monitoring of the flooding process.

The work package includes a literature inquiry, laboratory data and in-situ investigation of mine sites scheduled for closure and flooding.

2.1.1. Work carried out on task-by-task basis

<u>Task 1.1 - Evaluating existing data and literature</u>

Data on the substances dissolved in mine water (i.e. iron, sulphate, barium etc) are already available for many mining areas. Furthermore, in consequence of continuing mine closures increasing information exists about the development of mine water quality during the flooding process. These data need to be compiled to obtain an overview.

The available literature on quality development during flooding and quality prognosis tools was investigated extensively and a comprehensive picture of the actual state of mine water situation in European and international coal mining areas was determined. Due to intensive contact and data exchange with the partners within the project and other organisations more flooding data was acquired than anticipated beforehand. Thus a complete overview on mine water chemistry was accomplished which was then considered in the model development. A relatively poor availability of online monitoring equipment and model tools for mine water prognosis was ascertained. The work period for this task was extended and to allow the task to be successfully completed.

Especially the evaluation of existing data has been extended due to expansion of the model implantation on an international scale to coal mining areas in Poland and especially England (2006). In addition references to secondary literature had been checked in 2005. The situation in English coal fields was reason too for resumption of task 1.2 (substance sources and hazard potential) considering the salt content and surface near aquifers. Adjustment of the model and application to chemical processes at the above mentioned sites was reason for extension of task 1.3.

Concerning the geochemical processes in mine water, online literature research in specific technical scientific database clusters was carried out using the central key words, “mine water”, “flooding”, “monitoring” “equipment” and “measuring”. 492 references were checked by title / abstract / full text, (for the list of literature used, see Technical Report 4). Similar processes for the development of mine water quality before and after flooding are described for mines in coal and ore deposits. Information on coal mine flooding is available mainly from Great Britain, Poland and USA. Most investigations deal with pyrite oxidation as the source process for iron content and acidity. In addition, unpublished monitoring data on mine flooding were collected. Thus a sufficient data base was established for further adaptation in other countries of the reaction systems that are specific to the conditions of the of the Ruhr and Saar areas in Germany. Another principal area of study and research undertaken was the South Nottinghamshire Coalfield and the Durham Coalfield in north east England (figure 5.3.3).

In spite of the unrestricted search concerning monitoring methods for coal deposits, only a few publications with relevant content were found. Monitoring of mine water has previously been restricted to sampling of pumped water or discrete samples taken from boreholes or shafts. There are only few innovative approaches documented for continuous measurements or sampling during mine water recovery within the actively flooding area. The information obtained concerning appropriate probes resulted in the additional consideration for use in mines of equipment developed for offshore technology.

Task 1.2 – Determination of substance sources and hazard potential

Work during this stage of the project concentrated on identification of the sources of the hazardous substances dissolved in mine water and the causative mobilisation processes. The main focus was substances with hazard potential especially for the water environment.

The spectrum of possible coal strata deriving pollutants was completely checked for environmental relevance. The sources were analysed with respect to methods to control or limit the discharge with mine water. The activities undertaken proceeded as planned however an expansion of work was realised by resumption of work in 2006 to include the situation in English coal fields considering the salt content and surface near aquifers.

At underground coal mines the parameters iron and sulphate are of dominant general interest, while parameters like temperature, chloride, barium, manganese and other components could be of equal importance for the receiving water course but are limited to individual mines or group of mines. Iron is the substance contained in most mine waters undergoing a flooding process and contemporaneously the most sensitive parameter for most of the receiving waters.

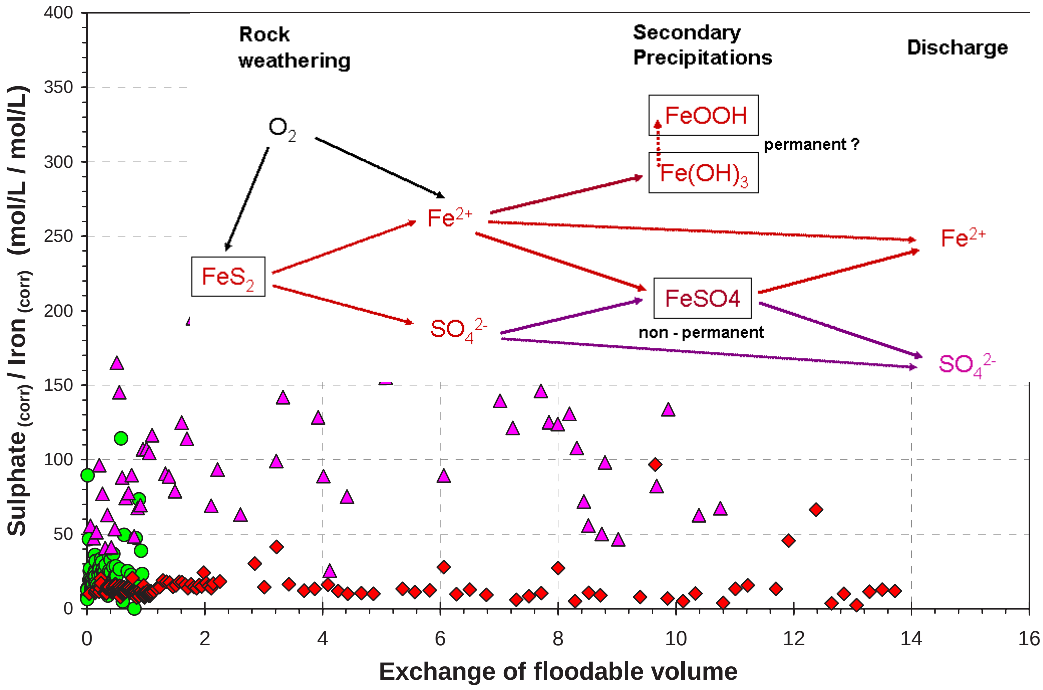

Figure 2.1.1: Oxidation of pyrite and following buffering and precipitation reactions resulting in solute transport of iron and sulphate.

The source for iron and sulphate is the oxidation of pyrite which is generally associated with the coal seams and the surrounding rock formations. Pyrite becomes unstable under ventilated mine conditions (figure 2.1.1). It has to be stated, however, that

- the mine water components observed can not be derived directly from the primary source materials,
- for most mine water components more than one source material exists,
- there are some intermediate products for which no complete dissolution during the flooding can be assumed.

A further mine water component of importance for water quality is manganese. For manganese no separate source mineral can be assumed. Several studies have indicated that it is very likely that manganese is a constituent of siderite, were manganese forms an integral part of the crystal lattice ($(Fe,Mn)CO_3$).

Siderite is, just as pyrite is, unstable under oxidizing conditions and with an excess of oxygen, a carbonic acid solution is formed.

The mine water constituents focused on were selected in terms of their environmental impact. The mobilised substances make a different impact to the environment depending partly on the receiving water and on the local critical concentration values.

Task 1.3 - Modelling of the chemical processes

Different approaches exist in numerically describing chemical reactions between solid, liquid and gaseous substances. Standard programs for geochemical calculations like PHREEQC allow the determination of contributing phases and the resulting water composition. However, there are deficits in validated data especially in describing the kinetics of the processes. This includes oxidation of the sulphidic phases in the rock as well as reactions with backfill, injection and damming materials. In addition, mixing with water from other mining sections has to be considered. This task is to examine the extent to which this software can be applied to mobilising processes that are significant for the mine water.

A method to consider all relevant chemical processes influencing mine water quality was developed combining the thermodynamic calculation tool PHREEQC with new features of the DMT BoxModel. These activities undertaken exceeded the task objectives in order to develop an all-purpose tool for international application.

To describe the initial increase in concentration levels as well as the exponential decrease actually monitored in mine water discharge after flooding of collieries, each process has been integrated in a different manner:

- The pool of mobile substances deriving from oxidation processes before flooding are given to the model as initial conditions (mass storage) depending on the extent of the mining activities and the properties of the host rocks.
- The mobilisation of this substance pool is represented in the model introduced by the research work by mass exchange between two subdivisions of the floodable volume. An easily percolated part (active phase) correlates with the open mine cavities and a stagnant part (passive phase) correlates with the mine workings (goaf areas) and the fracture porosity including adjacent pore spaces. The passive porosity contains well the soluble oxidation products in high concentrations.
- The mass exchange between the passive and the active porosity follows the diffusion law.
- The flow regime in the mine could be calculated by implementation of spatial distribution of open mine cavities, rock porosity, seepage water volume and quality, position of the water inflow in relation to the position of the outflow. This was possible by means of the BoxModel as described in Annex 5.1.
- Into the BoxModel a program code for thermodynamic calculations of processes relevant for mine water quality prognosis like mixing, supersaturation, dissolution and precipitation was integrated. There exist several codes basing on thermodynamic principles like WATEQ, SOLMINEQ, PHREEQE/PHREEQC, MINEQL, MINTEQA2, CHESS and EQ3/6. In general it has to be stated that the basic equations and operation modes used in these codes are more or less the same. The BoxModel implements just this basic code and not the adjacent user features. More decisive for the results is the correct transformation of the natural processes into the model (done by the user!) and a good thermodynamic database. There have been several reasons for selecting PHREEQC for use in the BoxModel:
  - The PHREEQC code is internationally very widely spread allowing exchange of data and comparison of results
  - The geochemical basis is uncoupled from the from the program code enabling the user to implement new reaction equations
  - The comprehensive thermodynamic database of the WATEQ code can be used
  - Calculated water compositions can be stored and reloaded for further calculations
  - The code is regularly improved and upgraded in the scope of features by U.S. Geological Survey (USGS) and can be downloaded as freeware

- PHREEQC provides all attributes required for integration into the BoxModel and water prognosis
- The PHREEQC code forms the basis of a multitude of other codes

- Chemical reactions are considered by precipitation reactions resulting from mixing of mine water in the active phase (e.g. sulphate salts) and buffering reactions with participation of carbonate phases in the host rock. It could be shown that this selected chemistry suffices to reproduce the dominating processes resulting in the mine water quality monitored. The model can be upgraded by all reactions with thermodynamic data available.
- Because of the importance of correct element activities used for mine water prognosis in highly concentrated brines, Pitzer-coefficients were incorporated into the BoxModel tool.

Task 1.4 – Selection of test sites for monitoring of flooding

For the monitoring of flooding and the calibration of the geochemical model mine sites scheduled for closure and flooding have to be identified and checked for suitability for the installation of measuring equipment. At the site identified all available data concerning water inflows, water qualities and mine cavities needed to be evaluated.

Mines recently flooded or planned for flooding in the Ruhr and Saar Area and following the criteria for an intense monitoring and calibration of the geochemical model within the runtime of the project were selected. Due to previously unforeseeable operational developments at Warndt/Luisenthal mine, the plans for equipping this mine, which had been planned for flooding in 2006, became impossible to implement. In order to rectify the situation in a reuptake of Task 1.4 the Haltern coalfield in the Ruhr coal district was identified in 2005 as an alternative site and adapted methods were determined subsequently (see Task 1.5). The monitoring equipment developed and constructed during the following year after the final selection of the test site was installed in 2006 (see Task 1.6). The work at the new test site, in the Emschermulde, progressed as scheduled.

The Emschermulde is the central part of the Ruhr coal district and has been intensively exploited during the last two centuries. Considerable changes to the Emschermulde mine drainage system have been initiated in 2001 when the last active mines in the Emschermulde were closed and mine water drainage ceased. Monitoring of the flooding is possible by logging and sampling in several open shafts.

In the Saar area, the adjacent French coal mines of the Lorraine coal basin ceased production in April 2004 and subsequently prepared for complete closure, including the abandonment of mine dewatering activities. The DSK owned colliery Warndt located south of the River Saar was also completely closed and scheduled for flooding concurrently with the French coal mines. During 2005 the workings were still accessible which made the Warndt/Luisenthal colliery a favourable test site for the installation of an in-situ monitoring system. The input data for a detailed box model Lorraine-Warndt were reviewed. First concepts indicated an initial overflow from the Lorraine mines at the order of 60 m³/min. After the flooding period a reduction of the overflow from the south down to 10 m³/min was expected.

The test site ultimately used for the installation of monitoring equipment was the Haltern coalfield area of the Auguste Victoria / Blumenthal mine, situated in the northern Ruhr area. The Haltern coalfield area provided some very favourable conditions because it is an area of workings with limited connections to the rest of the mine. Originally mined as the northern expansion of the Blumenthal mine, a new underground heading was built from the Auguste Victoria mine when the Blumenthal mine was closed. For this reason there are only two underground connections to the area, one from the Blumenthal mine in the southwest, which is currently being flooded and is separated completely from the Auguste Victoria mine by a high pressure 100 bar dam, and one from the still active Auguste Victoria mine with a dam under construction. The limited connections mean that the Haltern coalfield represents a clearly distinct flooding area with well known hydraulic properties.

Task 1.5 – Determining and developing measuring methods for in-situ monitoring

For the relevant mine water substances suitable monitoring parameters and appropriate measuring processes and techniques will be selected. If such methods are not available they will be developed during the course of this project stage. For this purpose the measuring equipment will be tested in selected mine areas.

Because of there was almost no existing equipment specific to mine water in-situ monitoring, concepts and equipment were developed and constructed to meet the site criteria. Site specific conditions and accessibilities demanded solutions for the Haltern coalfield in part different from the original Warndt site. Finally, the equipment constructed was comprehensive, intrinsically safe and therefore universally applicable in coal mining which accomplished the task objectives.

Since the possibilities for in-situ flooding monitoring are much more restricted than investigations from above ground, the number and kind of parameters feasible for in-situ monitoring and essential for geochemical modelling were limited. The information obtained concerning appropriate probes resulted in an adaption of equipment used in offshore technology.

During the project a control unit (CU) was designed and constructed which forms the central part of each underground measuring station and contains the electronic control equipment and the connections to the probes (figure 2.1.2). The control unit also provides data transfer and power supply and the connections are designed for water pressures up to 100 bars. Parameters to be measured are:

CU not intrinsically safe	CU intrinsically safe
Electric conductivity	Hydraulic pressure
Flow (direction and velocity)	Temperature
	Flow (direction and velocity)

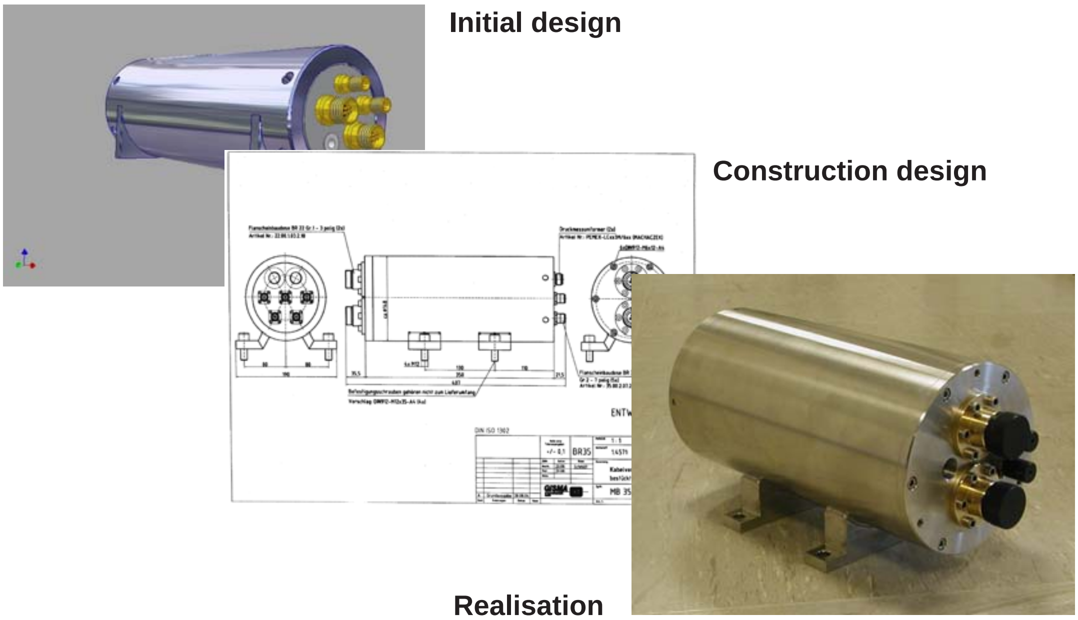

Figure 2.1.2: Development of a control unit for connection of sensors and data transfer.

The probes for hydraulic pressure and temperature are activated directly after installation. Non-intrinsically safe probes and electric components will be supplied with power only after a water level above these components have been detected using the intrinsically safe hydraulic pressure sensor.

Due to safety requirements of the supervising agency, the power supply and data transfer cable are intrinsically safe as well. The materials are derived from marine technology but the cable were specially designed and produced for this purpose. Measurement of flow (direction and velocity) was obtained using a paddle system.

In order to gain supplement information on substance concentrations in mine water and hydrochemical parameters (e.g. pH value) an additional pumping system was constructed. The pump intakes are placed near the measuring stations (control units). From these locations pumped water discharges through pipes and hoses which direct the water towards the gallery were the sampling takes place.

For direct access to mine water from surface, completely new equipment for water sampling in deep boreholes and shafts under intrinsically safe conditions was developed and constructed. A mechanical timer controls the inflow of water in defined levels (see WP 2).

Task 1.6 – Installing of measuring equipment and collecting data

Using selected or developed measuring equipment, measurements will be carried out at a mine site scheduled for closure for as long a period as possible. Measurement will be attempted at several mines or mine sections of various coal deposits in Europe for comparability of the data.

The Haltern coalfield in which the measuring equipment was successfully installed, started flooding in the end of 2006. This has resulted in a period without generation of data. However, this gap could be closed via extended collection of monitoring data from other sites in the Ruhr area and other European mining districts. For example, collecting of flooding water data via the deep borehole water sampler (see WP 2) was achieved at several sites in the Ruhr and Saar Area.

DSK conducted a study of all water inflows into the Haltern coalfield in order to quantify the total inflowing mine water volume. The largest individual inflow identified was about 12 m³/h while the total water inflow was a rate of about 40 m³/h. The individual 12 m³/h inflow is highly saline with Barium concentration of 1.300 mg/L. Other inflows also contain barium so that the overall geogene water inflow has a barium concentration of about 800 mg/L.

The measuring equipment triply installed consists of the control unit described in task 1.5 and a duplicate float valve mounted on a pendant steel platform (figure 2.1.3).

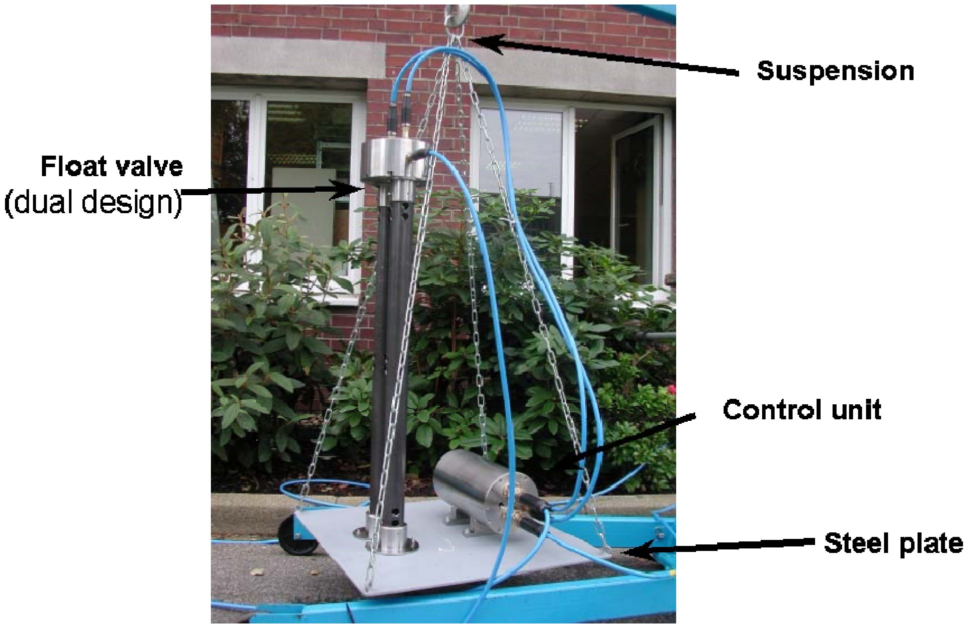

Figure 2.1.3: Installation and functional test of a complete measuring module.

By placing station 1 at the deepest point of the coalfield (-1.279 m bsl) the rising of the water table can be monitored during the entire flooding process. Two other stations with the complete sensory equipment are placed at -1.176 m bsl and -1.118 m bsl. The locations have been chosen for detecting possible water inflows from other levels and seams. At the end of this project the initial flush of mine water at the deep control unit was still being awaited. Activities will continue beyond the project period. Use of data is envisaged for at least 2 years (end of 2008) till flooding of the Haltern coal field is completed. Further operation of the system depends on condition of the probes, need of the data and operation period of the mine. Although the system is designed for a several years operation period the real lifetime under realistic conditions will be a result of the research work. Further application at another mine site scheduled for flooding is already planned.

Task 1.7 - Evaluation of data and calibration of the model

This task comprises an accurate evaluation of the collected data as mine water quality is the complex result of the interactions of chemical processes and the hydrodynamic situation. Having site specific results on these two factors the relevant processes affecting mine water quality have to be extracted.

Evaluation of the monitoring results will be followed by iterative adjustment and calibration of the geochemical model (see task 1.3) to the assessed real data. Proposals for an optimised monitoring equipment and installation will be evaluated.

Particular attention has been paid to differences and similarities between the various European coal deposits. Not only activities of the project partners but also data sets from other monitored flooding events (Poland, France, Germany) have provided information for the application and calibration of the BoxModel for different hydraulic and geochemical settings. The activities on this task started earlier than planned in order to meet the demands on the enhancements of the BoxModel and fulfilled the task objectives.

The monitoring data obtained from historic and current mine flooding form the essential basis for any mine water quality prognosis. The fundamental site specific data considered are the floodable void volume, the rate of recharge and the composition of the inflowing water. Numerous international data sets for concentration developments in mine water discharge have been compiled and normalised for statistical investigations. This has resulted in empirical exponential functions which are widely used for mine water quality prognosis and have proven their applicability at numerous sites. In order to make our evaluation results available for prognosis calculations we had to establish a correction factor as ratio "discharge volume / void volume" (Q/V).

Data for mine water recovery and discharge mine water chemistry for several UK mining areas has been provided for use in DSK/DMT modelling of the chemical processes during mine water recovery. The principal problem with UK mine water data is a lack of original mine water quality data. However, there is some mine water quality data from the deep mines in the Durham area that have been reviewed for use in the DSK/DMT box model.

Data from the Brassert partial mine flooding (Ruhr Area) have been applied for re-calculation by the geochemical reaction model. As an essential exercise a back analysis of the void volume flooded at the Brassert coalfield was performed using old mine survey maps and total production figures (converted to total volume extracted). The same method was also applied to the Haltern coalfield still to be flooded. For calculation of floodable void volumes the following properties of the workings were used: total volume extracted, depth, mining method, age, backfill. Mine water level data from the most recent Brassert flooding stage between 1999 and 2004 have been used to calibrate the mine flow model and to also forecast the mine water rebound within the Haltern field.

Another investigation area is located between Katowice and Krakow, in southern Poland – the north-eastern part of the Upper Silesian Coal Basin (USCB). In analysis of the inflow levels of mine water for Siersza and Grodziec the distribution of some so-called “head-dependent inflows” were calibrated. The main difference between the quantities of inflow is caused by the head-dependent inflow throttling itself during the flooding. Up to this date, only the Grodziec mine can be used to calibrate the model calculations for filling against the actual mine water level measurements and the development of the water quality by means of mine water quality analyses. The best fit resulted by assuming a total porosity of 0.13 % taking into account the exploited coal volume and the porosity of the geological formations represented by the box. In the same way the flooding of the Siersza Mine was also recalculated with the best fit having an assumed porosity of 0.9%. For an advanced understanding of mine water sources the inflow rates in the recent years before flooding were analysed. These correlations support the thesis of head-dependent dominated inflows into the Grodziec mine, which influences both the box model hydraulic setup and the calculation of the flushing process.

Task 1.8 - Application to mine water quality prognosis

After derivation of the standard processes for water quality development in coal mines and the main influencing site conditions, the model has to be applied as a predicting tool to forecast mine discharge quality under various operation conditions and under different scenarios of mine closure and flooding.

The final part of this task is the conclusions regarding the measures for the optimisation of the flooding process, e.g. pumping technology and environmental impact.

A development of a fully operational BoxModel was realised at four sites (Ruhr Area (Germany), Lorraine Basin (France-Germany), Grodziec mine (Poland) and Durham Coalfield (England) (figure 2.1.4). In complying with water management requirements, such as the pumping strategy, flooding control and scheduling of mine water treatment plants, the work accomplished exceeded the objectives initially planed.

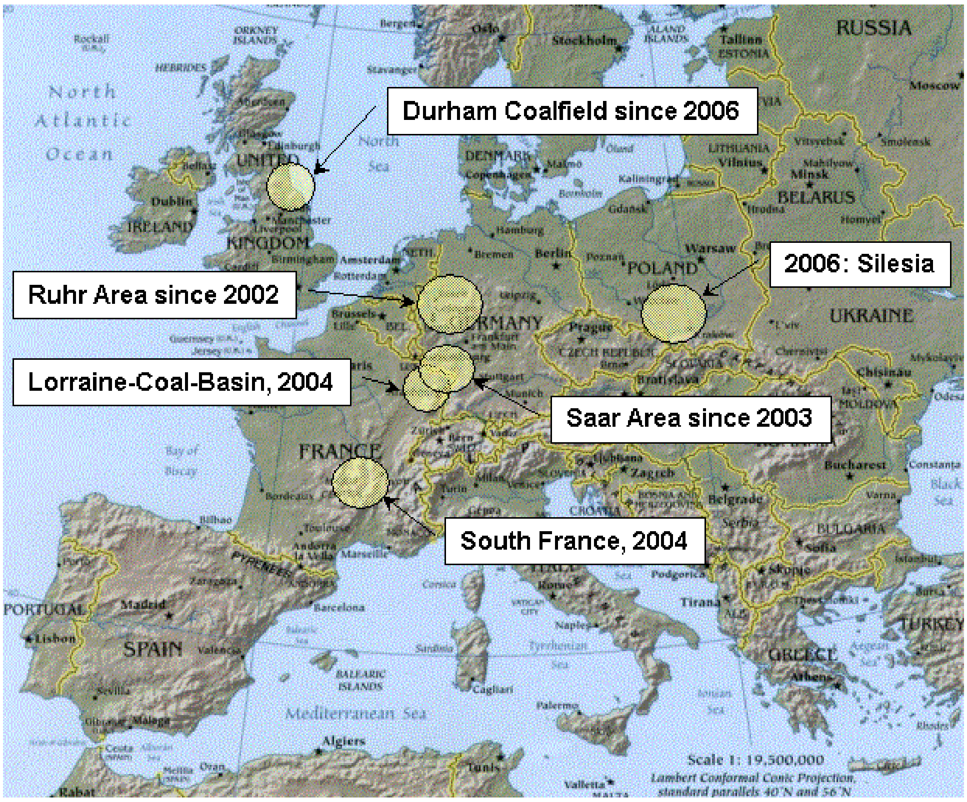

Figure 2.1.4: Mining areas with BoxModel implemented and/or contributing calibration data.

The work undertaken by DSK and DMT has resulted in the calibration and enhancement of a BoxModel covering major parts of the Ruhr coal district. The BoxModel, including the geochemical reaction programme, was employed to simulate the quality development during the flooding process to obtain reasonable initial conditions and to describe the ongoing flushing process. A section of this BoxModel was calibrated using data from the Brassert mine and applied to forecast the most important geochemical reactions for the Haltern mine field where flooding started in late 2006. With respect to investments for mine water treatment, the barium and iron concentrations were of major interest for the prognosis of the treatment required (for results see chapter 2.1.3 and annex chapter 5.1).

The geochemical tools developed during the period of this project were used for the first time in a flooding water prognosis started 2003 in the Lorraine Basin using the enhanced BoxModel. The challenge was to forecast the mine water rebound when flooding the French Lorraine coalfield and stopping pumping at the German Warndt colliery. The calculations were made for two alternatives for the development of mine water quality (parameters selected are iron, sulphate and chloride) at expected points of overflow respectively points of discharge.

The BoxModel calibrated during this project as described in task 1.7 was utilised to demonstrate the practical application of the geochemical reaction model for the prognosis of mine water quality in two more European mining areas. As a prerequisite the future mine water flow had to be calculated for the North-East field of the Upper Silesian Coal Basin to be combined in a subsequent step with the geochemical reactions. The lack of flushing data from the Upper Silesian Coal Basin meant that an initial passive mine water quality representing the total available oxidation product mass calibrated for the Ruhr area and French mines was used for the Grodziec Model. The calculated sulphate concentration of the discharge reflects very precisely the concentration development monitored. Other samples taken from different levels in the shaft during the flooding also correspond well with the model.

The specific properties of the Durham coalfield BoxModel consist of extensive interconnections of mine workings and interactions between the Permo-Triassic aquifer and the workings below this aquifer were studied by WYG. The first preliminary box model calculations performed during the research work considered the heterogeneous water inflow chemistry only (figure 2.1.5). Data on the influence of discharge level and pumping rate on salinity and the flushing process were available for future use.

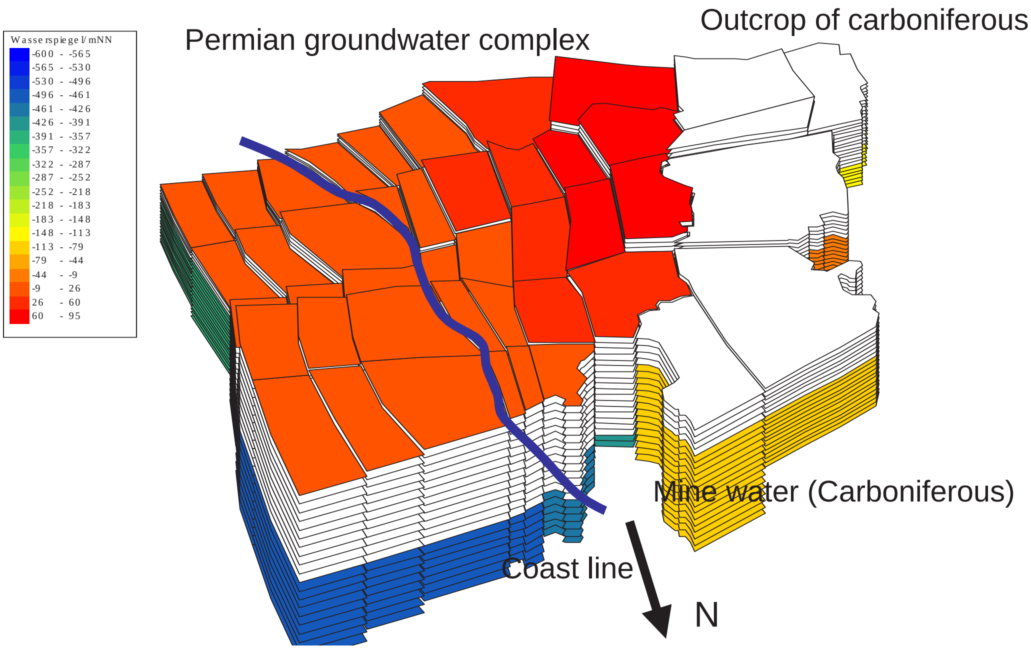

Figure 2.1.5: Model structure and water table of the Durham BoxModel.

Task 1.9 - Presenting and publishing of the results

Once work is complete the final reports will be prepared. The results will be made available to all interested parties in the form of lectures and publications if possible during the project runtime.

Several presentations have been made and papers published on the methods and achievements of this project. The most significant features of the research, the developments and results of the work packages described in this Final Report have been combined into the document "Geochemical reaction modelling of mine water in large coalfields" in the annex to WP 1.

The results of the DSK/DMT box model calculations have been presented and published in a number of conferences:

BLACHERE, A., METZ, M., RENGERS, R. ECKART, M., KLINGER, C., & UNLAND, W.: Evaluation of mine water quality dynamics in complex large coal mine fields. – Proceedings of International Mine Water Congress, , p. 551-557, Oviedo September 2005.

ECKART, M., KLINGER, C., UNLAND, W., RENGERS, R., METZ, M. & BLACHERE, A.: Prognose der Flutungsauswirkungen im Steinkohlenbergbau. – 5. Altbergbau-Kolloquium, 401 – 414, TU Clausthal 3. bis 5. November 2005. (Prognosis of mine flooding impact at hard coal mines)

SERSCH, W. & Uhl, O.: Vorbereitende Maßnahmen zur Flutung der Grubenbaue auf französischer und deutscher Seite im Rahmen der Stilllegung des Standort Warnd/Luisenthal. – 5. Altbergbau-Kolloquium, 415 – 432, TU Clausthal 3. bis 5. November 2005. (Preparations for flooding the French and German Mines in the process of closing the Warndt/Luisenthal Mine)

BABOT, Y., DUZAN, A., ECKART, M., KORIES, H., METZ, M. & RENGERS, R.: Flooding of the Saar-Lorraine coal mines: coupling of the regional model of the Lower Triassic Sandstones aquifer with a „box" model of the mining reservoir. – Post-Mining 2005, Nancy November 16 – 17, 2005.

Following article was published in a reputable German mining magazine:

ECKART, M., KLINGER, C., UNLAND, W., RENGERS, R., METZ, M. & BLACHERE, A.: Prognose der Flutungsauswirkungen im Steinkohlenbergbau. – Glückauf 142, Nr. 6, pp. 262-269, Essen, 2006.

On 28 March 2006 the status and applications of the box model were presented by DSK and DMT to the German Mining Authority in charge for the Ruhr coal district.

2.1.2. WP 1 Conclusions, Exploitation and impact of the research results

The box model, integrating a geochemical reaction model, has proved to be a very appropriate tool in simulating mine water rebound effects in large coal mine fields. Empirical analytical solutions can easily and for a number of applications adequately describe the development of mine water quality after flooding. However, large mine fields with fairly complicated hydraulics require a more demanding approach. Taking into account the often low availability of input data the approach adopted in the Box-Model using relatively simple and robust data sets is essential. The enhanced box model has proven its applicability and robustness in very complex mine fields when mine water flow, trends and transport of various components are to be calculated.

A reliable forecast of mine discharge quality under various conditions enables the coal mining industry to take into consideration pre-flooding measures for mine water quality control or alternative in-situ methods for water treatment. An optimised mine water management improves total production costs and protection of the aquatic environment.

The mine water quality, time till completion of flooding of the Haltern coalfield and the prognosis of the necessity for mine water treatment for iron and barium undertaken within this project are of special interest for the water management of the Auguste Victoria colliery.

To our knowledge the Lorraine/Warndt geochemical model used as basis for strategic design of cross-national mine water management is the first of its kind allowing meaningful forecasts on mine water developments at this order of magnitude (regional coalfields) and period of times (several decades) in the coal mining industry.

There will be numerous future applications of the geochemical BoxModel associated with the intended close-down of coal mining in the Ruhr Area within the next decade.

2.2. WP 2 Developments in surface environment monitoring and control

The overall objectives of Work Package 2 (WP2) were to offer solutions for effective mine closure, provide improved knowledge of ground water movement at working mines and effective surface environmental control of factors resulting from mining activities both past and present. To achieve these objectives WP2 partners undertook the tasks described in the following sections.

2.2.1. Work carried out on task-by-task basis

Task 2.1 - Evaluating existing data and literature

The objectives of task 2.1 were twofold. First was, to facilitate reviews of the available scientific literature and other information sources to establish and monitor the on-going state of the art in terms of technological advances, product suitability and the availability, and mine water related risk indicators. The second objective was, to accommodate the identification and evaluation of existing data from mines and other sources that would supplement the data produced within WP2 and also provide additional data input to other project work packages.

The activities undertaken proceeded as planned and fulfilled the task objectives.

The majority of the work in evaluating existing data and literature was largely undertaken and completed within the early stages of the Project. However, interrogation of the literature and other available information continued as an on-going activity within the remaining tasks. The specific results obtained from the literature surveys undertaken are discussed within the WP2 task sections to which they relate most directly.

The identification, collection and evaluation of existing data from mines and other sources undertaken within WP2 included:

- Evaluation of Technical Report data from the Nottinghamshire Coalfield. This data was used to determine sites for future monitoring of the Permo-Triassic aquifer and the mine workings below.
- Evaluation of first response hazard data held my MRSL at the start of the project.
- Hydro-geological, hydrological and quality parameters of the three lignite district areas of PPC in Greece; these were Megalopolis, Ptolemais, and Aliveri mines.
- Collection and evaluation of existing groundwater data, supplied by the UK Environment Agency and local public water supply companies, which were evaluated and employed in WP1(T1.2) and WP3(T3.4)
- Collection and evaluation of DSK monitoring data on the discharge quality of central pumping stations and active mines into the rivers Lippe and Emscher (Ruhr Area, Germany)

Evaluation of Technical Report data from the Nottinghamshire Coalfield indicated that the key area was in the city of Nottingham where very old shallow mine workings are overlain by the Permo-Triassic aquifer that has numerous water abstraction boreholes. The data for the Permian aquifer that was obtained included time series data on aquifer water levels and abstracted water qualities. This data was used in task 1.1 of Work Package 1.

The review of data obtained from the surface hazard response work in the UK indicated that, in general terms, most of the shafts and workings that had become exposed were shallow in depth, with obscure or unknown information associated with them. On occasions shafts of up to 100 metres had been exposed but the deeper, more modern shafts tended to be covered with more substantial surface caps with location markers and accurate records being kept by respective authorities. Examination of the data also revealed that water had been found on numerous occasions; therefore hazard response activities offered a potential opportunity to acquire data with respect to water quality and possibly water movement in relation to mines with a potential age of up to 300 years or more.

Evaluation of the existing data from the lignite districts of PPC and examination of the literature indicated that the main sources of pollution of mine waters at these open cast or underground mines were:

- Seepage through spoils

- Leaching from underground works
- Oxidation of pyrite in aquifers exposed to oxygen of the atmosphereAnd that elevated concentrations of:

- Fe, SO4, H: are due to oxidation of pyrite
- Si, Al, Ca, Mg: accelerated hydrolysis
- Mn, Zn, Ni, Co: both

Measures proposed to overcome these problems were:

- Selective management of spoils
- Improvement in the drainage systems of the waste dump areas of the mines
- Mixing with limestone and fly ash in order to neutralize the acidity of mine water

Task 2.2 - Instrumentation Package Component Development

Development of dedicated integrated environmental measuring capabilities with system components which are compact, intrinsically safe, self-powered, robust, have a long-life and have remote interrogation and self-checking capability

The activities undertaken proceeded as planned and fulfilled the task objectives.

A diverse range of monitoring equipment and sensors for environmental monitoring were already commercially available at the start of the project. However, it was unclear whether these could offer long unattended operating life, whether sensors for different parameters could easily be connected to the same data-logging and data transmission facilities and how suitable they were for situations where there was a requirement to employ intrinsically safe devices.

A typical instrumentation package required for use by the industry consists of a number of discreet modules, as illustrated in figure 2.2.1 below.

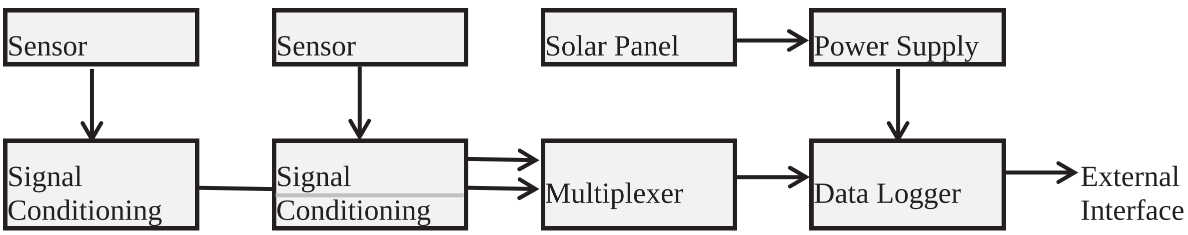

Figure 2.2.1: Block diagram of a typical instrumentation package

Reviews and assessments of a wide range of instrument modules, sensor techniques and data acquisition methods to facilitate the development of an instrumentation package were undertaken. The range of parameters that could potentially be monitored using commercially available remote monitoring devices or in-house devices that were examined included:

- Redox Potential or ORP (oxidation-reduction potential)
- Hydrogen ion concentration - or its logarithm, pH
- Conductivity - typically used as a guide to Total Dissolved Solids (TDS).
- Water Depth - primarily measured by means of hydrostatic pressure.
- Fluorescence and Turbidity - although there was considered to be no specific need to monitor these parameters, they are of interest to the water supply industry.
- Temperature - accurate measurement of temperature are also required for the calibration of ORP and pH meters.
- Flow Rate - measurement options examined included impeller, hot-wire and ultrasonic techniques.

It was concluded that ORP measurement is only likely to be useful if some knowledge of the species of ions that are present in the sampled solution is already available and that Hydrogen ion concentration, pH measurement, would be a more suitable approach. In a pH sensor, the glass electrode – although fragile – usually requires less maintenance. However, the reference electrode suffers from the problems of fouling and diffusion, which stem from the fact that the electrode needs to be porous. Possible solutions to the problem of sensor fowling using a "Refex" type electrode were identified and problems arising from the fragility of the tradition glass bulb sensor could be reduced by using solid-state pH sensors.

In general, it was concluded that rugged, self-powered sensors were already widely used for environmental monitoring and where possible commercially available equipment could be used. However, intrinsically safe equipment for water sampling in deep boreholes and shafts was not available commercially and had to be tailor-made for the purpose of the project. The final development work for this instrument is reported in task 2.4.

To further assist the industry and enable comparative reviews of currently available equipment, the findings from this task were also used to support the development of a state of the art demonstration system that also has a data transmission capability between remotely monitored sites and a 'base station' under tasks 2.3 and 2.4.

Task 2.3 - Integrated Mapping and Survey Capability

Assessment of the incorporation of an integrated mapping and survey capability using an embedded TCP/IP internet gateway for secure remote access capability, and integrated data logging analysis and alarm signal.

The activities undertaken proceeded as planned and fulfilled the task objectives.

A review and assessment of the methods available for the transmission of data from surface facilities, possibly from several points, to a central base station was undertaken. The equipment and methodologies addressed included:

- Radio Modems
- Cellular Radio Networks
- GSM (mobile phone) and Internet
- SMS (Short Message Service)
- FTP (File Transfer Protocol)
- HTTP-POST

Ranges of disadvantage associated with the use of radio modem based systems were identified. These included the facts that transmission range is often limited and the transmission is point-to-point and hence requires a dedicated base station. From the examination of the various GSM options, it was initially concluded that the favoured way to retrieve data was by using an FTP protocol for data uploading. However, further analysis led to the conclusion that HTTP was a more appropriate protocol.

A demonstration web site was developed and implemented for use by project partners. This site included an embedded TCP/IP Internet gateway to provide secure remote access capability, and demonstrated the development of integrated data logging analysis and alarm signal.

Laptop PCs with GPS facilities were configured to allow detailed mapping data of the users' current position, or a position held in a database (developed under task 2.8) to be displayed. A range of commercially available map packages were evaluated and automated links established between a database and the selected mapping software that provided 1:50,000 detail of the site being addressed. User feedback from trials of this integrated mapping facility indicated that:

- The system worked reliably – users found the software to be stable and the user interface to be intuitive and easy to use.
- The potential for gross GPS reading errors was minimised – use of the map display system provided an immediately available cross check on the reported hazard location

- The integrated mapping facility was found to be a valuable aid in locating the actual site of reported hazards.

Mapping software solutions that enable higher resolution map polygons to be stored and accessed directly from a database were examined. These were found to be less economically attractive, as they tend to involve purchasing specific mapping and geological data on a site-by-site basis. Collaboration between project partners revealed that this was the case for PPC. As a result PPC developed its own mapping system based on the maps of the mining areas, which they already held. Satellite images, which covered the areas around the mines, were purchased and automated links then established between databases and digitizing maps. These facilities were then used to create a range of maps to show the distribution of a physicochemical parameter for groundwater, for surface water and for different aquifers etc.

Task 2.4 - Instrument Development, Integration, and Refinement

Co-ordination and functional integration with surface geotechnical and geochemical measurement and monitoring suites. Instrument development and refinement, followed by a feasibility study to apply the instrumentation within environmental control schemes.

The activities undertaken proceeded as planned and fulfilled the task objectives.

A specialised piece of equipment for water sampling in deep boreholes and shafts was developed and constructed. The design originated from a joint effort by DSK and DMT engineers, who also performed the construction. The sampler is certified as "intrinsically safe" by the mining authority for use underground in a degassing atmosphere. This type of equipment was not available commercially and had to be tailor-made for the purpose of this project.

A state of the art demonstration system that allowed the transmission of data via a GSM/GPRS modem to a web server was also constructed. This system was then compared with the typical systems currently in use by the industry with a view to identifying the potential for improvements and refinements in the light of any shortcomings identified. The typical systems in use were found to be relatively power-hungry, requiring a 50W solar panel, and employing point-to-point communications systems using conventional modem techniques, which are implemented using GSM devices rather than land lines.

The systems in use presented a good argument for using standard 'off-the-shelf' equipment as they were found to be both practical and relatively reliable. However, this aspect of the project work identified and demonstrated aspects of remote monitoring systems where valuable improvements in design and security could be achieved in new installations, particularly in applications that demand advanced state-of-the-art designs.

Within PPC's lignite fields extensive pumping is required to achieve sufficient drawdown of the aquifers, which are influencing the mines. Consequently the major problem is the water table level and how it affects the mining works, the surface environment, slopes stability and the quality of water. Hence the primary focus of this work was directed towards:

- Recording the groundwater level, which in some cases were combined with EC or T, in water wells or shafts
- Protecting mine voids from the intrusion of seawater (case study of Aliveri underground mine which has been abandoned).
- Avoiding the interconnection of different aquifers or different quality waters

To achieve this, PPC installed a number of water level sensors, which were cheap, commercially available, compact and suitable for difficult mining conditions.

The main technical characteristics of the instruments used in Megalopolis were:

Sensors: pressure ranges 0-500 mbar up to 0-6 bars

Temperature	-5 ^{o}C to 50 ^{o}C	Accuracy	≤ ± 0.1% FS (P>0,5 bar)
Conductivity	20μS/cm up to 2ms/cm		≤ ± 0.25% FS (P≤0,5 bar)
		Interface	RS 232c

Data logger: Interval of measurement (and storage) 2 sec – 24h

Data memory   130.000 measured values

Battery lithium 3,6V (exchangeable by the customer)

In Ptolemais, PPC installed a telemetry system, which consisted of one main computer, an RS-232 connection, a modem, a GSM modem, and four remote stations. The stations were placed in 2 wells and 2 pumping stations. Every station consisted of a data logger, a GSM modem for the transmission of data to the main computer and a sensor. This telemetry system measured pH, T, E.C., Q and water level.

The main technical characteristics of the sensors used in Ptolemais were:

Temperature	-10°C to 50 °C (Accuracy ±1°C)
Conductivity	00µS/cm up to 2,5ms/cm (Accuracy ±10µS/cm)
pH	0 to 12 (Accuracy ± 0,1)

Task 2.5 - Monitoring, Sampling and Analysis of Ground Water

Monitoring, sampling and analysis of water from surface points was as an ongoing activity throughout the project to provide supporting data.

The activities undertaken proceeded as planned and fulfilled the task objectives.

Sites with historic water quality or water level data in the main study areas of Durham and Nottingham were regularly sampled for quality and most water levels were monitored using pressure transducers and data loggers. A new site for deep mine water level monitoring in the mine workings below the aquifer in Durham was provide by the drilling of a deep borehole (220 m) through the Permian aquifer and an existing deep borehole into mine workings was taken over in the Sunderland area. Two existing shallow boreholes in the Nottingham area were identified, one into the Coal Measures and one into the Permo-Trias; these sites were added to the Coal Authority monitoring list.

The sampling and logging of open mine shafts in the Durham area was undertaken as planned by Robertson Geologging Ltd., including two new shafts in the area of Durham, south of the Butterknowle Fault, where contamination of the Permian aquifer had previously occurred. The logging and sampling programme was carried out on four occasions, in September and December 2003, October 2004, October 2005 and December 2006. The other sites regularly monitored were the Coal Authority mine water pumping sites and the Horden pumping test site. All data obtained during this task was input to the Coal Authority Hydrolog 4 database and is available to all interested parties.

The mine water and ground water quality data obtained was used in both the input data and control data for the PHREEQC modelling undertaken in work package 4. Water quality, water level and the temperature and conductivity monitoring was used in the risk assessment undertaken with regard to the overlying and interconnected aquifers and to determine mine water flow paths both within the workings and to the Permian aquifer in the case of the previously contaminated aquifer.

Changes in fluid conductivity and temperature with the increasing mine water pumping rate in Horden shaft, including temperature inversion, clearly demonstrated the principal flow paths in the mine workings resulting from the stepped pumping test. Changes in mine water chemistry also helped to confirm the flow paths.

The deep mine water level monitoring at Silksworth and Sunderland showed that the mine water levels were significantly deeper than the East of Wear block and there was no immediate risk of aquifer contamination.

Samples from surface water and groundwater from exhausted and working mines were analysed in order to investigate the change to the quality after the end of exploitation. A total of 786 samples from different lignite areas (217 from Megalopolis, 536 from the Ptolemais basin, 31 from the Aliveri area) were collected. Figure 2.2.2 shows the sampling points used within the Megalopolis mine. The analysis for the determination of the concentrations was carried out according to ASTM standards.

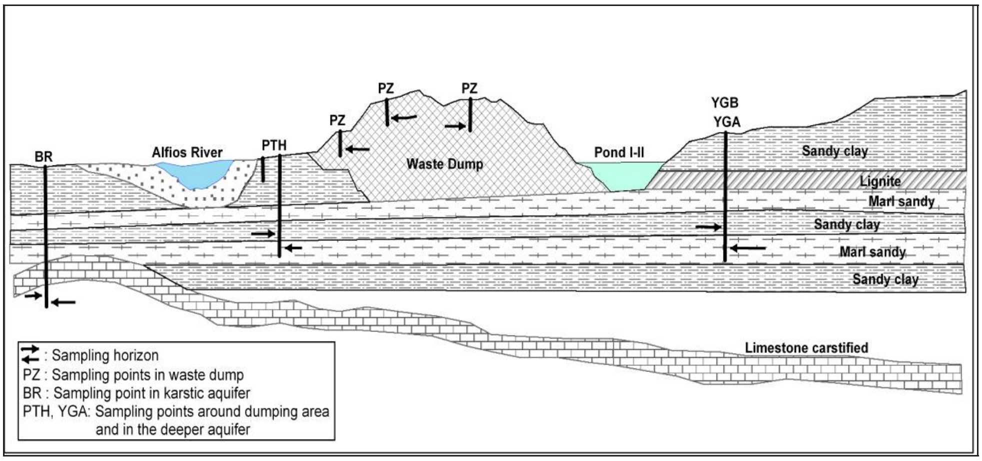

Figure 2.2.2: Schematic cross section of Megalopolis mine

In the Megalopolis lignite district, water level sensors were used to provide daily measurements of the groundwater table. Daily rainfall was also monitored. Figure 2.2.3 shows the fluctuation of both rainfall and the absolute elevation of the water table derived from these measures.

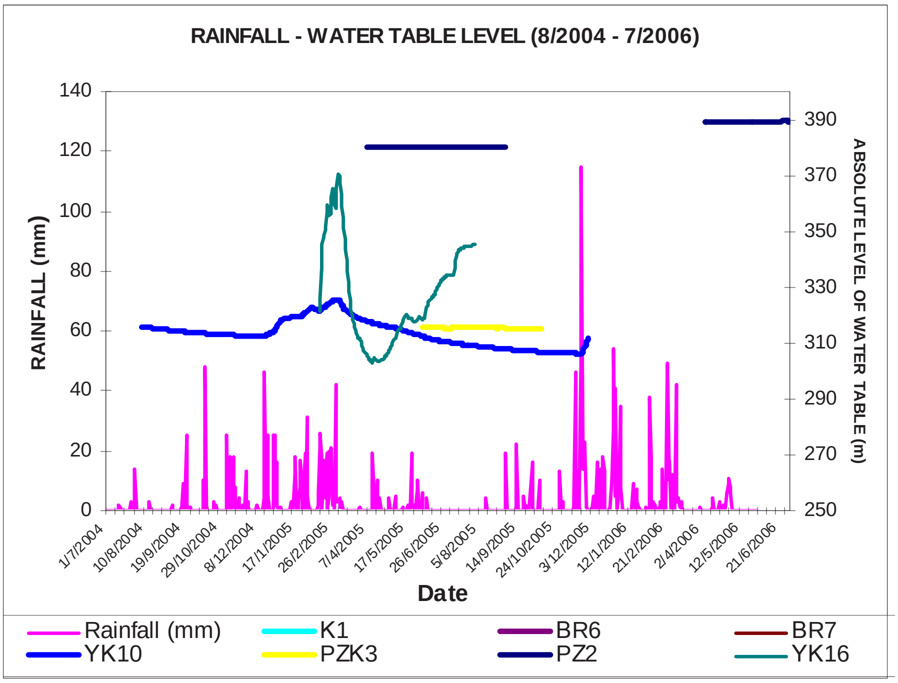

Figure 2.2.3: Rainfall and water table level in drills in the area of Megalopolis

Surface hazards arising from historic mining liabilities in the UK were investigated. Many of these incidents result in old mine shafts being detected, due to shaft collapse, infill settlement, capping disturbance and shallow working collapse, leading to surface cone depressions and ground fracture. This element of the research was used to assist in investigating the reasons for these incidents and to determine if there is a relationship with any changes or movement in ground water.

Water sampling at these incident sites was carried out manually throughout the duration of the project, although it should be noted that this was only done where safe access for water sample collection was possible. The data obtained from analysis of water from these surface incidents were used to assist in the investigation of the feasibility of acidic mine water having a corrosive effect on shaft lining, therefore potentially having a major contributory effect on the risk of shaft collapse.

The intrinsically safe equipment produced for water sampling in deep boreholes and shafts was used in the two shafts of Camphausen in the Saar area and Ewald 5 (figure 2.2.4) in the Emschermulde. The Emschermulde is part of the Ruhr area and represents, in this mining area, the largest area to be flooded at the moment. The water level in the Ewald 5 shaft had reached -1,050 m below the surface at the time, which corresponded with -991 m asl. After some problems with the timer of the release mechanism which opens the sample container, the system worked satisfactorily and 6 samples from different depths were obtained, with the samples showing a clear stratification with salinity and sulphate concentration increasing with depth.

Figure 2.2.4: Preparation of the sampler before use in the Ewald 5 shaft

Task 2.6 - Data Acquisition on Water Make and Movement

Collection and analysis of data on water make and movement from working mines.

The duration of this task was extended to enable more opportunities for the collection of data to be taken. This was done within the originally planed budget and the activities undertaken fulfilled the task objectives.

In all the lignite fields of PPC the major problem is the water table level and how it affects the mine workings, the surface environment, slopes stability and the quality of water. PPC installed and operated a number of water level sensors. Several piezometric maps of aquifers were created (figure 2.2.5).

The measurements of the piezometric surface were taken once a day and finally a continuous picture of the fluctuation of the water table (figure 2.2.6) due to the rainfall measurements was obtained. By knowing the water level, the direction of water movement was ensured, and by comparison with the results of chemical analysis it was concluded that:

- In the area of Megalopolis there are three different aquifers: the main karstic aquifer, the north one and the west one.
- There is no hydraulic connection between them.
- There is no direct hydraulic connection between mine workings and the karstic aquifers. The creation of new hydraulic pathways between karstic aquifers and mine voids was investigated in WP3.

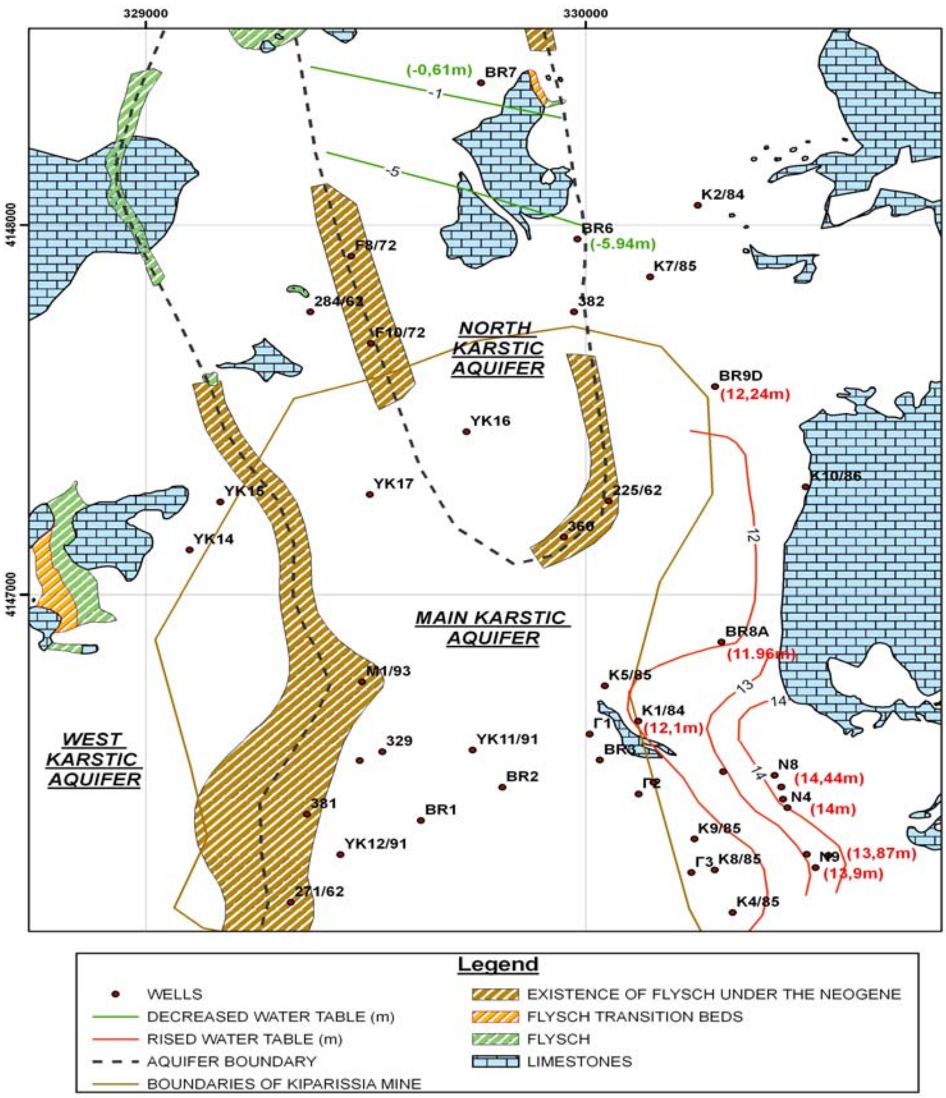

Figure 2.2.5: Fluctuation of water level (1/2005-1/2006).

The central part of the Emschermulde (Ruhr Area, DSK) is subject to an ongoing flooding process until mine water decants towards the central Zollverein underground pumping station. In several shafts level measurements were taken on a regular basis by DSK. The water level measurements from these shafts were used to calibrate and verify the modelling of the mine water rebound. These measurements were run by conventional logging technique, but initial trials to use pressure probes, installed at the bottom of the shaft before flooding, performed well.

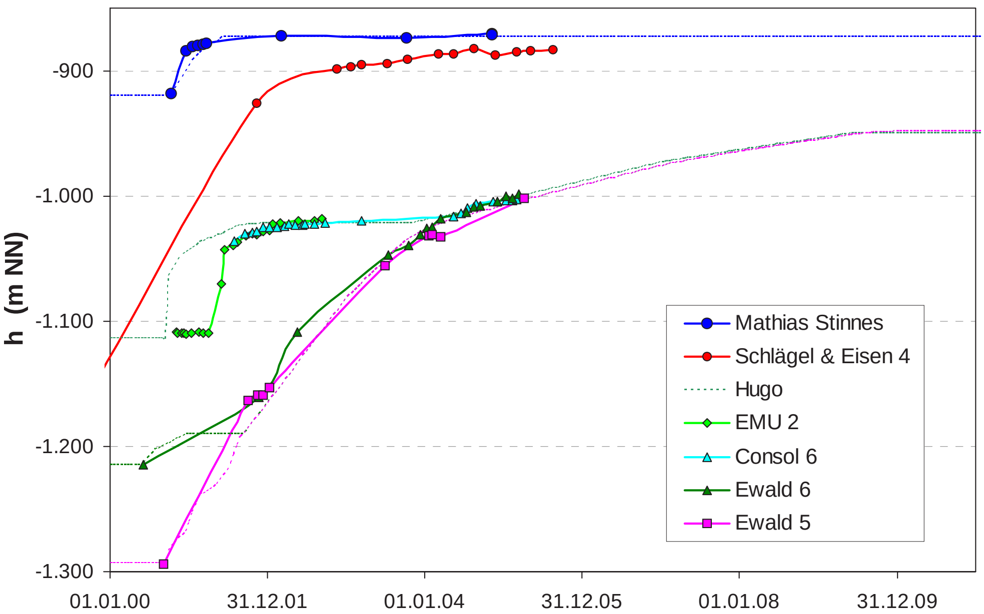

Figure 2.2.6: Actual mine water levels from shafts of the central part of the Emschermulde and forecast calculated by the box model.

Task 2.7 - Effect of Acid Mine Water on Shaft Lining Competency

Objective of the task was the investigation of the effect of acid mine water on shaft lining competency.

The duration of this task was extended to accommodate longer term soak testing of material samples. The work accomplished fulfilled the task objectives.

Immersion tests using simulated acid mine water and concrete cores were undertaken, with the aim of identifying and quantifying the physical and chemical effects. Concrete samples were immersed in tap water, de-ionised water, dilute sulphuric acid pH 5, actual acid mine water pH 4 and compared with un-soaked samples. Similar tests on grit and coal measure material were also conducted.

Geochemical and SEM analysis of the concrete samples showed:

- Shaft linings with any form of cement are subject to corrosive attack
- Attack is instantaneous at a liquid solid interface
- Attack continues in both acid and alkaline phases in stagnant and continuous flow conditions
- Formation of complex sulphates and silicates enhances attack in the alkaline phase

Geochemical and SEM analysis of coal measure shaft fill material showed:

- Chemical reactions are numerous and complex
- Material competency is reduced in days
- Volumetric reduction is approx 30%
- High number of historical surface hazards result from settlement of this type

Geochemical and SEM analysis of gritstone shaft fill material showed:

- No evidence of surface chemical reactions or surface deposition
- Reduction in weight of granular material by 3% after the soak period
- 3% conversion to fine sand – possibly due to weathering of the gritstone.

In Aliveri no underground mining activities have taken place since 1982. The open pit excavations, which followed, were completed since 1990. Several chemical analyses were performed in the shafts in order to clarify the quality and possible acidity of mine water. The results showed that the pH in Aliveri, 16 years after the closing of the mine, was not acid (pH=7.5) and the same conditions are expected for the other mines (pH range between 6-7), after the end of excavation.

Acid mine water is nearly unknown in West German hard coal mining. Only very few of the geogene mine water inflows show pH-values below 6. These can be located at the southern border area of the mining district near the outcrop of the coal bearing strata. Here no overburden exists allowing inflow of surface originating waters influenced by pyrite oxidation. The buffer capacity of the water unsaturated rocks are insufficient for the acid produced. However there is a strong correlation of pH and alkalinity and most of the mine water inflows show pH values between 6 and 8 which are typical for a carbonate buffering system. Extremely high alkalinities can be found in the water discharged from the central mine water pumping stations. This water represents, in nearly all cases, formerly flooded mines or coal fields with acid from pyrite oxidation reacting with sufficient reaction time and therefore intensively with carbonate phases of the rock strata. Altogether there is no evidence of acid mine waters influencing shaft lining or fills after flooding in the Ruhr Area.

Task 2.8 - Database development

The objective of the task was the development of databases to integrate all relevant information and enable exchange to computational model development.

The duration of this task was extended to allow for the collection and interrogation of data in the databases over the maximum possible time period within the duration of the project. The activities undertaken fulfilled the task objectives.

An integrated database system, which combines information on the type of surface hazards, liability, stratigraphy, geology and water regime and analysis, was developed. This database can also be linked to integrated GPS and mapping systems developed for use by the first response surface hazard teams. The data included in this database includes hazard data collected by first response teams and supplementary historical data provide for project use by the UK Coal Authority. Figure 2.2.7 shows the frequency of surface hazards reported in the UK and identified those that have, or have not, been identified as being related to coal mining activities.

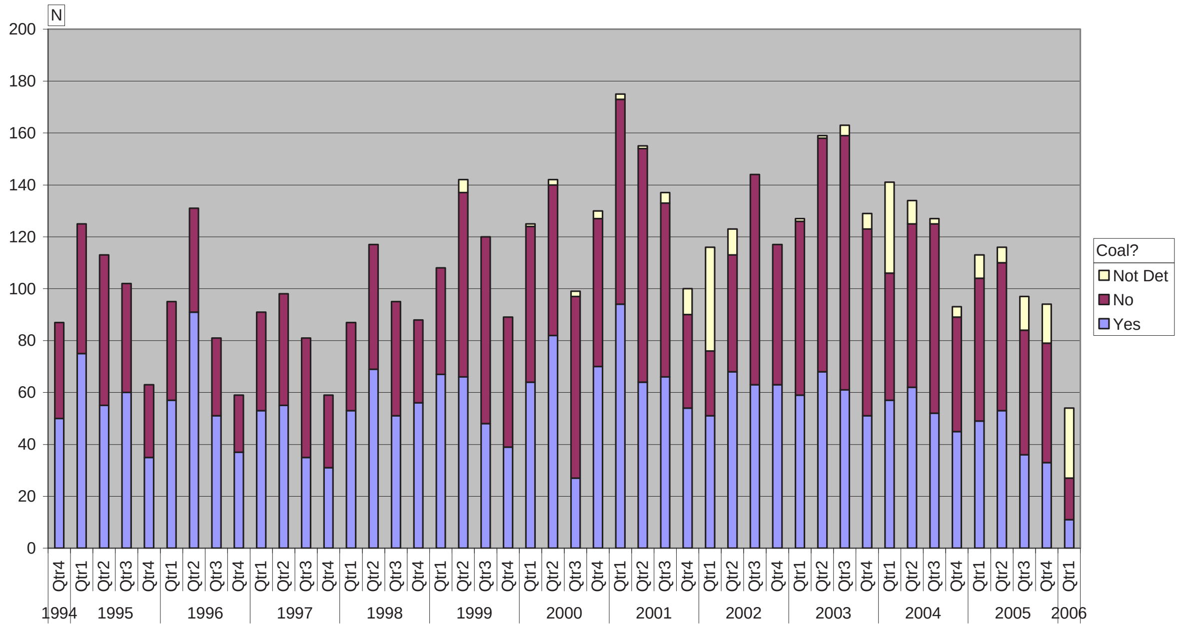

Figure 2.2.7:- Frequency of surface hazards reported in the UK

Further statistical analysis of the data was undertaken to determine if correlations could be established that would assist in predicting the risk of surface hazards occurring. The statistical results obtained positively identify hazard incidences clusters, based on geographical location, that could be related directly to areas of coal mining activity. However, although the results obtained in task 2.7 suggest that there may also be correlations with mine water variables; these could not be established from the available data. It is postulated that such correlations may still exist but are likely to be completely masked as a result of limitations in the historical data currently available and the currently unknown time scale of any mine water degradation effects.

An Excel database was produced to hold the data collected for surface and groundwater lignite mining activities. All the chemical analyses from these mining areas were imported into the database which contains information on:

Date of sampling and the characteristics of the sampling points

- E.C., p.H., ^oT and other physicochemical parameters
- Basic anions cations
- Trace elements and heavy metals

This database is also linked to Aquachem and ArcGis as shown below in figure 2.2.8.

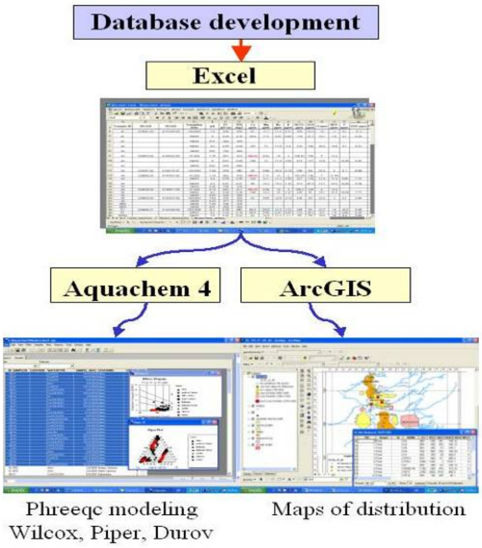

Figure 2.2.8: Excel database links

Task 2.9 - Presenting and publishing of the results

The central objective of this task was to ensure that data, research findings and results derived from the WP2 tasks are shared with other researchers and made available to the industry.

The activities undertaken proceeded as planned and fulfilled the task objectives.

This was accomplished by means of regular meetings with, and reports to, various bodies, for example:

- The results of fluid conductivity, temperature and discrete mine water sampling were presented to the UK Coal Authority, the Environment Agency and local stakeholders.
- The proposals for groundwater monitoring in the Nottingham area were agreed with the Coal Authority and presented to the Environment Agency, together with long-term proposals for the control and treatment of mine water in the Nottinghamshire Coalfield.
- PPC produced two papers for publishing the results of Megalopoli and Ptolemais, addressing the quality of water resources in these areas and the sources of pollution.
- The finding of the concrete core and shaft fill material immersions tests were presented to, and discussed with, the engineers responsible for managing surface hazard liabilities and the specification and supervision of shaft capping activities.

2.2.2. WP 2 Conclusions, Exploitation and impact of the research results

The potential scope for improvements in the reliability and data security of new data logging and transmission installations were demonstrated by the project. Details of the demonstration instrumentation produced during the project to enable more effective monitoring and data transmission were presented and made available to other interested parties. Comparisons with existing systems were used to illustrate areas for future improvements in reliability and reduction of cost. Field trials of an integrated mapping and GPS location system were to demonstrate a system to improve the reliability of data collected during first response calls to surface hazards and to streamline the recording and reporting process.

The availableness of sensors for long term monitoring of chemical mine water properties is very limited. Comprehensive information on the composition of mine water will still requires manual sampling and chemical analysis. Development of cost effective, long-term movement monitoring and warning devices to be placed in shafts to be filled and capped is needed.

Data obtained with the water sampling equipment in the initial phase of mine flooding enabled first-time calibration of BoxModel prognosis on water quality before the final water discharge.

Increased risk of potential surface hazards and, in turn, mine water pollution potential can be put down to the lack of adequate mine closure methodologies. These is a need to develop improved mine closure methodologies that further reduce the risk of future surface hazards occurring.

Continued monitoring of surface hazards and mine water regimes are required to establish quantifiable risk potential. Improved understanding of the potential for changes in mine water levels and chemistry to influence shaft structures, and hence the risk of surface hazards occurring, established by the project highlights the industry's need for improved closure methodologies and shaft fill standards.

The attack of cement based materials exposed to mine waters does not only occur in acidic conditions. Study methods of in-situ treatment for corrosion prevention in filled/flooded shafts and workings are required. Choice of correct shaft fill materials is vital to help prevent ground failure and pollution potential. Further studies on optimum shaft fill material types, especially for larger deeper shafts, should be undertaken.

The monitoring systems implemented play a key role in ensuring the protection of the main karstic aquifer witch is used as the water supply for the city of Megalopolis, other small villages in the area, and for the cooling towers of the power plants.

The information accumulated regarding water movement, quantity and quality will serve as a valuable resource of information. Due to global warming issues and the future availability of potable water resources, it is estimated that large quantities of mine water will provide a valuable resource. Furthermore, the assumed rise in the cost of such a valuable resource will allow purification to various levels for a range of uses.

2.3. WP 3 Mine water contamination of aquifers

The overall principal objective of this work package was to determine the types and sources of water in mines, the potential impacts of these waters on ground water and aquifers and to prevent or reduce the risks of aquifer contamination.

The research undertaken in work package 3 was divided into three main areas of work. Firstly there was the collection, analysis and evaluation of both historic and current data (tasks 3.1 – 3.3). Secondly there modelling of mine water chemistry including the determination of flow paths and the mixing of mine waters and aquifer waters (task 3.4) and thirdly there was the assessment of risks of aquifer pollution and the methods to prevent or minimise any potential contamination (tasks 3.5 and 3.6).

The collection and evaluation of data included the detailed examination and digitising of extensive areas of mine workings, the collection of historic data on coal quality, the chemical analyses of mine water inflows, rates of inflow and mine water pumping volumes during production, monitored mine water recovery rates and the in situ measurement and sampling of mine water and aquifer water qualities. The data was also used for the geochemical reaction model developed by DSK/DMT in work package 1.

The modelling of mine water chemistry and the effects of mixing with aquifer waters was carried out using PHREEQC geochemical modelling software (Parkhurst et al 1995).

The work to minimise or prevent aquifer contamination included and extended mine water pumping test to assess the impacts of varying rates of pumping on mine water quality layering and the flow paths within a large mining area.

2.3.1. Work carried out on task-by-task basis

Task 3.1 – Collection and evaluation of existing data

The main objective of this task was to bring together on one database all the historic data that was still available that could be used for the research into mine water contamination of aquifers. The data required for the various tasks included seam chemistry, mine water and aquifer chemistry, mine water inflow and pumping data and water level data for aquifers and mine water. To aid in the assessment of risks and the selection of sites for investigation detailed mine plan and mine entry data was required and this was converted to digital format for use in other work packages.

In the UK the main archive researched was that of the Coal Authority who also responsible for all Mine Abandonment plans for the UK. Other archives researched were those of universities with known interests in mining, the Environment Agency (EA), the government body responsible for water abstraction, discharge and pollution, water companies with aquifer abstraction licences (Northumbrian Water Ltd (NWL)), and private individuals know to have reports dealing with mine water problems. Published reports and relevant geological data on both the Carboniferous strata and the Permo-Triassic aquifers held by the British Geological Society (BGS) were also collected.

In the lignite mining area of Megalopolis the data collection was concentrated on the four main elements that make up the hydrogeology of the area, the River Alfios, the waste dump area of Thoknia, the higher permeability karstic aquifer and the lower permeability deeper aquifer which is developed in the sediments below the lignite layers (figure 2.3.1). There are no limits for levels of contamination of water in the Megalopolis mining area therefore any comparison was done with potable water standards.

In Ptolemais lignite field the mine water pumped from surface ponds and dewatering wells is discharged to river Soulou, which has been characterized as a sensitive aquatic receiver, and the lakes of Petron and Vegoritis. An important deep karstic aquifer exists in the basement of the graben. The most important aquifers are developed in the Neogene sediments of Notio and Amynteon hydrogeological basins.

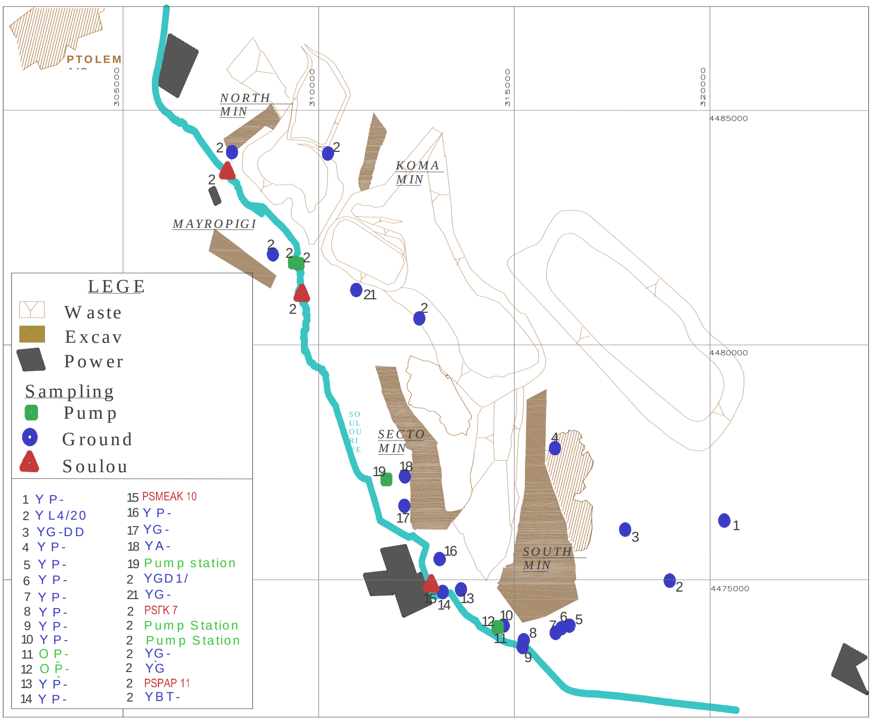

Figure 2.3.1: The West Macedonian Lignite Field near Ptolemais

All the planned searches for data were undertaken and in the majority of the cases more data than was originally envisaged was gathered. In the UK the area of the research where less data than would have been preferred was found was in the detailed seam chemistry and the chemistry of individual mine water inflows. Table 2.3.1 details the additional data obtained during the researches for the project. The work carried out was to a large extent governed by the fact that all the mines were already abandoned with no underground access. As all the mines were in the process of flooding any installation had to be via boreholes or open mine shafts. This together with the depth limitations that we found when researching the existing commercially available equipment (WP3) meant that in the UK monitoring could only be carried out at a limited number of sites and detailed in situ chemical analysis was restricted to two shallow boreholes in the Permian aquifer and one mine shaft. To supplement the lack of in situ chemical monitoring equipment discrete sampling of all open shafts was undertaken at regular intervals to determine both the spatial and temporal changes in mine water quality during flooding in the areas of the investigations.

Table 2.3.1: Data Collected for the Durham and Nottinghamshire Coalfields

	Data obtained as part of task 1	No. of sites/samples/area
Nottinghamshire	EA Aquifer abstraction data	21 sites
	EA Aquifer chemistry data	182 sites
	EA Water level monitoring data	86 sites
	CA Archived Reports	17 reports
	CA Specific Mine water chemistry	57 sites
	CA Mine Plan Data, shaft sealing	112 seams, 1363 km^2
	CA Monitoring sites for water/gas	33 sites or sub sites
	Unpublished Mine Water Reports	58 reports
	Published reports with data	19 reports
Durham	EA Aquifer chemistry data	103 sites
S of Butterknowle	EA Water level data	81 sites
and East of Wear	NWL Water abstraction data	27 sites
	NWL Water chemistry data	46 sites
	CA Archive mine water chemistry	5 sites

	CA Monitoring sites for water/gas	12 sites
	CA Mine Plan Data, shaft sealing	104 seams, 478 km^2
	Published reports with data	5 report
	Unpublished reports with data	10 reports

All chemistry and water level data obtained from archives, reports or third party data was input into the Coal Authority Hydrolog 4 database where it is available for public use. List of data, reports etc obtained are listed in the published reports detailed in task 3.7. Reports and other unpublished data obtained that was not held by the Coal Authority were archived at the Coal Authority for future use.

The data obtained in task 3.1 from the lignite mining areas concentrated principally on the water chemistry from either existing boreholes or surface sampling. The main findings from the chemistry data obtained in the Megalopolis area were:

- All the waters are alkaline, the chemical types being Ca-HCO_3, Mg-Ca-HCO_3, and Ca-Mg-HCO_3.
- The mine water ponds in the Thoknia area contained concentrations, above the potable water limits of E.C (4370μS/cm), Ca^{+2}(684ppm), SO_4^{-2} (1807ppm), Mn^{+2} (2154ppb), Mo (11110 ppb).
- The water of the River Alfios was generally very good quality, apart from high concentrations of SO_4^{-2} (573 ppm) , E.C. (1300 μS/cm), Ca^{+2} (229 ppm)..
- The quality of the water at pumping stations at the mines, high concentrations were observed for the following parameters: E.C. , Ca^{+2}, Mg^{+2}, SO_4^{-2}, NO_3^-, NO_2^-, Mn^{+2}, Ba^{+2}.
- The deeper aquifer samples show relatively good quality water.
- Karstic aquifers indicate very good quality. Only in one sampling point high values in Mn (1200 ppm) were recorded.

In the Ptolemais area the results of the water chemistry data showed:

- The Electrical Conductivity (E.C.) indicated moderately increased levels of mineralisation in all the surface and ground waters.
- The waters are alkaline with increased Total Hardness. The water types are Ca-HCO_3, Mg-Ca-HCO_3, and Ca-Mg-HCO_3.
- The analysis of heavy metals and trace elements showed low to very low concentrations.
- The physicochemical parameters exhibit generally low values.
- The River Soulou contains very low concentrations in all heavy metals. For the others elements Boron (B) and Cl^- concentrations were above the limit.
- In the mine water discharged from the ponds, the elements As, Cd, Pb, Hg, Ni, Cu, Zn and V showed very low concentrations compared to the limit values of Prefecture Decision N.A 555/1990.
- Water abstraction from wells, show very low concentrations of all the heavy metals except Cd and Hg, which have concentrations near the limits.

The data obtained from searches in the UK identified an contaminated area of aquifer above mine workings in Durham south of the Butterknowle Fault and resulted in a change of plan for the work undertaken in task 3.2, the assessment of risks and site selection and in task 3.4 the modelling of chemical reactions.

The aquifer water data obtained in the Nottinghamshire Coalfield also pointed to possible contamination of the Permo-Triassic aquifer in isolated areas with higher than normal levels of chloride (figure 2.3.2).

The aquifer data obtained from the East of Wear area showed no evidence of mine water contamination. The digital mine plan data, the coal chemistry data and the water quality data obtained for the East of Wear area were used by DSK/DMT for modelling of mine water chemistry during flooding.

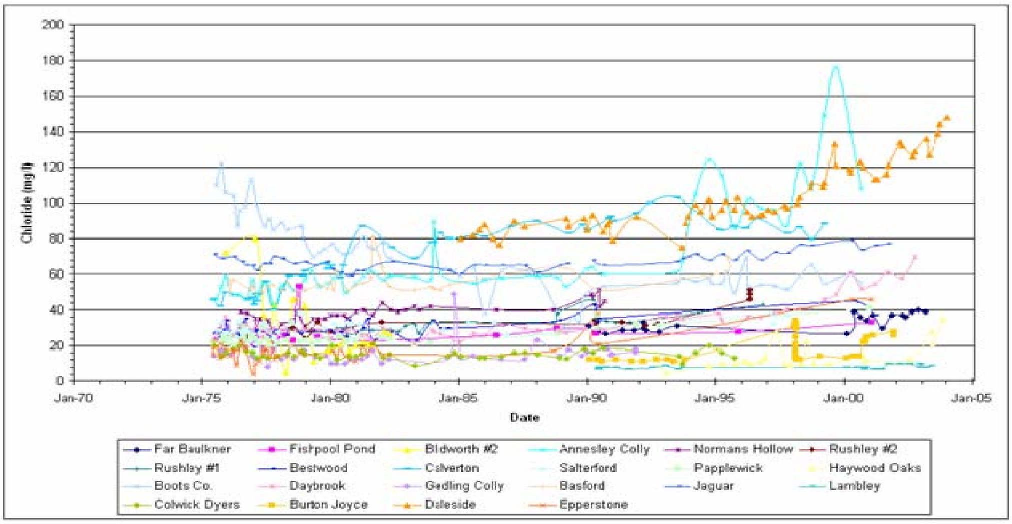

Figure 2.3.2: Chloride concentrations in the Permo-Triassic Aquifer in Nottinghamshire

<u>Task 3.2 – Initial assessment of risks and selection of monitoring sites</u>

The principal aim in task 3.2 in the UK was the risk assessment of the potential for contamination of the Permian aquifers in Durham and Nottinghamshire. The risk assessment involved detailed studies of the mine plans, mine entries, mine water inflows and the future piezometric heads in both the aquifer and the mine workings. These data were used to determine the likelihood of mine water flow to the aquifer, the sites of the potential flow and the potential quality of the mine water.

The lignite areas of Megalopolis and Ptolemais in Greece and the hard coal areas of South Nottinghamshire and Durham were assessed as planned. In addition, the Butterknowle area of the previously contaminated Permian aquifer was studied to determine the flow paths and other parameters that had caused the contamination for comparison with the conditions in the areas where mine water is still recovering.

In the lignite mining areas the work concentrated on those aquifers potentially at risk of contamination from mine water. The risk assessment identified the following potential pathways:

- Tectonic faults filled with permeable materials.
- Shafts or dewatering water wells allowing hydraulic connection between different aquifer systems.
- The thickness of the protective impermeable layer remaining at the bottom of the mine after the excavation. Where the protective layer above the permeable basement (mainly karstic limestones) is reduced there is a risk of sinkholes, as is the case at Megalopolis.

The areas of potential danger mine have been determined from the existing data collected and plotted on mine plans using of conventional surveying methods.

In addition to the existing 38 sample points at Ptolemais the risk assessment identified a additional 29 where regular water chemistry were required.

For the deep mined hard coal areas of the UK the work carried out required digitised plans at a scale of 1/50,000 of each seams worked, the base of the aquifer, and the hydraulic gradients in the mine workings and the aquifer. A detailed study was then made of all the mine shafts and mine abandonment plans to abstract the mine water inflow data that was then transferred to the overview plan. Based on the original rates of inflow, the type of connection and the current relative piezometric heads between the aquifer and the mine workings the flow into or from the mine workings was estimated. Figure 2.3.3 shows the Butterknowle area with the sites of the direct hydraulic connections between mine workings and the aquifer and the inflows when mining was taking place. The hydraulic gradients in the mine workings and the aquifer showing the area where the piezometric head in the mine workings is now greater than the head in the aquifer are in figure 2.3.3.

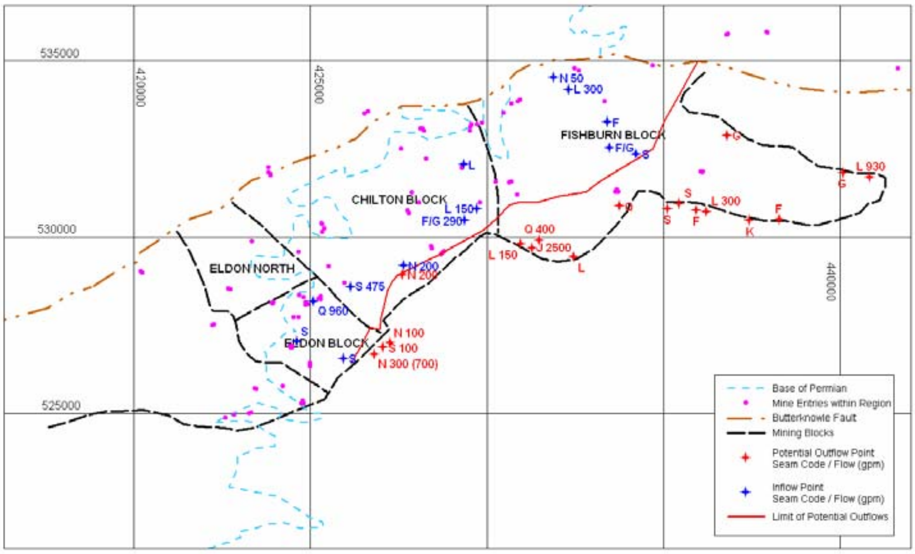

Figure 2.3.3: Mine water inflow points in the Butterknowle area of Durham

In the South Nottinghamshire area the studies of mine water connections and piezometric heads in the Permian aquifer and likely piezometric heads following recovery showed that the aquifer was at significant risk from mine water inflow from mine shafts sunk through the aquifer. The estimated total flow into the aquifer based on mining pumping rates and surface recharge was in the order of 450 l/s. Additional boreholes and monitoring sites were recommended to confirm the findings of the report and monitor recovery over the estimated recovery period.

The East of Wear area in Durham had previously been assessed as requiring mine water pumping to prevent surface discharge. The research carried out identified direct connections between mine shafts and the aquifer at levels below the levels of the surface discharges. These connections would allow mine water to flow directly into the aquifer and at sites in some cases within 200 m of drinking water abstraction boreholes. The sites with the greatest risk were the coastal collieries of Blackhall, Horden, Easington, Dawdon, Seaham and Ryhope. To control mine water levels, test the hydraulic connections, and monitor the impacts on mine water quality layering, a temporary, a pumping and scheme was established at Horden Colliery that commenced the pumping test in June 2004 (see task 3.6). To some extent the selection of sites was also determined by the initial investigations into mine water recovery and existing risk areas and the requirements of the Coal Authority who were providing the funding for the boreholes and the majority of the equipment. The Coal Authority and WYG had to make site selections based on the existing risks and this resulted in some changes to both the areas of investigation and the timing.

Task 3.3 – Installation of measurement sensors and collection of data

The objective of the task was to install equipment for monitoring of pressure temperature, conductivity and flow and to make an assessment and test commercially available in situ chemical monitoring probes for use in boreholes or shafts to provide continuous recording of key chemical parameters. In the case of the East of Wear area of Durham potential chloride contamination of the Permian aquifer was a specific problem and boreholes in the Permian aquifer close to known hydraulic connections to mine working were planned as potential monitoring sites.

The research into commercially available in situ chemical probes identified four potentially usable pieces of equipment. However, all of the equipment identified had limitations on use that made them unsuitable for deep borehole or shaft monitoring. The only equipment that had potential in the areas of study in the UK was the Troll 9000 manufactured by In-Situ Inc. Three sets of the equipment were purchased and installed in the East of Wear area of Durham primarily to determine their effectiveness in monitoring chloride levels in water. The probes were equipped with sensors to monitor pH, oxidation reduction potential (ORP), conductivity (EC), dissolved oxygen (DO), temperature (platinum resistance thermometer (PRT)), chloride (ion selective electrode (ISE)), and pressure. The sites used for the three probes and the depths installed were the mine water shaft at Horden (CA) at 100 m BGL, the

Permian drinking water abstraction borehole Hawthorn (NWL) at 140 m BGL and Hawthorn West Permian water monitoring borehole (EA) at 130 m BGL.

In the lignite mining areas in Greece during the period (10/2003-2/2007) seven sites were instrumented, (BR7, BR6, PZ2, K1, YK10, YK16, PZK3). The equipment installed was for monitoring of the aquifers in the Megalopolis mine area (task 2.4). In addition 4 instruments were installed in Ptolemais, 2 in pumping stations and 2 in water wells. These instruments are recording Q, pH, E.C., T^{o} C and additionally to water level.

The Troll 9000 sensors used in Durham require calibration to approximate chloride ranges prior to being sited and at regular intervals after installation, generally every three months. The Troll probe sited in mine water rapidly (4 days) became covered in ochre and the readings were highly inaccurate. It also took a number of hours to clean and recalibrate the sensors. Following a period of approximately one year with no success the Troll was removed. The Troll sensor sited in Northumbrian Water abstraction borehole was worked for a short period until a pump change was required and it was found that the sensor could not be removed prior to the pump removal. It removing the sensor with the pump the probe was damaged beyond repair and the monitoring of the NWL borehole was abandoned. The other Permian water monitoring probe in the EA observation borehole has remained in operation throughout the project. Comparison of the probe results with data from samples previously taken at the monitoring borehole showed that for pressure, temperature and conductivity the probe generally gave values similar to those expected or monitored by other means. However, the chloride sensor while giving chloride concentration values similar to the results from previous laboratory analyses took time to stabilise after calibration making their use for detection of small changes in chloride concentration limited. Therefore the use of this type of probe was for deep water chemistry monitoring is not thought to be practical. Discrete sampling of water from both the Permian aquifer and mine workings is still considered to be the better option for monitoring deep water chemistry.

A concept for installation of monitoring equipment adjusted to mining requirements and demands of the mining authorities was developed for the Ruhr Area. Specification to be regarded for intrinsic safety affects the beginning of the measurements and sampling depending on the flooding process. In order to simplify the electronic control system and to minimize the standards for intrinsic safety the power supply for the pumps was separated from the power supply and data transfer to and from the probes.

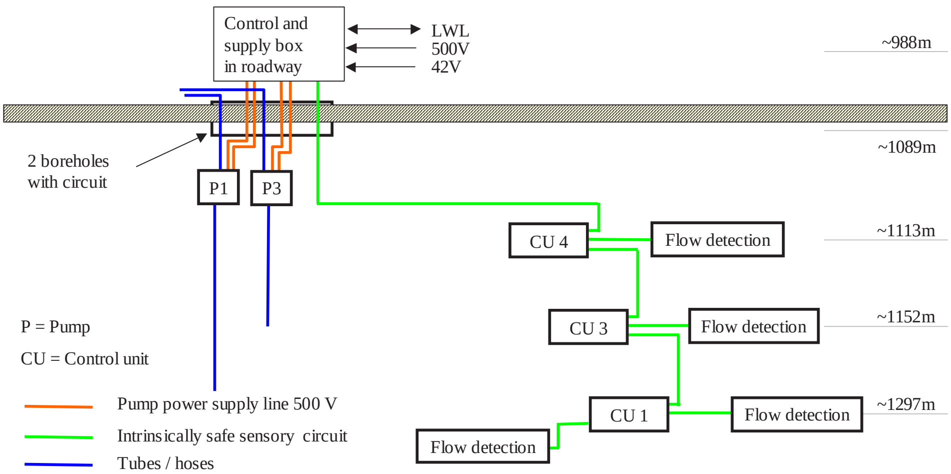

Figure 2.3.4: Scheme for placement and connection of pumps and control units in the flooded Haltern coal field.

Task 3.4 – Modelling of the chemical reactions and the diffusion and dispersion of contaminants

The modelling of the mine water chemistry that develops during the recovery of mine water levels is only one part of the problem of mine water contamination of aquifers. Of equal importance is the in situ geochemical reaction between different types of mine water and the groundwater and the reactions between the different types of mine often found in interconnected areas of mine workings or as layers of varying quality with depth? Where mine waters have recovered and resulted in contamination of groundwater the degree of contamination is normally reported solely in terms of the analysis of the groundwater not the amount or type of contaminating water. Conversely, the potential effects of mixing of mine water and aquifer water were not normally assessed in detail because of the uncertainties of mixing of aquifer water and mine water of uncertain composition in situ. The PHREEQC modelling package allows for many of the uncertainties of water mixing to be addressed and in particular if detailed, accurate chemical analyses of the is available on the waters to be mixed and some in situ information on the resultant mixed water chemistry. This allows many of the uncertainties associated with speciation, saturation indices, reversible reactions such as encountered in the aqueous and gas phases and irreversible reactions that are kinetically controlled or related to temperature.

The principal aim of this project was to assess the suitability of PHREEQC for determining mixing quantities of various mine water using modelling and assessing like levels of contamination resulting from the mixing of mine water of varying qualities and flows with groundwater. The two types of mining assessed were deep hard coal mining in the UK and shallow lignite mining in Greece.

The work planned in this task for the deep hard coal mining in Durham was divided into two categories.

Firstly to mix mine water with aquifer water at various ratios to assess the impacts. This work was expanded to compare the results of the mixing with the data available in the area of contaminated aquifer South of the Butterknowle Fault. This work replaced the planned work on the modelling of dispersion and diffusion of mine water as the collation and interpretation of actual data was considered to be of more use by both the Environment Agency and the Coal Authority at this stage. Modelling of the dispersion and diffusion based on the finding of this study will be carried out by others in the near future.

Secondly to mix mine water from the various mine water layers to determine quantities and flow paths of the mine water flowing to Horden Colliery during the pumping test.

The changes to the planned research in this work package were also the result of the data found in the initial data collection stages of the contract and the fact that as well as researching the problems associated with mine water recovery WYG are also on behalf of the Coal Authority, actively trying to solve the problems and have to be pragmatic in responding to the Coal Authorities requirements. The presence of a significant level of existing mine water contamination in the Permian aquifer that was migrating towards an area of drinking water abstraction in part of Durham meant that some of the WYG research effort was diverted to an assessment of the causes and the risks, the monitoring requirements and potential solutions. Rather than modelling the potential chemical reactions and the diffusion and dispersion of contaminants in an aquifer WYG concentrated on the continued acquisition of data and research into the flow paths in the contaminated area to allow additional monitoring sites to be identified, a future modelling work to be carried out using real data and future contamination prevented.

The work planned in the lignite mines of Greece looked at the areas of Megalopolis and Ptolomais.

In Megalopolis the impact of mine water on the two aquifers that lie below the mine void (the deep aquifer in the sediments below the bottom of the mine and the karstic aquifer forming the basement strata and on the Alfios River.

In Ptolemais district area the modelling investigated the influence of the mine water on the quality of the water of Soulou stream.

The simulations carried out using PHREEQC in Durham are listed below in table 2.3.2.

Table 2.3.2: PHREEQC Simulations carried out in the Durham Area

Simulation Description	**Number of Runs**
Mixed in-situ shaft samples for 4 different dates for Horden	4
Mixed in-situ shaft samples for 4 different dates for Dawdon	1
Mixed in-situ shaft samples for 4 different dates for Hawthorn	1
Mixed Dawdon & Hawthorn mixed shaft waters together at different	10

ratios to get similar quality to that recorded in Dawdon shaft	
Mixed L. Main water (Horden Water pumped at 35 l/s) with unknown mine water quality, and Hutton water to determine likely pumped quality at Horden.	5
Mixed Dawdon/ Hawthorn mixed waters with Hutton & shallow minewater in Horden shaft & compared to pumped water at Horden	5
Mixed Dawdon water with Hutton & shallow minewater in Horden shaft & compared to pumped water at Horden	5
Mixed Hawthorn water with Hutton & shallow minewater in Horden shaft & compared to pumped water at Horden	5
Mixed Hawthorn water with Hutton & shallow minewater & Murton in Horden shaft & compared to pumped water at Horden	5
Mixed Hawthorn water with Hutton & shallow minewater & Edmonsley in Horden shaft & compared to pumped water at Horden	5
Mixed Blackhall & Blackhall sump water with Hutton & shallow minewater & Edmonsley in Horden shaft & compared to pumped water at Horden	10
Mixed Easington water with Hutton & shallow minewater & Edmonsley in Horden shaft & compared to pumped water at Horden	5
Mixed Murton water with Hutton & shallow minewater & Edmonsley in Horden shaft & compared to pumped water at Horden	5
Mixed Edmonsley water with Hutton & shallow minewater & Edmonsley in Horden shaft & compared to pumped water at Horden	5
Mixed Permian water with Horden mixed shaft waters	8
Mixed Permian water with Mainsforth shaft waters	8
Mixed Permian water with Stoney Hall mine water	8
Total PHREEQC Models Run	95

The modelling using PHREEQC of mine water mixing with aquifer water and comparison of the results with real data from an area of contaminated aquifer has shown that the modelling can accurately predict the contaminants and the levels of contamination if the flow rate of the contaminating mine water mine water is known.

Where the flow is not known the risks to the aquifer can be determined as in the case of the high iron and chloride mine waters in the East of Durham area which predicts high chloride levels even when small percentages of mine water are mixed with aquifer water.

During the report period the numerical code of the BoxModel was expanded to also consider the carbonate/bicarbonate balance in mine water. Compared to other solid phases carbonate dissolution is controlled in addition by the CO_2 content and more than other minerals by the pH. All influencing factors are taken into account in the BoxModel. Carbonate phases integrated into the model are: dolomite, siderite, manganese carbonate, barium carbonate. The above mentioned CO_2 content is influencing the lime - carbonic acid balance. There has to be a distinction between an open and a closed system. This expanded numerical code has been tested using a relatively simple but realistic example. Test calculations were performed for the box Haltern (Ruhr Area, Germany).

In the lignite mining areas of Greece the Phreeqc modelling of mine waters mixed with aquifers in Megalopolis gave the following results for the aquifer waters.

- All the simulations of mixing gave a very good quality aquifer water with pH values of 7.4
- The major constituents Al, Ba, Ca, Cl, F, Fe,K, Mg, N, S, Si have similar concentrations after mixing with the initial waters.
- The simulations show that the concentration of Zn, Mn, Na are higher or slightly higher values than the initial.

The general conclusion is that there are no significant affects from the mine waters of the ponds on the aquatic system of the area.

The results of the Phreeqc modelling in Ptolemais were

- The mixing gave a very good quality water with pH values of 7.35
- Ca, Mg, Na, S, Si in the mixed waters have a lower value than the initial ones
- Na, and Cl have higher concentrations than the initial surface water.

The general conclusion from the modelling in the Ptolomais area is that there is no significant effect in the surface water of Soulou stream from the mine water mixing. The main problem of elevated concentrations of NO^-_3, NO^-_2 and NH4+ in the river result from the agricultural activities in the area not from the mine water mixing.

Task 3.5 – Investigation of shaft stability and shaft fill

The objective of the research was to use optical surveys taken of mine shafts to determine if the current state of open mine shafts through aquifers posed a risk to aquifer contamination.

Several open shafts were inspected during the period of the study including all the open shafts through the Permian aquifer in the East of Wear area of Durham. The main problem encountered was one of poor visibility in mine water resulting from the reflection of light from particles suspended in the water or the humidity and gas flows within the shafts.

The equipment used for the surveys was generally borehole logging cameras due to the risks associated with the light sources for more conventional CCTV surveys. These types of camera tend to have lower level light sources.

In general the surveys confirmed that there were no problems with the stability of the mine shafts. Only one shaft in the survey carried out (Kiveton in the Notts/Derby Coalfield) had apparently become unstable. This appeared to have resulted in a collapse at mine inset that had blocked the shaft. No problems were encountered in the shaft sections passing through aquifers. Several shafts, both open and filled, reportedly had flows of water through the shaft linings at points below the base of aquifers. It is believed that these flows are the source of the Permian water observed in the upper mine water layers.

In the German Ruhr coal district many centuries of intensive mining left a legacy of risks associated with close to surface mining voids, adits and shafts. Experts estimate a total of > 40,000 surface openings to exist, about one third of these are documented and clearly identified. Collapses and damage to housing and infrastructure continue to occur in abandoned mining areas and are expected to increase in frequency and intensity when the mine water rebounds closer to the surface.

There is still need to catalogue and evaluate the actual risk situation. For the time being characteristics like geometry, filling, age, geology, groundwater situation and use of land are applied to separate into very simple risk classifications. These categories are used now to prioritise the sequence of investigations. Site investigations are used to then identify the true risk situation, any remediation required and what type of remediation.

Task 3.6 – Interpretation and development of methods to minimise risks of aquifer contamination

The objectives of the work in this section were use the information obtained in the other tasks in the work package and see what methods could be developed or adapted to minimise the risks to aquifers of contamination by mine water. The alternative methods were expected to vary with the type and depth of mining, the mine water chemistry and the local geological setting. The type of work envisaged included shallow pumping at varying rates to determine the effects on the piezometric heads in the mine workings, the quality of the mine water and flow paths, the use of plugs to alter mine water flow paths and low permeability barriers to minimise potential flow of mine water to aquifers.

Various methods to minimise the risks to aquifers have been identified and some were tested during the research period. The methods identified were:-

- The pumping of mine water in the East of Wear area of Durham at multiple sites to reduce the level of contamination of the pumped mine water and lowering the chloride concentration levels in the shallower mine water quality at greatest risk to the overlying aquifer.
- Siting mine water settlement lagoons away from areas identified as at greater risk of connection to underlying aquifers and using low permeability liners to further reduce the risk.
- Increasing retention time in settlement lagoons to maximise the reduction of contaminants within the mine water prior to discharge to surface watercourses.
- Clearly identifiable flow pathways connecting mine workings with aquifers were identified in both deep hard mine coal areas and in lignite mining areas. However, the numbers identified and the risks and costs associated with methods to seal the connections were such that control of mine water levels to prevent contamination was considered to be the better option.

The shallow pumping of mine water at varying rates while monitoring and assessing the impacts on mine water quality layering was started in June 2004 in the East of Wear area of Durham and continued through to the end of the project. The initial results showed that even at low flows the chloride levels of the mine water would pose a significant risk to the aquifer and given the type and number of connections between the aquifer and the mine workings sealing of all connections was not an option. The longer results of the pumping at varying abstraction rates on the chemistry of the pumped mine water, the mine water quality layers at both the pumping shaft and the other open monitoring shafts in the block were monitored which together with the PREEQC modelling work (task 3..4) and risk assessment (task 3.2) was used to determine the pumping scheme that would minimise risks to the aquifer while ensuring the optimum methods of mine water treatment. A second pumping station is currently being developed and a second phase of research with balanced abstraction and monitoring at the two pumping site is planned.

In the Butterknowle area none of the mine to aquifer connections identified are suitable for sealing and pumping has been identified as the best option for control of mine water flow into the aquifer. A borehole is planned into the area of connection that is believed from the monitoring and modelling to have the highest flow to check on the chemistry of the mine water and determine the feasibility of pumping.

The DSK/DMT BoxModel has been applied to a risk assessment to identify the preventive measures to minimise aquifer contamination of an important drinking water resource in the French German border area of Lorraine and Saarland. This trans-border model provides answers to the important hydrogeological issues arising as a result of the planned mine closures and the resultant flooding. The geochemical model developed in this project was employed to also obtain the best forecast possible on mine water quality developments (iron, sulphate, chloride) and potential impact on groundwater and surface water quality.

The model calculation based proposal which was preferred comprises pumping stations installed in shafts Simon 5 and Vouters of the Lorraine coal basin to maintain the mine water level at an elevation necessary to avoid ponding and saturated zones in urban settlements and ingression of mineralised mine water into the Lower Triassic Sandstone aquifer. The result will be a very limited discharge of mine water at the Gustav shaft of the Warndt coal mine which then can be handled without further provisions.

In the lignite mining areas of Megalopolis and Ptolemais additional lagoons were constructed (150m x 80m x 5m) and tests were undertaken to show that extended retention time (5 to 24 hours) lowered the total dissolved solids (TDS) in the mine water as well as suspended solids.

Task 3.7 – Presentation and publication of results

The main objective of this task was to ensure that all the data, research and results of the various tasks undertaken was quickly passed on to the relevant authorities, other researchers in the same field and where appropriate made available to the general public.

This was accomplished by means of regular meetings with and reports to various bodies, for example the Coal Authority, the Environment Agency and water abstraction companies in the UK. Papers have been presented or presentation is planned at several water seminars.

The following papers have been or are in the process of publication. Papers and meetings by DSK/DMT are listed in work package 1.

> "Rehabilitation of aquatic balance in the post mining period. Case study of Megalopolis open pit." PPC. The International Symposium on Continuous Surface Mining (IMCSM 2006) at Aachen, Germany.

In this paper is investigating the water balance of the lake, which will be created in the final voids of Marathousa and Choremi mines in Megalopolis area. We estimated the inflows and outflows of the lake (evaporation, rainfall, groundwater inflow), which is important in order to determine the mixing rates for Phreeqc and estimate the final quality of the pit lake.

> "Impacts of mining activities on water resources to Megalopolis lignite district area" PPC. The European Geosciences Union General Assembly 2007 Vienna, Austria, 15 – 20 April 2007.

> "Predicting mineral weathering rates at field scale for mine water risk assessment", S. A. Banwart, K. A. Evans and S.Croxford. Published in Mine Water Hydrogeology and Geochemistry, Geological Society Special Publication, No. 198.

> "Application of the PHREEQC Geochemical Computer Model during the Design and Operation of UK Mine Water Treatment Schemes", IMWA Conference Papers, November, 2004.

In addition to published papers, internal reports were prepared and regular meetings were held with the following interested parties from the North East of England and Nottinghamshire to allow the results of the monitoring, research and pumping test to be discussed.

> The Coal Authority, Environment Agency, Newcastle University, Durham County Council, Seaham Town Council, Horden Town Council, Northumbrian Water Ltd and Hartlepool Water Ltd.

All data obtained is held on the Coal Authority database and results from specific tests such as Horden pumping test are posted on the Coal Authorities web site.

2.3.2. WP 3 Conclusions, Exploitation and impact of the research results

The results of the project have highlighted several key points linked to rebound of both the aquifer and the mine water and the type of hydraulic connections between the aquifer and the mine workings:

PHREEQC can be used to assess the degree and type of contamination of the aquifer resulting from mixing of mine waters and aquifer waters.

Data obtained from modelling, monitoring and pumping can be used to determine if mine water level control by pumping is required to prevent contamination of an aquifer.

No significant contamination of the karstic aquifer or the sediments below the lignite deposit at Megalopolis Lignite area.

Moderate increase in mineralization of both surface and groundwater related to mining at Ptolemais Lignite area.

Work on the optical assessment of shaft lining stability was carried out at several sites but due to poor visibility in mine water resulting from floating particles results were generally poor. However, the work confirmed that open mine shafts through aquifers appeared generally stable.

The use of commercially available in situ chemical monitoring equipment for monitoring mine water chemistry is not a practical option based on the equipment investigated due to the impacts of contaminants, in particular ochre on the sensor heads. The future challenge resulting here from is the development of adjusted sensors and sampling technology.

The mine water pumping tests linked to the monitoring, investigations of pathways and the modelling undertaken in Durham have significantly helped in the understanding of the sources of mine water, the mine water flow paths and the development of the mine water quality layering. The research has been used to determine the sites for mine water pumping, the abstraction rates and to optimise the type of mine treatment required. Further research on mine water layering and the optimum abstraction rates and sites pumping of mine water should be undertaken.

WYG is continuing with all the research and additional monitoring boreholes identified as part of the Waterchem project have already been drilled since the end of the research work and further boreholes and shaft monitoring is planned.

2.4. WP 4 Development of methods to separate flooded areas safe and fast

The objective of this WP is to study and develop solutions for construction of underground plugs to protect areas of active mining from mine water inflow from abandoned areas. Rock characteristics and their potential for improvements are to be studied and tested to design improvements of existing plugs. Novel approaches for construction of plugs, especially those allowing fast implementation, are to be investigated. Development of a performance monitoring of underground plugs and their interactions with the mine water also form a significant objective of the WP. HUNOSA is the WP leader and cooperating with AITEMIN on this WP.

2.4.1. Work carried out on task-by-task basis

Task 4.1 - Evaluating existing data and literature

The objective of this task is to perform a review of the available documents and studies on existing experiences of underground dam construction (plugging systems) to separate flooded areas, and its associated problems.

The planned activities within this task comprised basically the search and compilation of technical papers about the existing experiences in closing underground flooded areas and abandoned mines.

The task was accomplished as planned, obtaining detailed information on different aspects of the construction of underground plugs in general, and concrete plugs in particular. In parallel, a search on the hydrogeological issues related to the groundwater and closure of abandoned coalmines was performed.

The search for information on the construction of underground plugs has been carried out through specialised publications, in the Internet and by means of direct requests to involved professionals and companies.

Information on the construction of underground plugs has been obtained: different sealing experiences around the world, both successful and unsuccessful, types of sealing barriers, constructive technologies, composition of the concrete used, alternative used materials, monitoring strategies, etc.

Special attention was paid to the case of HUNOSA's abandoned mine of San José in Valle Turón (Asturias, Spain). This mine was initially considered as a possible investigation/application area for the project. In this mine, several mass concrete plugs had been constructed a few years ago to separate the abandoned areas from the working areas in order to prevent the flooding (figure 5.4.1). The sealing with these plugs was unsuccessful.

With regard to the hydrogeology, in a first stage a compilation of general bibliography on the main issues related with the groundwater and coalmines was obtained: groundwater flow and water quality, groundwater rebound in abandoned mines, groundwater monitoring, etc.

In a second stage, a recompilation of specific documentation from the selected investigation sites was carried out (figure 2.4.1). The documentation included:

- Climatologic data: rain and temperature data from weather station
- Surface water data: total output in the rivers gouge stations
- Water well inventory around the investigation area: springs, dug wells and drilled wells.
- Geological information
- Water quality information
- Mining works information

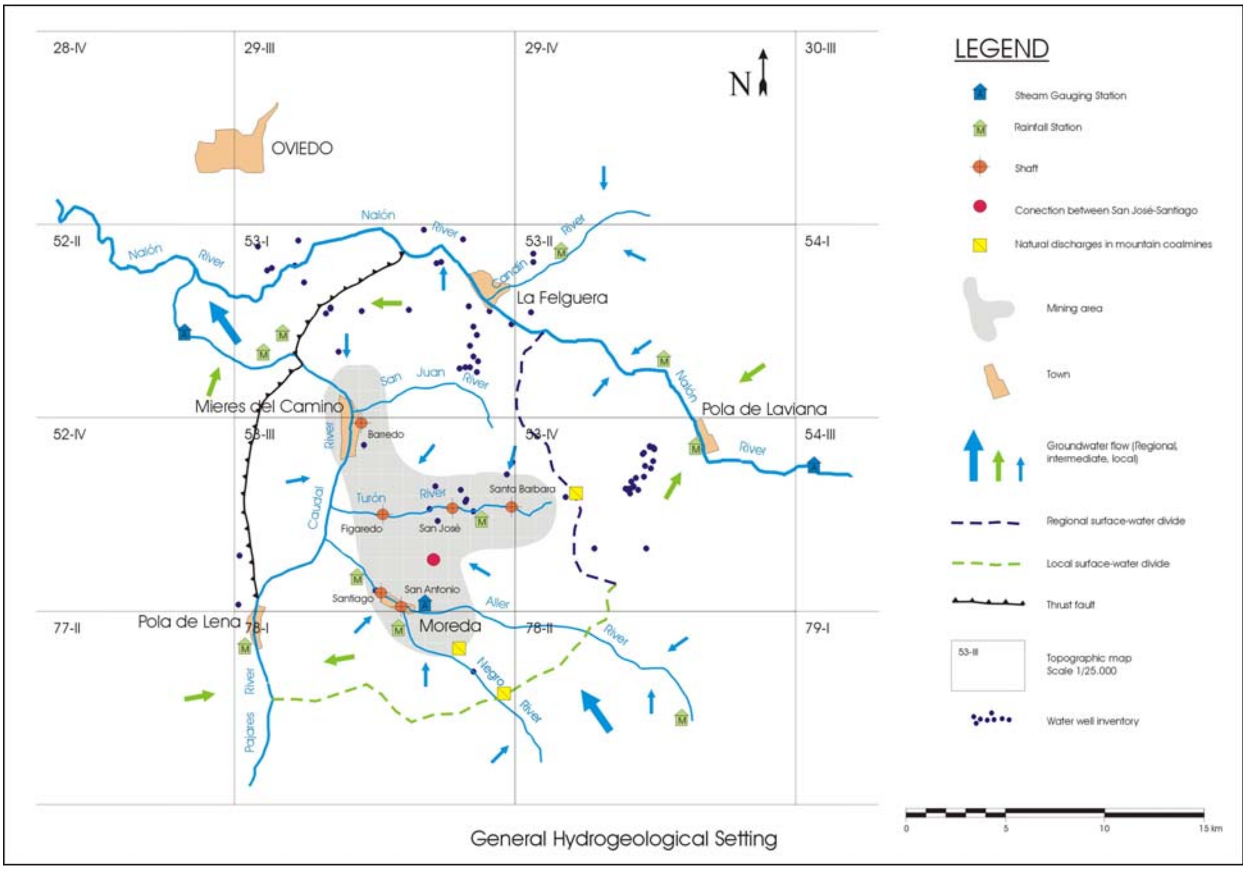

Figure 2.4.1: Gathered information in the Asturian coal basin.

<u>Task 4.2 - Selecting test areas and developing geological and hydrogeological models</u>

The main objectives of this task are: firstly, to select the most interesting investigation/application area according to the characteristics of the mines; and secondly, to develop hydrogeological and geochemical conceptual models in order to learn the hydraulic working in the area and to define the adequate site for the construction of a demonstration plug.

The planned activities within this task were the study of the geological and hydrogeological characteristics of the mine where to develop the plugging solution, analysing all the data obtained and selecting the appropriate gallery section for the test plug.

This was a challenging activity. Due to diverse problems along the project, five different areas have been evaluated up to find the most suitable test site and finally, the task was accomplished as planned. The areas investigated have been: three mines in Asturian coal basin (San José, Santiago and Figaredo mines), one coalmine in León (Lumajo mine), and another one in the Laciana school-mine of Fundacion Santa Barbara.

HUNOSA's San José mine was studied as a first option to carry out the construction of the plug, but it was discarded as it had no accessibility for the equipment and the galleries were lined with concrete in the different potential points where the plug should be constructed.

After discarding that mine, HUNOSA's Santiago mine, located in the same coal basin and near San José mine was studied to install the plug in order to control the flooding in several zones. Diverse technical problems (ventilation, pumping equipment, stability of the access) impeded the construction of the plug so it was necessary to change the test site.

As a new option, the abandoned mine of Lumajo (León) from MSP Group was studied (figure 5.4.4 and figure 2.4.2), but after several works carried out into the mine, the geotechnical characteristics analysed in the rock mass were found not appropriate to work in this area (low stability, number of fractures, etc), and the collapse risk was very high. Hence, it was decided to change the site again.

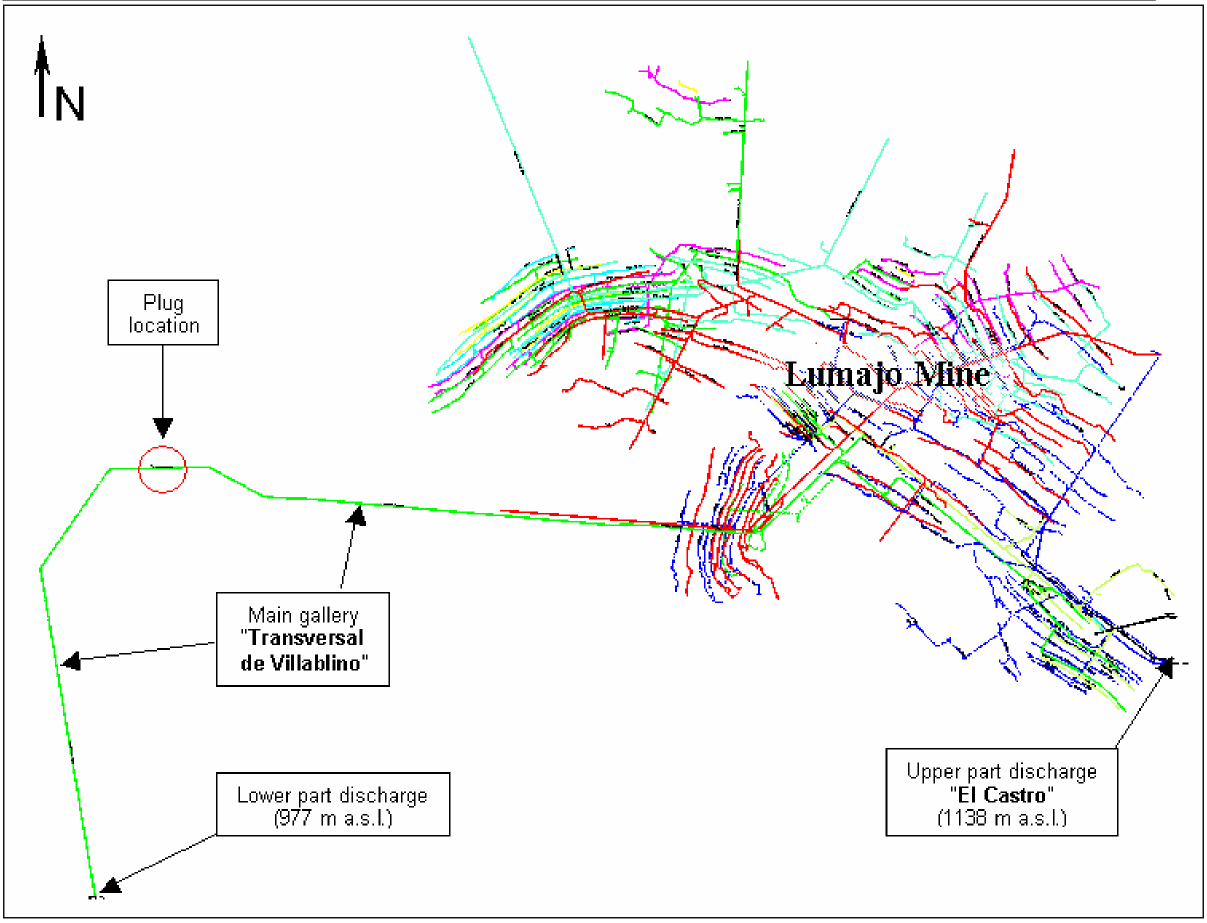

Figure 2.4.2: Plan view of Lumajo Mine

Finally, HUNOSA's Figaredo mine was selected as the most adequate area for the construction of the plug from the operative and technical point of view. This mine is located between San José and Barredo mines in Turon valley and has been active until the end 2006, although the site selected for the construction of the plug is located in an abandoned gallery of this mine. Detailed studies in the selected gallery section have been carried out for the construction of the plug. After the plug design was ready, the plug was constructed in February 2007 (see task 4.7). Due to the low water pressures expected to be supported by this plug, another underground experimental plug has been constructed in parallel in the Laciana school-mine of Fundacion Santa Barbara (located nearby León), in order to test under higher pressures the plugging solution developed.

In every case, some important aspects have been controlled inside and outside of the mines in order to define a hydrogeological conceptual model. These aspects have been; geological characteristics of the area (lithology, structure, fractures and joints, stratification, etc); hydrogeological characteristics (permeability of the materials, discharge and recharge areas, water well inventory, groundwater flow; natural mine drainage, output and input flows); water quality (electrical conductivity, pH, temperature, iron and sulphates content); seismic risk, etc (figure 2.4.3 and figure 2.4.4).

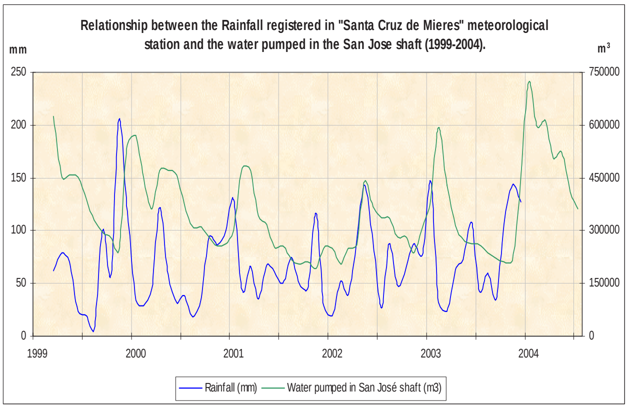

Figure 2.4.3: Relationship between rainfall and mine water pumped in San José mine.

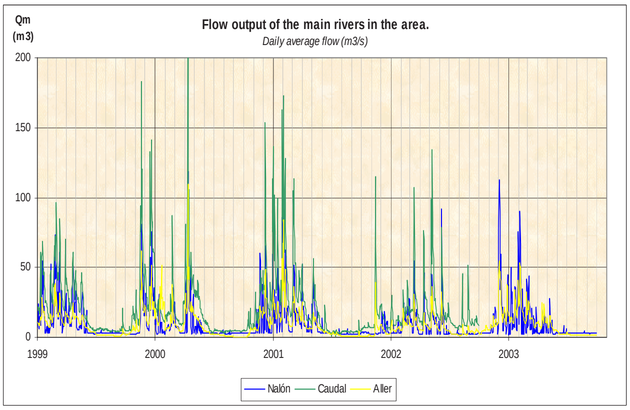

Figure 2.4.4: Daily water discharge of the main rivers of the area (Nalón, Caudal and Aller).

Some of the most important aspects that have been determined in Figaredo area are the followings:

- The infiltration of the rainfall is very fast probably because there are many mountain type coalmines abandoned in the zone and the altered area of mining works are quite close to the surface. Due to this phenomenon an important pumping is necessary in order to protect actives areas of the mines from water coming from abandoned areas.
- In general, all the geological formation in the zone has low or very low permeability. These formations contain little local aquifers drained by springs whose water flow often is lower than 1 l/s.
- In an undisturbed situation the recharges would take place preferably in the interfluves and high areas. Due to the low permeability of the materials, the natural infiltration would be low. Most of the discharge would be by local flows, across the springs, creeks and the nearest riverbeds. But in the current situation, the hydrodynamic system of the rock mass is totally modified by the influence of the mining. The mountain type coalmines group constitutes a catchment of underground water of big dimensions and complex geometry that changes notably the previous hydrodynamic scheme.

Task 4.3: Analysis of construction alternatives

The objective of this task is to analyse the different alternatives for plug design and construction techniques, including new experiences and solutions adopted in other industrial sectors for different applications.

The planned activities within this task comprised a thorough search, organisation and summary of the information compiled on plug construction.

The task was accomplished as planned, obtaining a technical report with useful information as a sorting of different alternatives on plug construction with pros and cons, and an overview of the different stages to be accomplished in order to perform a successful construction, including guidelines and recommendations on each stage.

The technical report includes in first place a summary of the existing data, literature and other information on experiences of underground plugging systems, with a list of the most relevant references. These include among others:

- Experiences about plug construction published by specialised firms
- Studies on methods of plug design and construction from particulars or from government's institutions
- Analyses and studies on specific problems as the acid rock drainage
- Other uses of plugs or barriers as those constructed to retain tailings stocked in galleries closed to work, to obtain water-and-gas-tight sealing of underground stocks of gas, or sealing in underground repositories of high level radioactive waste.

After this, the different types of underground plugging system are reviewed: dam, fill-retaining barricade, bulkhead and plug in its different configurations (figure 5.4.2).

The key aspects to be taken into account for plug construction are described afterwards. These include:

- Recommended site investigation, to select the most suitable location
- Conditioning for plug construction, as the preparation of the site and pre-grouting if necessary
- Determination of parameters for plug design, mainly the plug length and the chemical composition of the concrete
- Plug construction technique, as mass concrete, shotcrete, or concrete combined with other materials
- Testing for quality assurance, both during the construction, and afterwards for a possible post-grouting
- Recommended instrumentation for performance supervision

Finally, the main conclusions obtained are compiled (see chapter 2.4.2).

Task 4.4 – Development of a dam monitoring system

The objective of this task is to design a monitoring system for measuring the hydraulic and mechanical parameters of the test plug.

The planned activities comprised the definition of the main hydraulic and mechanical parameters to be measured, the selection of the most suitable instrumentation and its integration into a complete layout of the plug. This part of the task was completed as planned.

The monitoring of performance could be an essential component for a successful construction and operation of a plug in some cases. Instrumentation is used to determine the initial conditions at plug site, to survey the conditions during construction, and to carry out a long-term performance of the plug during its operation. Thus, the different elements and alternatives for monitoring systems for underground sealing plugs where studied and the information was compiled into a technical report.

This report included the recommended instrumentation for a wide range of plug performance supervisions, which effectively depend on the type of plug constructed and the functions to be fulfilled by the monitoring system.

The basic parameters to be monitored to assess the plug performance are:

- Pressures
- Movements and displacement
- Temperature
- Seepages
- Pressure release

The basic criteria for adequate instrument selection are:

- Use of off-the-shelf components as much as possible, seeking for availability.
- Reliability of measurements (range, resolution, accuracy, repeatability).
- Long-term stability and instrument longevity.
- Environmental conditions such temperature and humidity.
- Ease of automation for real time monitoring and efficient data management.

Other parameters to be controlled in some cases are the air quality (environmental measures): concentration of methane, CO and CO_2 in the gallery to avoid explosive atmosphere or poisonous and asphyxiating gases.

A general scheme of the instrumentation for a complete supervision of plug performance is shown in figure 5.4.19.

Task 4.5 – Impact of the substances dissolved in mine water on the impermeability of shafts and dams

The objective of this task is to determine, within the Figaredo area selected for the plug construction, the impact of the substances dissolved in the mine water have on the plug construction materials and the surrounding rock, and to use this knowledge to select the appropriate materials.

The planned activity within this task have been the analysis of the water quality in the water discharge of the studied mines and around the test areas by means of measurements of electrical conductivity, iron and sulphates content, pH and temperature. These measures were carried out in places inside and outside the mines.

The task was accomplished as planned, obtaining enough data to compare the water quality in different areas and to determine dissolution rates and risk of erosion for the known hydraulic gradient over the service life of the plug.

In order to check the water quality in the area, during the field works were measured the main physic-chemical characteristics of water (electrical conductivity, Fe_{Tot} and SO_4) in several springs, discharge from abandoned mines and other water well inventory items.

The water quality in the area is, in general, good. The electrical conductivity change between 400 µS/cm and 1.500 µS/cm been the mean value around 800-900 µS/cm. The pH is lightly basic (7.22 – 7.95) and always it is around 7. These data indicate a medium degree of water mineralization.

Usually, the electrical conductivity and the pH are upper in the active mines than the inactive mines but the iron concentration is upper in the second case (figure 2.4.5).

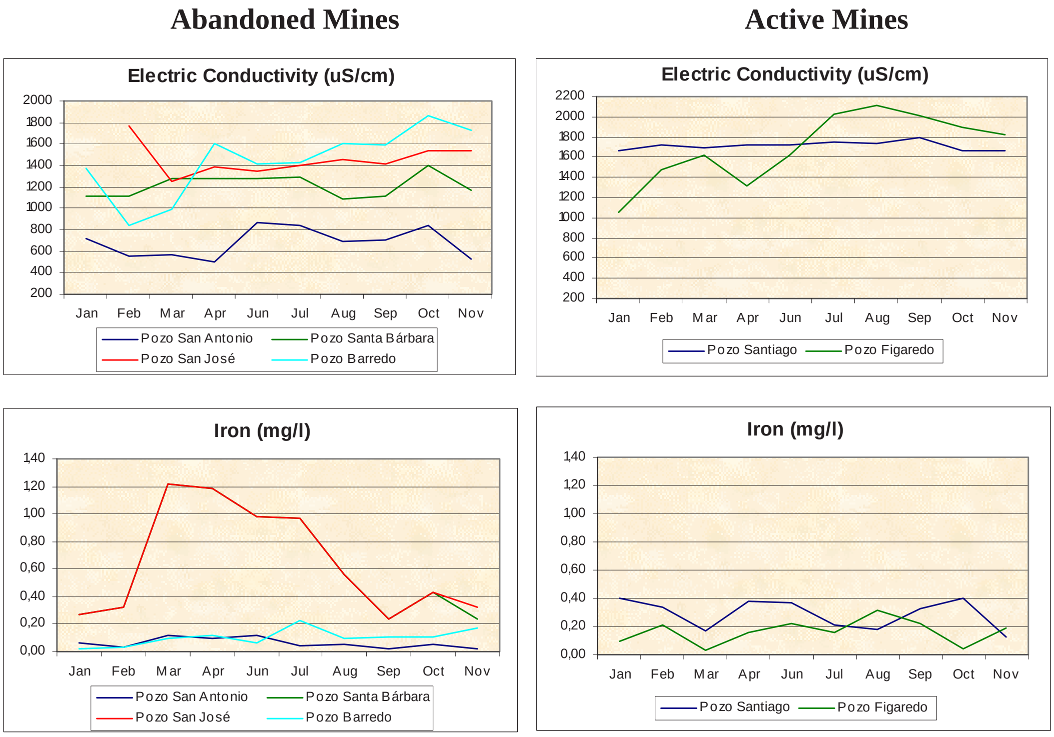

Figure 2.4.5: Electric conductivity and iron concentrations in active and inactive mines.

The iron content is relatively low (below 1 mg/l) except in some points where values around 3 mg/l was measured. Nevertheless, the values observed in all the controlled points are relatively low for an important mining activity area.

About the waters analyzed in surface points it can be observed that the springs in the mining area have low conductivity values, around 100 µS/cm. The pH is similar to measured inside the mine, with values around 7.6. The iron and sulphates concentrations are very low in all cases (below 0.05 mg/l) (figure 2.4.6).

Figure 2.4.6: Water quality control during the field campaign.

Hence, the effects that the substances dissolved in the mine water will have on the plug are supposed to be negligible; anyway it is quite possible that the water quality could change in the long term because of the increase of the transit time of groundwater after the construction of the plug.

Task 4.6 - Underground test

The objective of this task is to perform underground tests in real conditions aimed firstly to develop and trial a valid procedure for the construction using the wet shotcrete technique of an underground sealing plug, and secondly to construct such plug as a demonstration using that procedure.

The planned activities within this task comprised the definition of a concrete formulation for shotcreting, followed by the necessary underground shotcreting tests to, and finally the plug construction.

The task was accomplished, although with a delay in the construction activity due to the dilation on the selection of site. The concrete formulation was defined and, following the planned procedure, underground shotcreting tests where carried out to trial the validity of that formulation in terms of mixing, pumpability, sprayability, compatibility with the accelerant, etc. The tests confirmed the validity of the formulation and the construction technique. Finally, two underground plug tests were constructed, one of them in Figaredo mine as a real case demonstrator, and another one in the Laciana school-mine of Foundation Santa Barbara, in order to perform a specific test under higher hydraulic pressure.

A standard concrete formulation was developed, based on standard Ordinary Portland Cement (OPC), with limestone filler as an inert part of the binder. The amount of cement was thus reduced so to obtain a concrete with low heat of reaction, negligible shrinkage, a Young modulus below 25 GPa, and a low compressive strength, between 10 and 20 MPa. The formulation was completed with a standard aggregate with a 0 - 12 mm grading curve, and off-the-shelf additives from a well known manufacturer.

The aim was to obtain a shotcrete plug fast and safe, well casted in the rock (good adherence) and with a certain degree of “elasticity”. A plug of this type constructed in an underground mine will undergo a certain rock-concrete deformation under the expected hydraulic load on the upstream side. This deformation will transmit the hydraulic load throughout the plug mass to the host rock, producing a better sealing of the joint rock-concrete and increasing the total strength of the plug. Given that the pressure applied in the upstream side is hydraulic, another aspect to be taken into account for the plug performance is the hydraulic conductivity of the concrete, which should not be higher than that of the housing rock.

A series of tests were carried out in the Bierzo school-mine of Foundation Santa Barbara in order to check the behaviour of the formulation developed and to assure the feasibility of the plug construction operation in different working conditions with said formulation.

In first place it was considered one of the main operative problems that can arise when tackling the construction of a plug into an underground mine: the case that a concrete plant is not available reasonably close to the plug installation site, or that it is difficult to transport the concrete to the site. In this case, two solutions can be implemented (or a combination of them). In first place, the transport of concrete to the site with low-profile underground mixers, and in second place the on-site manual pre-weighing and mixing of the required amounts of concrete in mobile mixer. A manual mixing test was carried out and the concrete obtained was compared with the same concrete produced in an automatic mixing plant. No variations were found between the two batches of concrete, but the manual pre-weighing and mixing resulted in quite a laborious and time consuming operation.

The second case considered was that, due to constrained space or to restrained access, it is not possible to install the concrete pump close to the site. In this case, it is necessary to perform a long distance pumping of concrete from the closest suitable area for mixing and pumping, to the application point. A test was carried out simulating this situation by placing the concrete pump at a certain distance, over 90 m, from the application point. The concrete was pumped along a steel pipe with curves without problems.

Finally, a manual shotcrete test was carried out over wooden panels located into tunnel to tackle different aspects that could result problematic during the plug construction: feasibility of shotcreting without robot due to space constraints, potential heterogeneity of the concrete in the edges close to the rock, caused by a local rebound effect, and potential appearance of retraction cracks during the first hours of hardening caused by an excess of generated heat. The operator could perform the manual shotcreting without problems, obtaining a uniform thickness throughout the panel. The shotcrete obtained showed good adherence, little rebound, and an homogeneous appearance. The temperature of the shotcrete during hardening was below 26 ºC, and the analyses of samples carried out after 28 days of hardening yielded the expected results on compressive strength, elastic modulus and hydraulic conductivity.

Based upon those results, a 2D asymmetric model was developed for a cylindrical plug shape with a diameter of 3.5 m and a length of 4 m, having a vaulted upstream side (figure 5.4.18). According to this model a pressure of 23 bar would be sustained without problems. Hence, a plug between 1.5 m and 2 m would sustain a pressure over 9 bar, well over the expected pressure of 2 bar in principle in Figaredo mine and allowing margin for checking different pressures in the Foundation Santa Barbara experimental test plug.

The experimental plug in the Laciana school-mine of Foundation Santa Barbara was constructed in January 2007. It was constructed by shotcreting into a dead end mine gallery leaving a short chamber in the rear end (figure 5.4.20). The plan is to inject water into that chamber, so to learn the behaviour of the plug under different hydraulic pressures. For this purpose, the rock wall at the end of the gallery was first sprayed with a watertight membrane (1), in order to avoid the injected water flooding into the host rock, and injection and deaireation tubes were installed (3) passing through a wooden wall (4). The existing metallic supports were eliminated in the length of the plug (2). In this case, scaling was not necessary as the rock in that zone was quite intact. The plug measuring 2 m in length was constructed by shotcreting in parallel layers with a thickness between 20 and 30 cm (5), leaving the chamber ready for water injection after a hardening period of at least four weeks. A pressure injection system was installed consisting of a high flow, high pressure water pump with the necessary valves, connections and manometer to control and monitor the hydraulic pressure applied. Displacement sensors where placed too in the plug front to measure potential movements of the plug.

The site selected in the Figaredo mine for the demonstration plug was the 7th floor, close to the operation loop where the pumping station and the access pit are located (figure 5.4.22). The characteristics of the gallery are: section 2UA, horseshoe shape, width aprox 3.5 m, height aprox 2.9 m and irregular surface.

The plug constructed in this location allows the flooding of the north works up to the 6th floor. The water flows from 4th to 5th floor through an existing ventilation pit, and from this to 6th and then to 7th through two boreholes especially excavated. It also receives water from Barredo mine through a connection in the 5th floor (figure 5.4.23).

After the preparation works in Figaredo mine, comprising deinstallation of rock support, rock scaling and cleaning, supply of ventilation, power and compressed air, and waterproofing of the rock in the upstream side, a plug measuring 1.6 m in length was constructed. First a support was constructed at the upstream side, with tubes provided with the necessary valves passing through the plug for water pressure control, and afterwards the plug was done by shotcreting, again in parallel layers with a thickness of around 30 cm.

Task 4.7 - Monitoring

The objective of this task is to carry out a monitoring of the plug during a sufficient period of time so to check up on the success of the plugging solution, including a monitoring of the hydrogeological parameters of the mine.

In the hydrogeological stage, the planned activities within this task comprised in first place an hydrogeological assessment of the rock mass surrounding the water barrier, prior to the plug construction, in order to identify potential connections as far as possible, to predict the changes in the water regime after the construction of the plug, and to determine the probable resulting water seepage around and beyond the plug in service. This part of the task was accomplished as planned, obtaining from the monitoring system valuable data on the water discharge of the mine that served to improve the comprehension of the hydrodynamics involved.

With regard to the monitoring of the plug, the activities in this task comprised the gathering, storing, processing, presentation and interpretation of the data acquired by the plug monitoring system in the Figaredo mine during a sufficient period of time, in order to check, together with in situ visual checking the success of the plug. A hydrogeological monitoring after the construction of the plug was foreseen to confirm the predictions from the hydrogeological models. Given the difficulties found to select the site (see task 4.2), and the subsequent delay of the construction phase (see task 4.6), the monitoring phase could not be started within the Project lifetime. With regard to the plug in the Laciana school-mine, the test under water pressure could neither be carried out for the same reason.

In a first step, a field campaign has been carried out in order to seek for a suitable water well where to install pressure probes in order to control the piezometric levels around Figaredo area, which has connections with Barredo and San José coalmines.

During this field campaign no suitable water wells were found, so finally the water discharge from three abandoned mountain type coalmines has been instrumented (see figure 2.4.7 and figure 2.4.8). This has provided indirect data about the possible fluctuation of water level in the test area.

Figure 2.4.7: Datalogger to register the water level changes in the discharge channel.

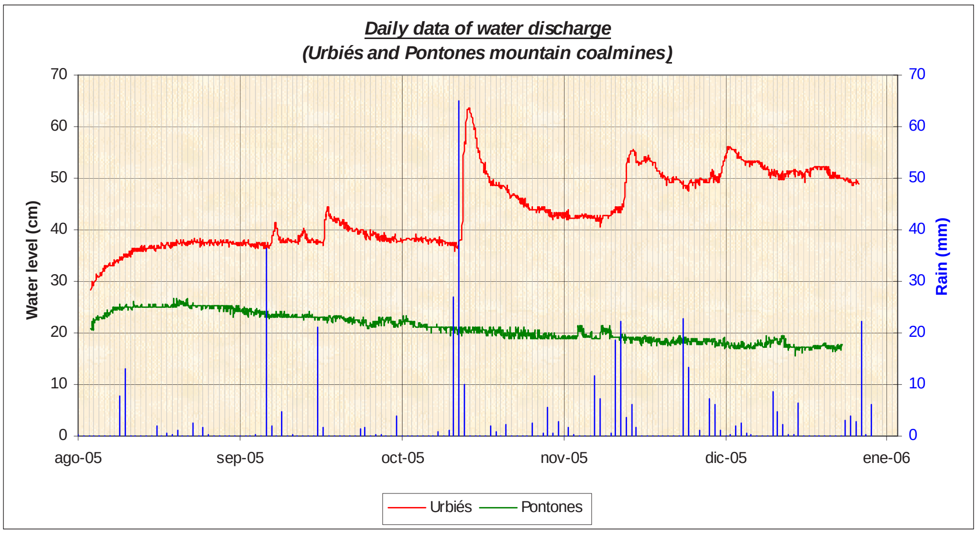

Figure 2.4.8: Water discharge measured with pressure probes in mountain coalmines (Turón Valley).

As it can be observed, the lag-time between rainfall and discharge is around two days in some of the mountain coalmines, whilst there is no discharge fluctuation in other ones.

Water discharge from instrumented coalmines has been controlled in order to improve the hydrodynamic comprehension of the area and to complete the conceptual hydrogeological model. These data confirm the previous assessment: the infiltration of the rainfall is very fast most likely due to the existence of many abandoned mine works close to the surface in the zone.

As mentioned above, the monitoring phase could not be started neither in the Figaredo mine nor in the Laciana school-mine plug due to the delays accumulated during the selection of site.

Task 4.8: Optimising methods, presenting and publishing results

The first results were presented in the 9th International Mine Water Association Congress (INWA) that was held in Oviedo (Spain) from 5th to 7th September 2005. The title of the communication presented in this congress was *"Plug Construction to isolate active zones of inactive zones in coal mine. WATER-CHEM Project"* and it was written by technicians from AITEMIN and HUNOSA, mainly Bárcena I., LLamas B., Bueno J., García- Siñeriz J.L., Suso J.M., Arduengo B.

Also, a communication with the final results of the project will be prepared to be presented in the 23rd International Applied Geochemistry Symposium (IAGS) that will take place in Oviedo (Spain) from 14th to 19th June 2007.

In the same way, the possibility to send other presentation to the IMWA Symposium 2007 is being considered. This congress will be held in Cagliari, Sardinia (Italy) between 27th and 31st of May.

The application of MASTERSEAL 345 from BASF as watertight membrane to be used for the underground test plugs was of great interest for this company. A technical note on this application will be issued in their second quarterly Internal Bulletin of 2007.

2.4.2. WP 4 Conclusions, Exploitation and impact of the research results

According to the hydrogeology in the Figaredo test site, several conclusions have been obtained. They apply in particular to this area, although some of them can be extrapolated in general to other similar mining areas:

Due to the existence of many mountain coalmines abandoned in Figaredo area, the infiltration of the rainfall into the mine is very fast and an intensive pumping is necessary in order to protect active areas of the mines from water coming from abandoned areas.

The lag-time between rainfall and mine water discharge is very short, around two days in some cases.

Nowadays, the coal basin is totally modified by the mining which one constitutes a catchment of underground water of big dimensions and complex geometry that changes notably the hydrodynamic system.

In general, the mine water quality in the area is acceptable with electrical conductivity values around 850 µS/cm, pH slightly basic and very low iron content. For this reason, the effects that these substances will have on the plug are not important but it is quite possible that this could change in the long term.

With regard to the construction of underground sealing plugs, the main conclusions obtained are the following:

Construction of underground plugs with shotcrete technique is feasible even in difficult conditions or when the time factor is essential

Main operative problem found is the supply of concrete on site

Length of the plug is determined upon the allowable hydraulic gradient and the shear strength of the concrete and surrounding rock mass

Thorough geotechnical and hydrogeological assessment is recommended for any permanent plug

It seems evident, upon the results obtained from the work performed, that in the near future HUNOSA will face the construction of underground plugs to cope with the problem of pumping in its abandoned mines.

Besides, AITEMIN is currently maintaining contact with MSP mining company (located in Villablino, León) in order to study the possibility of applying the knowledge obtained about constructive technologies of underground plugs in particular cases:

The MSP is analysing the possibility of constructing a plug in one of its abandoned underground mines, in order to monitor the waters gathered in the abandoned galleries, eliminating any need of pumping. As an additional goal, the viability of producing electricity using the controlled outflow of the stored water through the pipes embedded in the plug is being studied.

In another mine of the group, which is in operation in the lower floors, the construction of an underground plug in one of the middle abandoned floors is being considered. This would be used to create intermediate water storage, allowing to introduce an intermediate step for pumping. This way, instead of pumping the water from the lower floor in operation to the surface in a single step, it would be pumped to this water storage and from here to the surface in the off-peak hours of power consumption.

3. List of figures and tables

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4. List of References

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5. Appendices

5.1. Geochemical reaction modelling of mine water in large coal fields

5.1.1. Objective

The partners WYG, DSK and DMT have directed their efforts to improving the forecasts of mine water qualities when flooding large underground coal fields. The goal is to supplement the tools already available by combining a flow model with a multi-component mass-transport-model. Currently there is no standard program readily available to fulfil this task. The approach taken for the research work is to develop a geochemical model which is tailor made to suit the flow model already in use.

Application of the geochemical model at various complex mine fields will be used to determine its applicability and robustness in forecasting effects of regional mine water rebound.

5.1.2. Relevant geochemical processes in coal mines

Substance mobilisation during flooding is a consequence of geochemical processes before the flooding. The input of oxygen for ventilation and the lowering of the water table are the most significant factors that change the geochemical environment during mining activity. The prevailing conditions and the host rock composition form the variables determining the intensity of the well known geochemical interactions that have their origin mainly in pyrite oxidation. These processes are well described in literature and need no further discussion because the methodology applied in this paper does not deal with these primary conversions but addresses directly the mobile substances already existing in storage at the beginning of the mine flooding. This includes not only products of the rock weathering processes, but also building materials used for construction works in the mine (e.g. gypsum, lime) and any backfill.

As a first approach we have identified all mine water quality parameters which are more or less common to the coal mines under consideration and provide an adequate base for establishing a new model. However, the philosophy is maintained that the numerical model has to be kept flexible so it can integrate further parameters and individual mine conditions at later stages of its development.

The parameters selected under the conditions described above fall into 4 different categories:

- Substances with a hazard potential, where “hazard” is understood as a significant environmental impact as well as a detrimental impact on equipment and treatment processes:
    - iron, manganese
    - chloride, sulphate
    - barium
    - temperature
- Additional basic parameters required to allow geochemical modelling:
    - pH, Eh, O_2
    - calcium, hydrogen carbonate
- electric conductivity as a summarizing parameter and
- additional parameters for hydraulic modelling and mass balances
    - hydraulic pressure
    - flow (direction and velocity).

The most important solid phases to be considered in coal seams and host rocks are sources of iron and carbonate minerals which determine the buffer capacity:

- pyriteFeS_2
- siderite (Fe,Mn)CO_3
- calcite $CaCO_3$
- ankerite $CaFe[CO_3]_2$
- dolomite $CaMg[CO_3]_{2.}$

Relevant sulphate und iron loads (and often manganese) are usually observed and monitored during the flooding of hard coal mines, e.g. in the Durham Coalfield, the Lorraine Basin and the Ruhr coal mine district. Reactive mass transport modelling (e.g. precipitation of barium sulphate in some Ruhr coal mines) also has to be considered to reflect the interactions between the dissolved substances and with the loads of permanent geogenic mine water inflows.

During and after flooding the availability of atmospheric oxygen is restricted resulting in non-oxidising or in the long term reducing environmental conditions. Under these conditions $FeSO_4$ gains relevance as a migrant as well as salts like $CaSO_4$ und $MgSO_4$, with solubility almost unaffected by pH value and redox voltage.

Once further oxidisation and mobilisation processes cease, the loads carried in the mine water decrease with time predominantly related to the flushing rate and flow dynamics. The methodology detailed below provides a practical basis for describing the dynamics of these processes and for the prognosis of substance concentrations in mine water discharge.

5.1.3. Modelling approach

In practical applications the geochemical modelling of groundwater and mine water is mostly attached to hydraulic flow modelling, because both processes deeply influence each other. In general, the methodology in use consists of:

- separate modelling of geochemical processes which is often realised with standard 1D flow simulation codes such as WATEQ4F, MINTEQA2 or PHREEQ (all U.S. Geological Survey) with results being used in a batch mode by standard flow models
- or the simulation of reactive transport models which integrate geochemical developments and hydraulic flow.

A well proven and straight forward “non – model” method to predict development of iron and sulphate concentrations was developed by (YOUNGER 2000) and has been further adapted by (YOUNGER & BLACHÈRE 2003) to reflect experiences made at French hard coal mines. The method is a simple statistical evaluation of numerous mine flooding and apparently suits requirements as long as mine water hydraulics are not very complex. According to the mine flooding events evaluated the reaction products of pyrite oxidisation (Fe and SO_4) reach typically maximum concentrations very quickly at the initial stage of flooding and decrease in an exponential mode.

For more complicate geochemical environments we resorted to PHREEQC modelling to describe the status and future developments of mine water in the Durham Coalfield. In our work it became apparent that sole geochemical modelling like application of PHREEQC is not the adequate methodology to describe the complex reaction of large coal fields on mine flooding. The following represents the modelling approach taken and some major achievements made during our research work to incorporate features which are of practical requirements.

5.1.3.1. Fundamental hydraulic model

Large underground mining results in hydrogeological peculiarities like large linear voids (shafts, adits, roadways) connected with low porosity rock, fractures and also with large permeable areas (goafs) which cannot be handled by standard groundwater modelling (ADAMS & YOUNGER 2001). DSK and DMT have advanced a specific model over the last years, which is termed “BoxModel” and has become their working tool when looking at optimisation of mine water pumping systems and forecasts on changes to the underground water flow.

Figure 5.1.1 displays an example from the central part of the Ruhr coal mine district. Boxes coincide with large abandoned mine fields characterised by an uniform hydraulic head and water levels indicated are kept low by various pumping stations. A box is assigned all important information and components of the mine field in the hydrogeological sense: storage volume, conductivity, recharge, discharge and also information on mine-water-quality: pH, Eh, temperature, concentrations, stored contaminants, typical minerals etc.. The features of the BoxModel have been described elsewhere in detail (ECKART et al. 2004). It is in essence a volume – balance model and uses the finite difference approach. Its features include laminar and turbulent flow, time variant input data and comfortable processing of input and output data.

While developed specifically for water flow in underground mines, it can also be used for any other groundwater flow problem and can be connected with standard finite element numerical flow models (research work completed under ECSC Research Contract 7220-PR-136 in 2005).

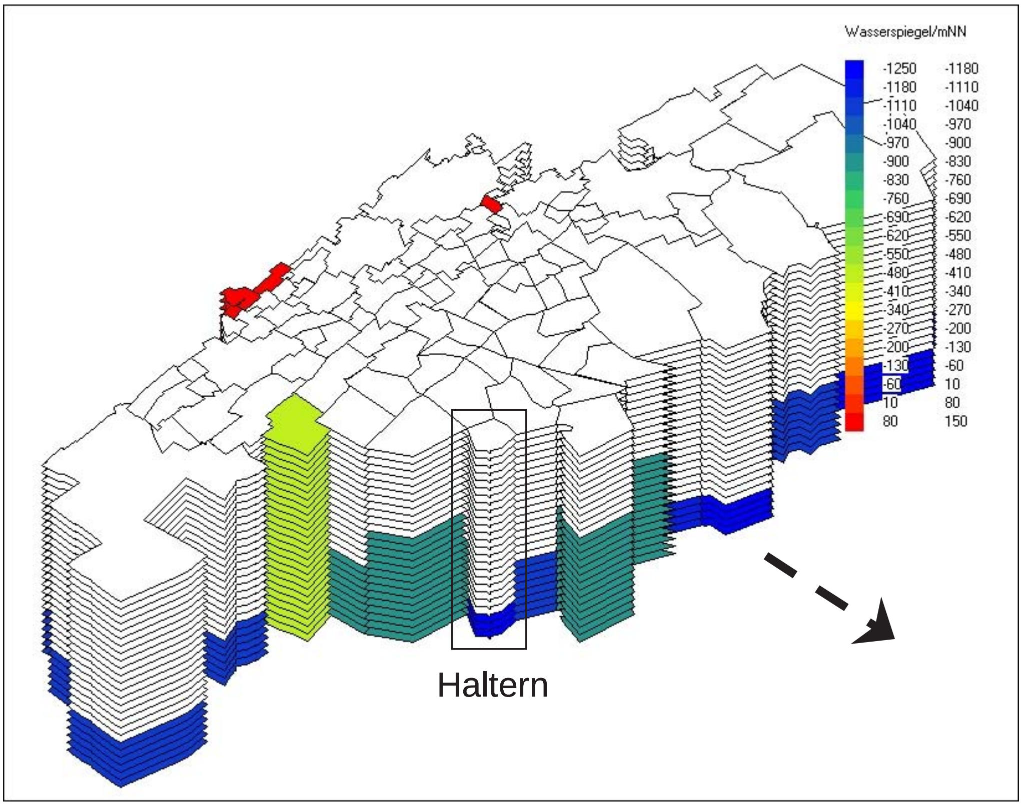


Figure 5.1.1: Sectional view of Ruhr BoxModel showing Haltern box (note: arrow points to North).

5.1.3.2. Concept of active and passive mass storage

Filling of void volumes during the flooding is in contrast to a stationary flow system with constant water levels during mine activities. Hereby the long term observed concentration levels generated by continuous reactions like pyrite oxidation and inflow of mine water are increased by dissolution of easily soluble salts from rock surfaces. In addition substances become activated which were stored in highly concentrated pore waters and in "dead water" areas experiencing previously practically no flow. This results in the well known specific intense increases of concentrations and loads.

Another important process which is known in principle is the decrease in concentrations as the consequence of flushing of the void volume by inflowing water. The exchange rate is influenced by various factors like

- open mine cavities,
- rock porosity,
- seepage water volume and quality,
- position of the water inflow in relation to the position of the outflow

and must not be homogeneous for an entire mine. The dynamics of this flushing process are controlled by convective flow as well as by diffusion processes and subsequent delivery from the pore volumes as well.

Any model to be applicable for practical purposes has to describe both the sharp initial increase in concentration levels as well as the exponential decrease as actually monitored (figure 5.1.5). The modelling technique has to provide for an adequate mass storage to consider the long term concentration development. Starting model runs with initial concentration levels beyond those observed would be unrealistic and not acceptable. We therefore resorted to a simplifying dual system to be incorporated into the geochemical model and reflecting the concentration developments actually observed. The concept provides for an active and a passive storage element (figure 5.1.2), subsequently titled "porosity" which includes all floodable residual void volume consisting of man made voids, fractures, cleavages and rock pore space, and can be described as follows:

- the floodable volume is subdivided into an easily percolated part (active phase) and a stagnant part (passive phase)
- the easily percolated (active) volume correlates with the open mine cavities
- the stagnant (passive) part correlates with the mine workings (goaf areas) and the fracture porosity including adjacent pore spaces.

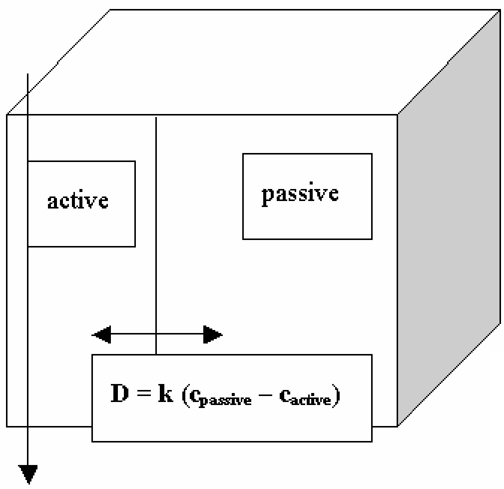
In the large coal mines investigated the approximate spatial distribution of the residual void volume is about:

- 20 % open mine cavities + 80 % workings and fracture porosity.

The fundamental understanding for the hydraulic and mass transfer processes is as follows:

- the convective flow takes place only within the active porosity
- the passive porosity contains well soluble salts in high concentrations
- solution processes of weathered products take place in the passive porosity
- mass exchange between the passive and the active porosity follows the diffusion law.

This concept has been integrated into the geochemical reaction model. It principally allows higher mass storage in the passive porosity without resulting in high outflow concentrations. By this concept e.g. the high sulphate loadings actually observed can fairly easily be considered.



K	Kinetik coefficient	[1/s]
D	Transfer rate	[mg/L/s]

Figure 5.1.2: Separation of active and passive parts of a box.

The mine water quality components are primarily released from the passive porosity and transfer is provided by the diffusion law into the active porosity with the latter being hydraulically connected to other boxes. The exchange coefficient k (see figure 5.1.2) is controlled by a mine specific factor which is described further below (figure 5.1.3).

5.1.3.3. Influence of flow rate and residual void volume

Geochemical processes depend on the specific properties of any individual mine. Nevertheless, some common features apply to the overflow monitored during and after most mine flooding. When describing the concentration development C(t) with time t starting at the time t_0 available data imply a dominant influence of the floodable residual void volume and the inflow rate (= outflow rate) of mine water. These two parameters are the basis to describe the washing process once a mine is completely flooded and allow to calculate the time needed per exchange of the flooding volume. They provide a coordination system to characterise and compare the mine water quality developments of different mines with differing void volumes and hydraulic properties.

Our statistical investigations indicate a correlation of the flushing dynamics with the intensity of flushing which can be specified by the ratio "discharge volume / void volume" (Q/V). Experiences from Southern France and Germany give reason to adjust the exponential function normally used by a correction factor (F) for the exponent to take specific flow conditions into account:

$$C(t) = C_o * e^{-Q/(V*\mathbf{F}) * (t-to)} \qquad (1)$$

This correction factor F allowed to match calculations with concentration developments observed. Our evaluation of flooding events in large coal mines indicates that the adjusting factor F follows a regular pattern. There is apparently a strong relationship with the intensity of flushing expressed by the ratio „Q/V". In order to make our evaluation results available for prognosis calculations we had to replace the somewhat arbitrary correction factor F by a generally valid functional relationship to the Q/V ratio (figure 5.1.3). Using this approach also allows to describe the flushing of complex mine fields with large interconnected collieries. This relationship is compatible for direct transformation to the mass balance equation used in numerically–discrete models. The site-specific factor F represents the influence of the void volume participating actually in the flushing process.

In contrast to the above analytical solutions the BoxModel applied in our research work is designed to already take complex hydraulic situations into account. When re-calculating flooding events and comparing with analytical solutions, the BoxModel renders very satisfactory results. In our view this confirms the adequacy of simplifying analytical solutions like equation (1) at mines or mine fields with a fairly straight forward flow pattern. However, large mine fields with fairly complicate hydraulics require a more demanding approach like the BoxModel calculations.

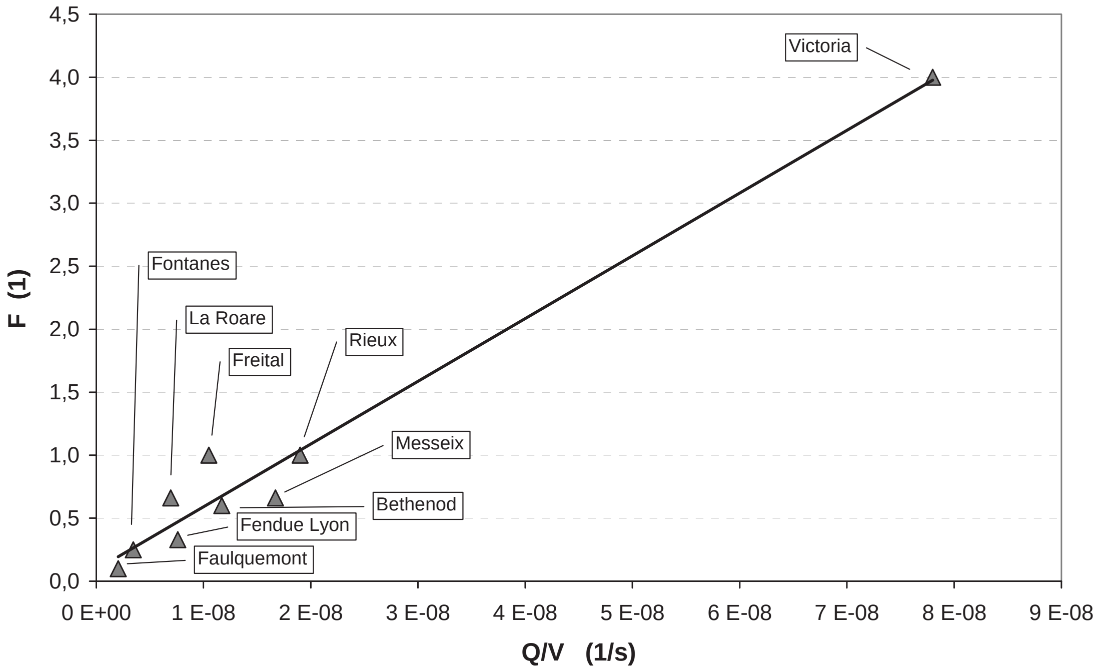


Figure 5.1.3: Relationship between volume-correction factor F and ratio "Q/V".

5.1.3.4. Geochemical reactions

An international standard to investigate geochemical processes occurring in aquatic systems is the PHREEQC geochemical model, designed by Parkhurst (1995). WYG has successfully used PHREEQC to balance the chemistry between the secondary, aqueous and gaseous phases taking place by using a series of geochemical reactions. The PHREEQC geochemical model has also been used to predict the effect of mixing various mine waters with surface and groundwater induced by pumping in the Durham Coalfield. Mixing processes have also been recreated within the PHREEQC model to determine the quality of the final effluent that could require treating from a mixed mine water.

A numerical equilibrium and reaction code (similar to PHREEQC) using the PHREEQC data set has been developed and directly integrated into the BoxModel (an earlier approach to couple PHREEQC directly with the BoxModel code as an external program resulted in intolerably slow execution rates). The BoxModel has been further developed to integrate a multi-component reactive transport model.

Chemical reactions in the liquid phase do occur and make it impossible to simulate the transport of chemical components separately. To model the real world it is necessary to describe the transport of the dissolved salts parallel for each box, at the same time interval. As a minimum the following components are required:

Kations: Ca, Fe, Mg, Na, K, Mn, Ba, Sr, Al, B

Anions: SO_4, CO_3, Cl, NO_3

The integration of the chemical reaction mechanisms yields totally different results from what would have been obtained by transport modelling and application of simple mixing formulas. A fairly drastic example is the mixing of water at one of the deep mines in the Ruhr district: incoming flow from the north contains high salt concentrations (Ba-concentrations > 100 mg/L) and meets incoming flow from the southern direction (low salt but relatively high sulphate concentration > 200 mg/L). The dominant reaction when mixing these waters is the precipitation of barite which was actually observed.

Many mines in the German Ruhr area show mine water qualities during flooding with a mineralization of more than 100 g/L. Typically for such and also for more diluted water are **geochemical activities** different from the mass concentrations of the dissolved elements. Activity and concentrations are equal merely in infinitely diluted solutions. For this reason for geochemical modelling of highly saline water an activity coefficient is introduced to describe the activity in relation to mass concentration:

$$a = \gamma \cdot c$$

a - activity (mol/L)
γ - activity coefficient (1)
c - concentration (mol/L)

The so called "Pitzer-theory" has been established for geochemical calculation of species distributions in highly concentrated brines. Because of the importance of correct activities used for mine water prognosis we included in our research work the implementation of the Pitzer-theory into the BoxModel tool. Programming of the Pitzer-equations for the chemical reaction model within the BoxModel was realised by DMT using published equations and interaction coefficients. The Pitzer theory gains practical value when ionic strengths is larger than 0.1 and gives a activity-coefficient differentiation between ions with the same valency.

The pH data monitored during and after flooding of many hard coal mines indicate considerable buffering reactions. The buffering system is recognised as a very important part of the factors influencing the mine water quality. Main materials providing neutralisation potential are known to be

- carbonates (host rock, backfill) or
- hydroxides (underground construction materials, backfill).

The thermodynamics of the reactions involved are principally well known and included in the PHREEQC calculation tool. Within a more or less closed system reactions result in elevated CO_2 partial pressures releasing CO_2 into the gaseous phase when e.g. mine water move upwards into open voids. Therefore the gas phase has also to be considered in the reaction model. The buffering reaction stops when all acid generated is consumed depending on the geochemical equilibrium realised. In a typical mine water environment the reaction system consisting of acid – sulphate – calcium – carbonate the concentrations of calcium and sulphate are controlled by the solubility of gypsum, therefore, precipitation of gypsum is expected to occur. The formation of bicarbonate also influences the solubility of siderite and hence the mobility of iron.

It is therefore obligatory to include the buffering capacity and buffering reactions into the geochemical reaction model. The same processes also apply in mine water treatment influencing the treatment process and the reaction sludge produced so that there is a twofold benefit in establishing a suitable practical tool simulating the carbonate reaction system. Work concentrated on improving the numerical code to include the complex buffer system.

As a final result the geochemical reaction model includes following features:

- Many elements are transported at the same time (transport equation is being solved very often for the 28 components in the actual model version)
- Reactions are not based upon accumulated concentrations but upon species distributions depending on temperature and including pH and Eh values (using PHREEQC)
- Consideration of reactive gas phase constituents (O_2, CO_2)
- Precipitation and resolution of solid phases (= minerals) (using PHREEQC)
- Calculation of the geochemical balance
    - in each flow element (box slice)
    - at each time step
- Reactions depending on specific reaction rates.

The expanded numerical code has been tested with the Haltern box demonstrating the successful augmentation of the numerical code including detailed buffering reactions. For practical use and in consequence of the often limiting availability of input data it is reasonable to limit chemical reactions considered on precipitation reactions resulting from mixing of mine water in the active phase (e.g. sulphate salts) and buffering reactions with participation of carbonate phases in the host rock. It could be shown that this selected chemistry suffices to reproduce the dominating processes resulting in the mine water quality monitored. This represents a major achievement for the practical application of the geochemical reaction model for mine water rebound.

5.1.3.5. Model calibration

An excellent opportunity to calibrate the chemical reaction model derived from numerous chemical analysis data obtained when partially flooding a mine in the Ruhr coal district. The flushing process resulted in a typical sharp increase and subsequent exponential decline as shown for actual sulphate concentrations during a 4-year period in Figure 5.1.4. It took about 10 exchanges of the pore volume until the sulphate concentration assumed again the previous mine water concentration of about 210 mg/L. In order to reflect this pattern in the numerical calculations the storage concept involving an active and a passive porosity needed to be applied. Figure 5.1.4 shows the best fit of concentrations of sulphate calculated vs. those observed using this concept.

A matching for iron concentrations could be achieved in the same way confirming that the model concept is able to reproduce in general the variations in concentration levels.

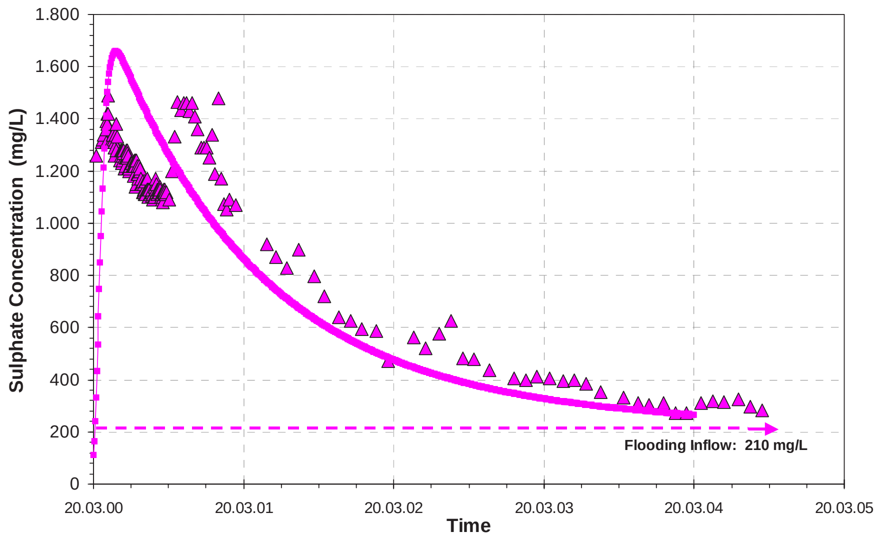
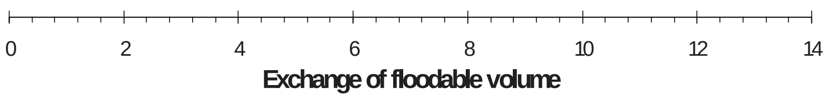


Figure 5.1.4: Model fit for sulphate concentrations calculated (squares) vs. measured (triangles) using the concept of active and passive porosity on chemical reactions.



Similar calibration efforts were successfully obtained for other applications of the BoxModel during the research work. These calibrations include:

- Brassert mine in Germany
- Grodziec mine in Poland
- Durham coalfield in England.

5.1.4. Practical applications to mine water quality prognosis

After calibration various BoxModel applications were performed during the research work.

5.1.4.1. Ruhr area (Germany)

Main efforts concentrated on a BoxModel covering major parts of the Ruhr coal district (figure 5.1.1). A section of this BoxModel was calibrated using data from the Brassert mine and was applied to forecast the most important geochemical reactions for the **Haltern mine field** where flooding started in late 2006. A highly barium concentrated water will change into a sulphate dominated water but for a period of only approximately 3 years (figure 5.1.5). Subsequently the barium concentrations will raise over time until it the original input level again. This implicates the need for water treatment with respect to iron for the years after the initial water discharge and while iron contents decrease the need for treatment to precipitate barium arises.

As a consequence of the geochemical model prognosis the requirements for treatment of Haltern mine water were confirmed and specified. The technical planning by DSK takes the initially high iron concentrations into account. Since barium could be forecasted as a problem to appear in subsequent years only alternatives are looked into to direct barium bearing mine water into old workings containing surplus in sulphate with the intention to keep precipitations of barium sulphate underground.

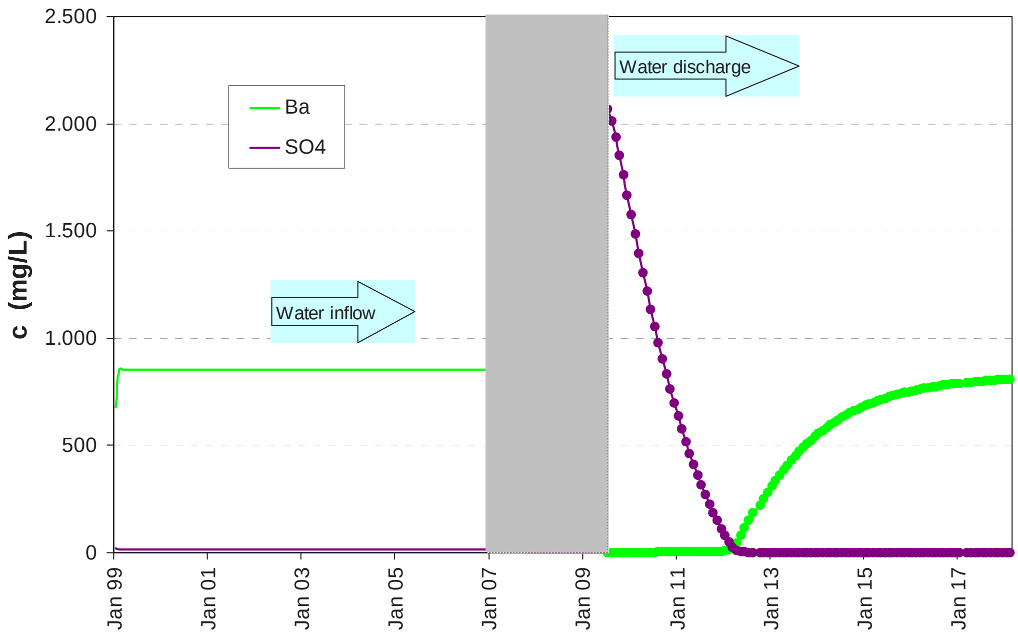


Figure 5.1.5 Model calculations (barium and sulphate) for the flooding of the Haltern coal field.

Further BoxModel calculations are presently performed at other coal mines and pumping station in the Ruhr coal district/Germany to optimise the mine water management and to obtain a suitable basis for assessing environmental impacts and financial investments. These locations are:

- Underground pumping station Zollverein which needs to be expanded.
- Walsum colliery which is scheduled for closure in mid 2008.
- Underground pumping station Carolinenglück which needs major changes due to progressive mine closures.

5.1.4.2. Lorraine Basin (France - Germany)

In 2003 development of a BoxModel started in the French/German border crossing coal district to forecast the mine water rebound when flooding the French Lorraine coal field and stopping pumps at the German Warndt colliery (see chapter 5.3.4.3).

Various alternative mine water rebound scenarios using the newly generated geochemical features were calculated. After evaluating the model results a consent was obtained in a joint French-German meeting in October 2005 to pursue the Alternative 2 shown in figure 5.3.8.

To our knowledge the Lorraine/Warndt geochemical model is the first of its kind allowing meaningful forecasts on mine water developments at this order of magnitude (regional coal fields) and period of times (several decades) in the coal mining industry. Work on updating and improving the Lorraine/Warndt BoxModel continues.

5.1.4.3. Upper Silesian Coal Basin (Poland)

During the research work DMT gained the support of the Polish Central Mining Institute (GIG) in Katowice for developing and testing a BoxModel for the situation at the Upper Silesian Coal Basin, Poland**.** DMT experts provided some transfer of knowledge under the GIG managed ToK-DEV Water-Norm project (contract No. MTKD-CT-2004-003163) which is part of the EU 6th Framework Programme. After calibration the BoxModel was then used to perform some preliminary calculations on mine water developments assuming some scenarios for mine closure and optimising mine water pumping. Forecasts on sulphate developments could be made on the basis of some sparse monitoring data available (figure 5.1.7). Efforts are undertaken to improve the data base and to define some realistic mine water management scenarios. The Polish side expressed continued interest in further development of this BoxModel and applications for funding are initiated.

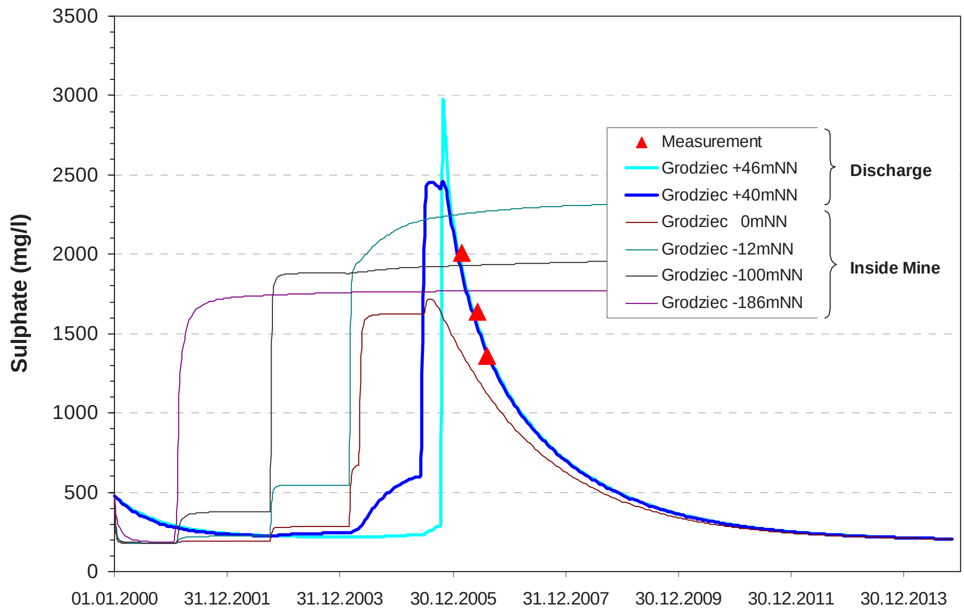


Figure 5.1.6: Model results (lines) and measurement of sulphate concentrations

5.1.4.4. Durham coalfield (England)

During the research work WYG and DMT developed a BoxModel for the East of Wear area of the Durham Coalfield/England where mine workings underlie a major Permo–Triassic drinking water resource. The East of Wear area extends from the outcrop of the coal seams in the River Wear valley in the west to the most recent deep undersea workings in the east. The northern and southern boundaries of the block are major faults or pillars of unworked coal through which there are no known hydraulic connections. The area is further subdivided by an east west trending fault (LuworthWhin Dyke), narrow pillars of unworked coal and underground roadway dams. The mine workings are overlain unconformably by the Permian Magnesian Limestone from which some 36,000 m^3/day of potable water are abstracted.

The East of Wear area is unusual in that there are interconnected mine workings dating from the earliest known workings (14th Century) to the most recent (1993). Historically mine water levels in the old shallow workings were controlled by pumping at three long abandoned collieries, Sherburn Hill, Nicholsons and Lumley 6th. Mine water pumping at these three collieries continued after all mining in the area was abandoned in 1993. Mine water pumping was stopped at Sherburn Hill, Nicholsons and Lumley in 1999 when it became clear from monitoring of water levels in the deep mines that the pumping was not significantly influencing the mine water recovery in the workings below the aquifer.

The cessation of pumping at Sherburn Hill resulted in a period of recovery followed by a sudden drop in mine water level resulting from the failure of a dam (plug) constructed in a roadway through the LuworthWhin Dyke. This resulted in a flow of mine water to more modern workings connected to Horden Colliery on the coast. The cessation of pumping at Nicholsons and Lumley resulted in a combined recovery but with no overflow to adjacent mining blocks with which there were recorded connections. In order to prevent a uncontrolled discharge of mine water into the River Wear mine water pumping (50 L/s) was restarted at Lumley in late 2005.

Due to the continuing mine water recovery and the known direct hydraulic connections between mine shafts and the aquifer the mine water levels have been controlled below the piezometric head in the aquifer since 2004 by the temporary pumping and treatment sited at Horden shaft (figure 5.1.8). During the mine water recovery period no significant impact on water levels in the Magnesian Limestone have been noted probably because of the high rate of abstraction from the aquifer when compared to the inflows that occurred between the aquifer and the mine workings.

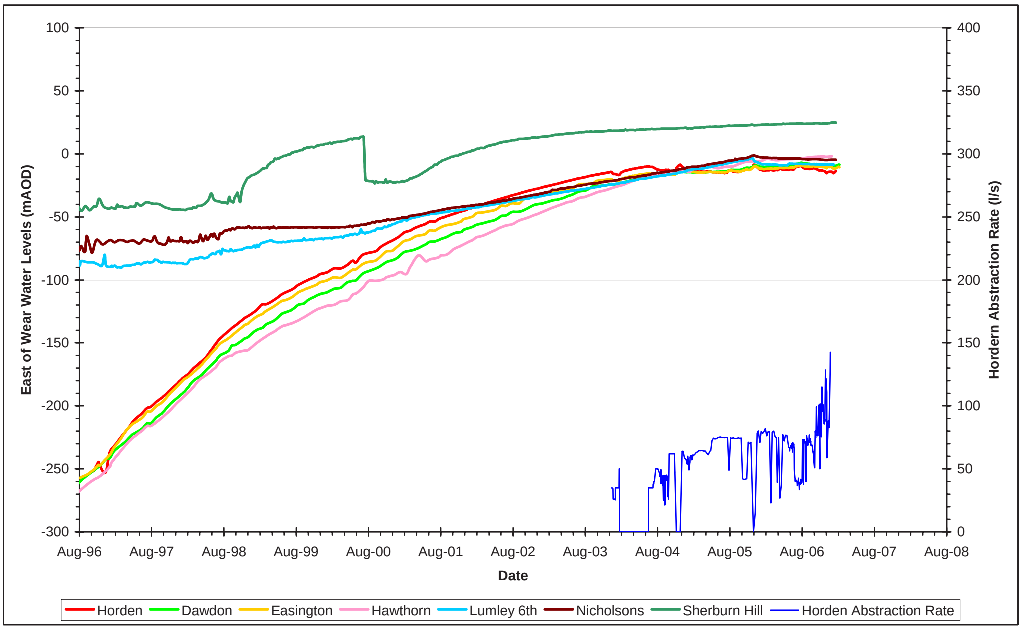


Figure 5.1.7: Mine water recovery in the East of Wear area since 1997.

PHREEQC geochemical modelling has provided a good understanding of potential contamination of the aquifer by mine water quality when different water quantities are allowed to mix and the likely sources of the mixed mine waters. However, the various hydraulic scenarios identified need to be integrated using the BoxModel. The first preliminary BoxModel calculations performed during the research work (figure 5.1.9) indicated that chloride concentrations will remain a long term problem. According to the results the slow increase of chloride concentration in the near surface pumped water can be on the one hand referred to the slow increase of pumping rates in reality (the model calculation was run with a constant maximum pumping rate) and on the other hand on the time need for equilibration of the hydraulic system after beginning of pumping.

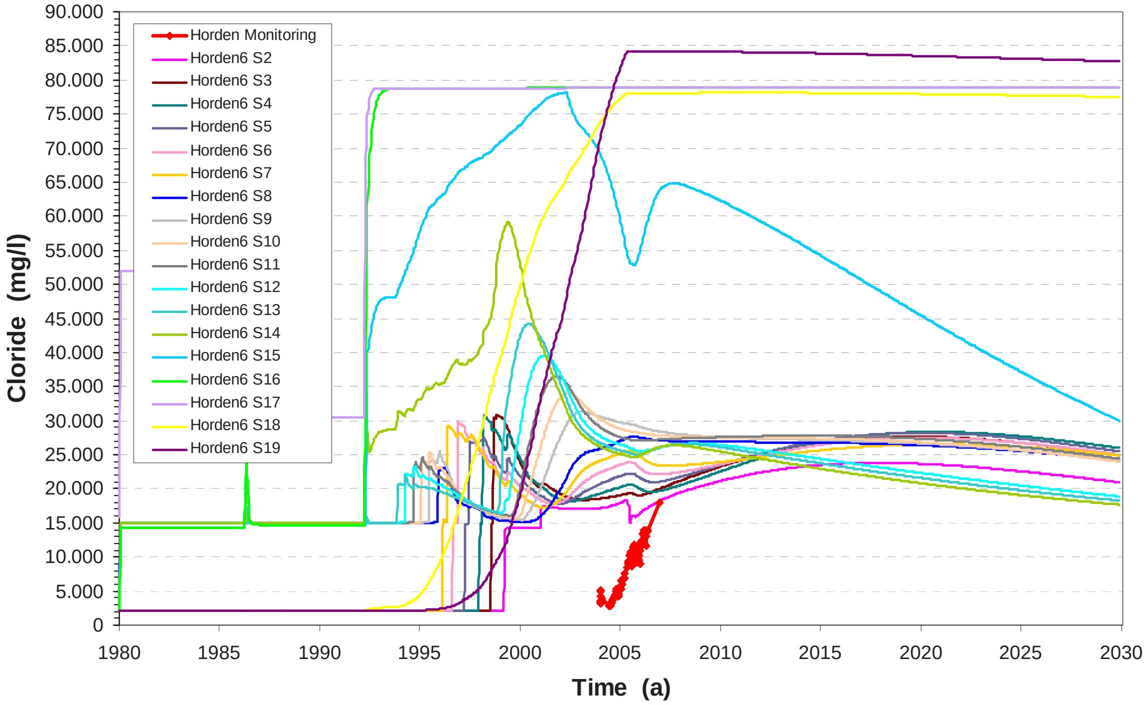


Figure 5.1.8: Preliminary results on chloride concentration developments in the Durham Coalfield.

Further investigations will check the influence of variable pumping rates. The actual model result implicate with relative homogenous concentrations in the upper shaft levels that the relatively high salinity of the discharge can be controlled by pumping rate only to a minor degree. The Coal Authority has expressed interest in further model developments to assist in determining an optimum long term strategy on the mine water rebound.

5.1.5. Conclusions

The objectives of the research work could be fully achieved. The BoxModel integrating a geochemical reaction model proved to be a very appropriate tool in simulating mine water rebound effects in large coal mine fields. Less sophisticated empirical solutions and pure geochemical modelling like the application of PHREEQC seem to be adequate in relatively simple situations. For practical purposes the complex hydraulic dynamics inherent to large coal mining areas proved to be the dominating factor for mine water flow and geochemical reactions. The BoxModel approach was successfully calibrated and continues to be convincingly applied in several large European coal mine fields.

5.2. Developments in surface environment monitoring and control

5.2.1. Introduction

The overall objectives of this work were to offer solutions for effective mine closure, provide improved knowledge of ground water movement at working mines and effective surface environmental control of factors resulting from mining activities both past and present. To achieve these objectives the project undertook a range of research and development tasks that fall broadly into one of the following three main topic areas:

1. Selection, development and improvement of mine water sampling and monitoring systems
2. Analysis and monitoring of ground water movement at working mines
3. Surface environmental hazard - identification and control of risk factors resulting from mining activities

5.2.2. Improvement of mine water sampling and monitoring systems

The first step in establishing an improved understanding of mine and ground water influences, and hence combating any potential hazards that may arise from them, was to ensure that the industry had access to effective environmental measuring capabilities. This required system components which are compact, self-powered, robust, have a long-life, with remote interrogation and self-checking capability and where necessary, intrinsically safe. Rugged, self-powered sensors were already widely used for environmental monitoring. However, it was not clear whether these could offer the long unattended operating life often required by the coal industry, and whether sensors for different parameters could easily be connected to the same data-logging and data transmission facility. Additionally, operating power requirements for systems operating in remote areas on battery, wind or solar power needed to be considered.

The characteristics and potential measurement limitations across the range of parameters that the industry was most likely to require measured and/or monitored was examined. Practical problems associated with the electrodes typically used for measurement of pH, led to a more detailed investigation being undertaken into recent technological advancements in this area.

AgCl Reference Electrode

In a pH sensor, the glass electrode – although fragile – usually requires very little maintenance. However, the reference electrode suffers from the problems of fouling and diffusion which stem from the fact that the electrode needs to be porous. A company in Ireland – Refex Sensors Ltd – **www.refexsensors.com**. had developed and patented a reference electrode that claimed to solve these problems. The Refex™ electrode still relies on an AgCl half-cell reaction in saturated KCl. However, the electrolyte is bound in a conductive salt-loaded polymeric matrix (see figure 5.2.1 below).

There is no liquid contact between the medium under test and the internal half-cell reaction. The manufacturer claims that Refex continues to perform even when completely coated with crude oil and sewage. However, the coating deposit must remain wet and conductive or else electrode dehydration causes the impedance across the Refex interface to increase out of specification. Another claimed advantage of the Refex electrode is that the entire surface area is active, which helps to maintain a stable output in the presence of contaminants. Additionally it means that the unit has a very fast response to changes in pH. Traditional electrodes, with a small ceramic plug, can have a slow response and are obviously more susceptible to errors caused by fouling.

In a combination electrode, the glass electrode appears as a small glass bulb in the tip of the probe, whilst the Refex reference electrode comprises the side walls of the probe. In some Refex products the glass electrode bulb is replaceable.

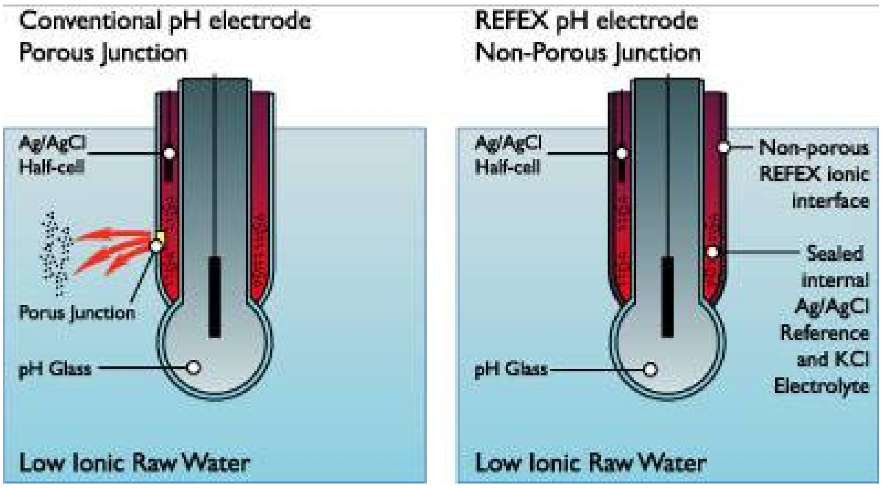


Figure 5.2.1: Comparison of conventional and Refex reference electrodes

Refex electrodes are stored in a 3M solution of KCl and the manufacturer advises that a newly-installed electrode will take two hours to become conditioned to the flowing water at the sample site.

The main problem with the glass electrode in a pH sensor is that it is fragile. It can also deteriorate at high temperatures or in high pH conditions. In the 1980s research by Leeds & Northrup's Solid State Physics group led to the development of the ion-sensitive field-effect transistor (ISFET). The active surface of the doped silicon is separated from the test solution by an insulating layer and it responds in a similar fashion to the glass electrode. Some ten years ago, the Durafet® pH electrode was developed using an ISFET device and featuring a gelled KCl solution within the reference electrode. More recently, Leeds & Northrup was taken over by Honeywell, www.honeywell.com, and the Durafet solid-state pH sensor is one of their range of industrial measurement products.

Another development, mentioned at www.sensorex.com, is to use a flat sensor surface instead of a glass bulb (see figure 5.2.2 below). The advantages for this are claimed to be:

1. Self Cleaning Operation. When the electrode's flat measuring surface is exposed to turbulent flow, the resulting scrubbing action provides a self-cleaning effect in most applications. For the typical spherical electrode, the downstream side is shielded from the flow; coating forms on this dead flow area, causing sluggish and drifting signals.
2. Abrasion Free Operation. Particles sweep by the electrode's flat, non-protruding surface without impinging on or abrading it, thereby extending the electrode life. The non-protruding design virtually eliminates electrode breakage. For the typical spherical electrode, particles impinging on the upstream side of the bulb can cause abrasion, calibration shift, and shortened lifetime.

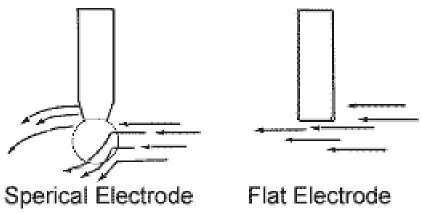


Figure 5.2.2: Comparison between flat and spherical electrodes. [Diagram from Sensorex web site]

5.2.2.1. Development of data transmission capability

Several candidate approaches and systems were investigated. In the simplest case, a commercially produced radio modem that transmitted data to a radio receiver connected to a computer terminal could be employed. For simplicity and ease of implementation it was clear that making use of the mobile phone network (GSM: global standard for mobiles) and the Internet would be the preferred option. For transmission by GSM there are several options in addition to using the network as a long-distance point-to-point radio modem. These are:

- Transmission by SMS**:** The short message service, or ‘text messaging’ facility of a mobile phone is accessible via its RS232 interface. Such a method is essentially point-to-point (i.e. it allows communication with a single computer connected to a cellphone) rather than being a gateway to a computer network.
- Transmission by FTP**:** The concept of a mobile phone dialling into the Internet and transmitting data to a web server using FTP (file transfer protocol) is highly attractive. Not only does it remove the necessity for a radio base station (TETRA systems for example, require the operator to purchase and erect a base station), but the data is instantly available over the Internet. The FTP protocol can potentially use the cellphone’s RS232 interface to upload data directly to a web server.
- Transmission by HTTP POST**:** Hypertext Transfer Protocol is used to serve web pages, where it involves a dialogue between the server and the client browser. As part of this dialogue, the web browser can POST data to the server. Typically, this would comprise HTML form data or file uploads.

From an examination of the various GSM options, it was initially concluded that the favoured way to retrieve data was using an FTP protocol for data uploading. However, further analysis led to the conclusion that HTTP was a more appropriate protocol.

5.2.2.2. Development of a “state of the art” system

A demonstration system using a Triangle Digital Services TDS-2020 data logger was constructed to allow the transmission of data via a GSM/GPRS modem to a Web Server. This system comprises a PCB mother-board that contains the component modules shown in figure 5.2.3 below.

This prototype hardware was used to prove the concepts involved in the use of GPRS devices for uploading data to the Internet and sending and receiving text messages via SMS.

To support the hardware a demonstration web site was developed and implemented for use by project partners to enable testing and assessment of the typical state of the art facilities that could be used by the coal mining industry. This site included an embedded TCP/IP internet gateway to provide secure remote access capability, and also demonstrated the development of integrated data logging analysis and alarm signal capabilities. The range of web server functions developed during the project are illustrated by the screen shot of the user interface page of the demonstration system (see figure 5.2 4 below).

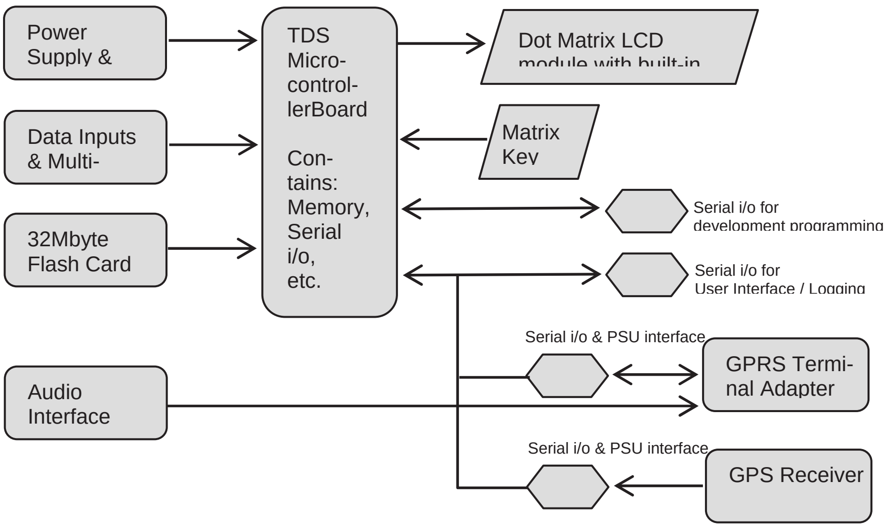


Figure 5.2.3: Block diagram of prototype data logger

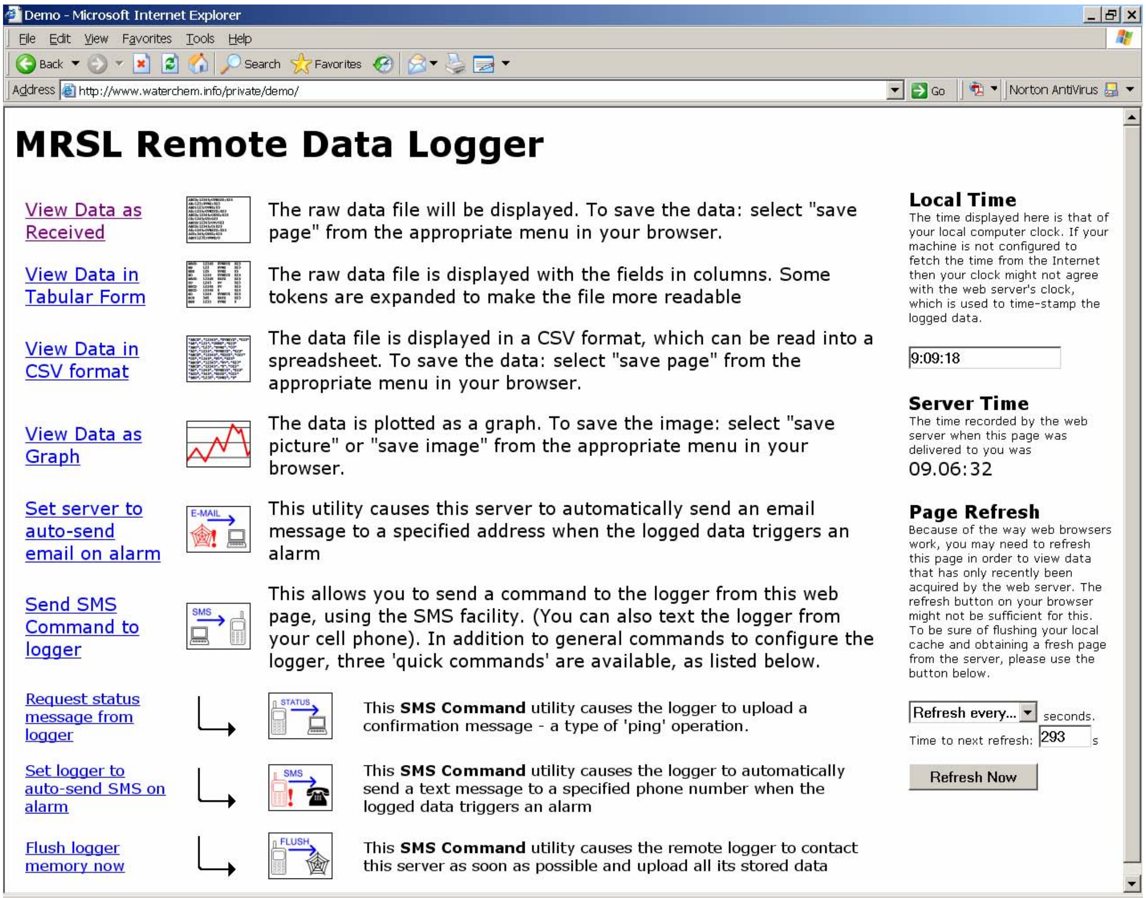


Figure 5.2 4: A screen shot of the main demonstration page from waterchem.info private/demo/

Having effectively established a benchmark for the current state of the art, this system was then used as the basis for comparative assessments of the equipment typically being used to monitor a number of remote sites by employing commercial bought-in modules including data-loggers, solar panels and GSM modems. It was concluded that even relatively new commercially procured systems could be improved by using ultra-low-power data logger and computer-controlled power management system. This would in turn allow a smaller, less expensive solar panel to be used. The provision of low power sensors would help this aim. It was also demonstrated that the provision of a terminal adapter (GPRS modem) or a proprietary 'Internet' solution (e.g. the SWI 300) allowed a more flexible method of data communication, and enhanced security of access.

A specialised piece of equipment for water sampling in deep boreholes and shafts was also developed and constructed. The design originates from a joint effort of DSK and DMT engineers, who also performed the construction. The sampler is certified as “intrinsically safe” by the mining authority for use underground in a degassing atmosphere. This type of equipment was not available commercially and had to be tailor made for the purpose of the WATERCHEM Project. The sampler is about 2.1 m long when lowered down a shaft and elongates to about 2.8 m after collecting the mine water sample. The body is shaped to facilitate the lowering down to about 1,000 m and basically consists of a tripping device at the top and a sample chamber forming the bottom part (see figure 5.2.5). A special release mechanism allows the sampler to take the mine water sample in a specific water interval. A mechanically operated timer opens the bottom valve at a pre-defined level to collect a water sample by piston movement. Sampling tests have been conducted successfully in the Emschermulde (see task 2.6, chapter 2.2).

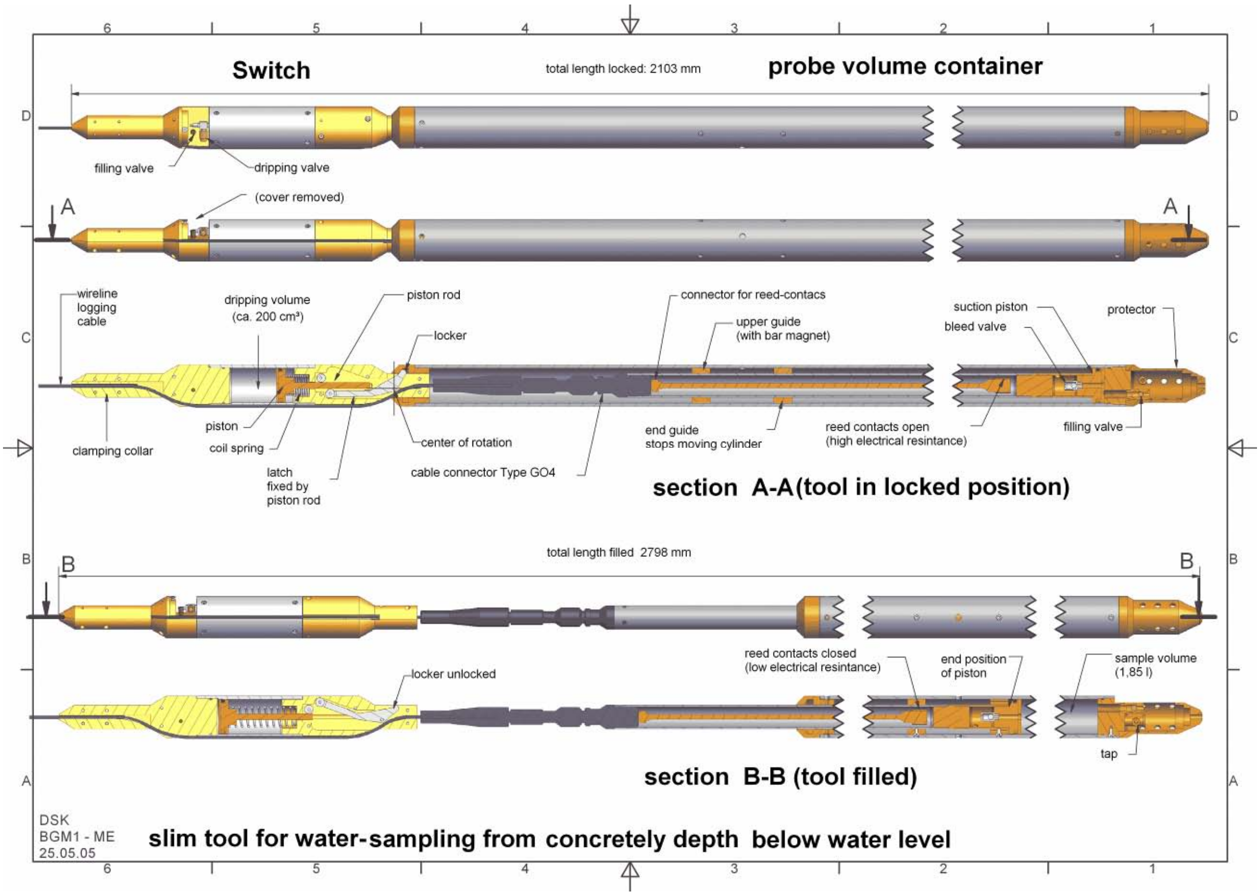


Figure 5.2.5: Details and cross section of the intrinsically safe sampler designed to collect water samples in mine shafts at pre-defined levels.

5.2.3. Monitoring of water make and quality

In the course of the project monitoring, sampling and analysis of water from surface points was as an ongoing activity throughout the duration of the project. This data was collected to provide an improved insight into water make and movement at working mines and at historical mine sites. The mine water and ground water quality data obtained was used in both the input data and control data for the PHREEQC modelling undertaken in work package 4.

Water quality, water level and the temperature and conductivity monitoring was used in the risk assessment undertaken with regard to the overlying and interconnected aquifers and to determine mine water flow paths both within the workings and to the Permian aquifer in the case of the previously contaminated aquifer.

In the opencast lignite fields of PPC in Greece, extensive pumping needs to take place to ensure sufficient drawdown of the aquifers, which are influencing the mining operations. This operational requirement gave rise to a need for detailed examination of:

1. The water table level and how it affects the mining works, surface environment, slopes stability and the quality of water.
2. The mine water quality and how it affects the water resources of the area around the mine.

The first step in this examination was to create suitable maps of the areas under investigation. This was done by combining satellite images which cover the area around the mines with existing mapping data held by the mines. GPS equipment was used to determine the exact coordinates of the drills and the sampling points using the HGRS87 reference system. These data were input in ArcGis and maps were created, which show the water table level and the distribution of selected physicochemical parameters for ground and surface water.

Based on results of chemical analysis of the water samples collected, the most important parameters, apart from water level, were identified as being S.S., pH, E.C., NH_4^+, NO_2^-, NO_3^- and some heavy metals or trace elements.

The instrumentation options investigated by the project indicate that the main parameters, which can be reliably measured on a continuous basis, using on site instruments, are water table, EC, PH, T^o (Temperature), DO (Dissolved oxygen), turbidity. Continuous monitoring was required to:

- Record the groundwater level, in order to protect the mine workings from groundwater inrush and ensure the safety of personnel,
- Protect mine voids from the intrusion of seawater (case study of Aliveri underground mine, which has been abandoned).
- Help avoid interconnection of different aquifers or waters with different quality.

Water level sensors were installed and operated in 9 water wells and in 2 ponds. The water level sensors did not operate for the whole period of the project due to: exhausted batteries, vandalism (one sensor) and the need for recalibration. Two piezometric maps were created (1/2005, 1/2006) for Megalopolis and two piezometric maps for the Ptolemais area. Also one map, which reveals and compares the fluctuation of the water table of the karstic aquifers around Kiparissia mine was produced. The conclusions reached from this work were:

- That within one year (1/2005 – 1/2006) the water table in the main karstic aquifer has risen by 11-14m, while, in the north karstic aquifer, it has decreased (figure 5.2.6).
- This verifies the existence of two independent karstic aquifers in the same geological formation (karstified limestones) in the vicinity of the mine.
- The aquifers in loose sediments and in karstic formations reveal a rapid response to rainfall, which could not be predicted before with the usual methods.
- The risky areas for creation of sinkholes on the surface of the mine area have been identified.

The results derived are of a great importance as the main karstic aquifer is used for the water supply of the city of Megalopolis and other small villages in the area and for the cooling towers of the power plants. Also there is an indication that before slip or a movement of the slope occurs in an open coal mine, a variation of the water level of some piezometers near the excavation was observed. This information cannot be obtained with manual water level measurements every month or every 15 days.

As only limited quality parameters can be continuously monitored by instruments, the main part of this work concentrated on collecting and analyzing samples from surface water and groundwater. A total of 784 samples were taken (217 from Megalopolis, 536 from the Ptolemais basin, 31 from the Aliveri area). In both areas, Megalopolis and Ptolemais, chemical analysis included:

A. Heavy metals: As, Hg, Cd, Pb, Ni, Crtot, Cu, Zn, V
B. Trace elements: Al,Sb, Ba, Be, Bi, B, Co, Mo, Se, Ag, Sr, Tl, Sn
C. Principal physicochemical and microbiological parameters.

In the Megalopolis lignite field the 217 samples were taken from:

A. Surface waters. 47 samples were collected (sumps in the mine: 35, ponds: 12) from 9 sampling points
B. Alfios River**.** 50 samples were collected from the Alfios river (6 sampling points)
C. **Groundwater.** 120 samples were collected from ground water (karstic aquifers: 8, deep aquifer in Thoknia: 11, surrounding of the waste dump: 46, groundwater in waste dump of Thoknia: 55), from 15 sampling points.

In Ptolemais lignite field data from surface water and groundwater samples were taken from the area of the 4 mines: Notio, Kardia, Amyndeon, Mauropigi. The 536 samples were collected from:

A. Surface water. Taken from the water pumped out from the sedimentation ponds**,** in the excavation area (216 from 6 sampling points).
B. Soulou River (stream). From the Soulou stream 38 samples were collected from 3 sampling points.

C. **Groundwater**. 282 Samples were collected from 20 sampling points around and in the vicinity to the mines.

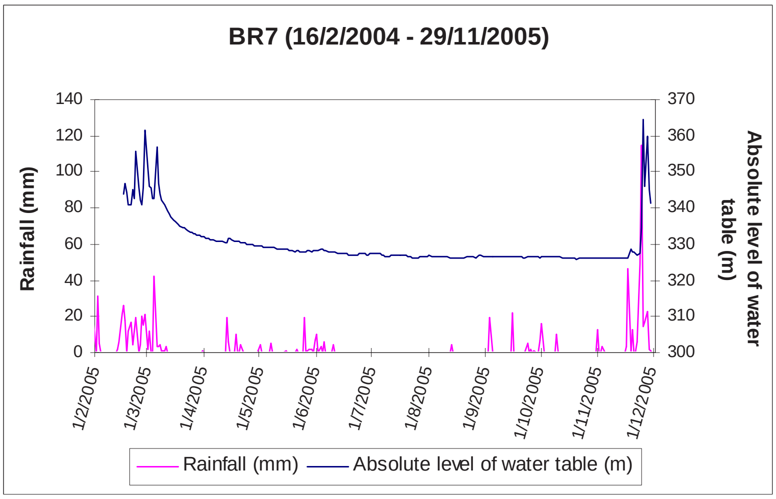


Figure 5.2.6: Fluctuation of the water table in BR7 well.

5.2.4. Surface hazards

A significant number of surface incidents arise as a result of historic mining activities. In the UK these incidents include old mine shafts being detected due to collapse, infill settlement, capping disturbance and shallow working collapse leading to surface cone depressions and ground fracture. Some of these occurrences are found in urban or industrial areas and may not be associated with any specific seam or other stratum.

Figure 5.2.7: Results of a Coal Mine Shaft Collapse

Figure 5.2.7 shows the results of the collapse of a disused shaft that had been filled and capped. The collapsed shaft is known to have originally been 3m in diameter, 285m deep and to have 7 insets. A tractor and the trunks of three Elm trees had to be removed from the hole caused by this shaft collapse. This aspect of the research focused on ascertaining the reasons for incidents such as these and determining if a relationship between the changes in ground or mine waters, and the risk of such events occurring could be established.

In the UK, MRSL are contracted to provide a first response service designed to address the immediate risks to the public that may arise from such surface hazards. Procedures were instigated to obtain water samples and additional related data as an integral part of the first response teams' activities. This data was supplemented with historical data provided by the Coal Authority and collected in a data base that was designed and developed specifically for the project. The data obtained from analysis of water at the surface sites was also used to assist in predicting the potential for quality deterioration or water table pollution, hence allowing contingency plans to be made and remedial action taken before environmental problems become catastrophic.

An analysis of the data related to surface hazards allowed the identification and selection of a sample of sites where mine water was most likely to have been a significant contributory factor. For each of the surface hazards within this sample, more detailed studies and follow-up investigations were undertaken. The data obtained provides information concerning:

- Mining Position - No of Seams, Date Worked, Depth, Interconnected, etc.
- Shafts - Construction, filling and capping etc.
- Minewater Position - Associated water, water quality, water regime

- Potential for Pollution - Aquifers, water abstraction, water Courses
- Potential for Future Hazards - Other shafts and adits

When assessing complex mining situations, especially with long-abandoned coal mines, the plans available in the UK Mining Records Office do not always provide a complete or accurate record of mine workings. Whilst many mine owners kept plans and records of their mine workings for their own use, there was no statutory obligation to do so until the Inspection of Coal Mines in Great Britain Act 1850. This Act required mine owners to produce accurate plans of their mine workings and appointed Inspectors to examine the plans. The Act did not, however, require the mine owners to keep or deposit the plans on the abandonment of the mine even though an Office of Mining Records had been set up 10 years earlier in 1840. Whilst several Acts of Parliament were passed in the next ten years there was still no requirement for plans to be deposited until the Coal Mines Regulation Act 1872. This Act required an accurate plan of abandoned workings to be deposited with the Secretary of State within 3 months of the abandonment. It was not until the Coal Mines Act 1911, however, that there was a requirement for a qualified Surveyor to certify the position of the mine workings and a Mining Engineer to certify that no further workings had taken place after the date of the Abandonment Plan preparation.

The geology of the area in which a shaft is situated can reveal many of the features that may have a significant impact on shaft stability and the likely success of any treatment (i.e. the engineering characteristics of the soils and rocks around the shaft). However, an examination of the associated geology indicated that a potential shaft collapse is not limited solely to a particular combination of geological circumstances with hazards occurring throughout strata in which coal in the United Kingdom is normally associated.

5.2.4.1. Effect of mine water on shaft linings, fill material and concrete structures

Analysis of surface hazards resulting from past mining activities had shown that many shafts have been filled and/or capped and the fill has settled to create voids or holes in the surface. Many capping have collapsed and there have been several instances of a more catastrophic failure of the shaft lining/support resulting in massive surface craters with radial surface fissures being formed. There is little that can be done with respect to historical mining activities which develop into surface hazards other than to carry out remedial work to finally seal off the problem and ensure the health and safety of people and secure any affected properties. However, consideration must be given to how any shafts are closed presently or in the future. The choice of whether to fill and cap a shaft, or just to cap the shaft and allow it to fill with mine water is becoming increasingly important. The cost of filling a shaft at current depths and diameters in the UK would be approximately 2 to 3 million Euros. Capping the shaft alone is the more cost effective method of closure and this would allow easy access to a potentially large source of water in the future. Whichever method of closing a shaft is adopted, there is a need to consider the likely effect of mine water on shaft lining/support and type of fill material.

Effect of mine water on concrete

In order to ascertain the effect of acid mine water on concrete strength over a period of time, a set of immersion tests using simulated acid mine water and concrete cores was undertaken. A total of 100 concrete cores were made for testing purposes. All the materials used to produce the test cores were weighed and a slump test was carried out on each mix following the requirements of BS EN 12350-2:2000 ‘Testing fresh concrete – Part 2: Slump test’.

Acid mine water with various pH values was simulated by mixing 0.01molar sulphuric acid to tap water in an acid-proof container to the required pH (nominally 5). A baseline test was also conducted using tap water with a pH of 7. Immediately after immersion, it could be seen that the cores were effervescing heavily which indicated a chemical reaction had been initiated. It must be noted that mine waters of pH 5 or less are not uncommon in the UK. Further sets of samples were placed in actual acid mine water of pH 7.2 and deionised water. Table 5.2.1 shows the monthly pH values with test comments for both the acidic water and base line immersion tests. (1 = acidic water, 2 = mine water, 3 = tap water, 4 = deionised water)

Table 5.2.1: Monthly pH values for concrete core immersion tests

Month	1	2	3	4	Comments
0	4.8	7.2	7.0	7.0	Cores in acid water effervescing, cores in water have surface covered in bubbles.
1	9.0	9.3	9.0	9.2	All cores are covered with bubbles, some pitting on the surface of cores in acid water.
2	9.1	9.7	9.0	9.5	All cores with surface bubbles, slight deposit in each container base.
3	9.2	10.6	9.1	9.5	Some surface bubbles on all cores, deposit formed on base of both containers. Some pitting evident on all cores.
4	10.0	10.4	9.4	9.5	Bubbles on surface of cores not as prominent, deposit on base of acidic bucket lighter in colour and quantity than in base line container
5	10.0	10.5	9.0	9.5	No visible bubbles on any cores in each container.
6	9.1	10.5	9.0	9.4	No visible bubbles on any cores in each container.

The results show that there is a major shift to the alkaline phase within the first month of immersion for both the acidic water and base line tests and that a relatively equal value of alkalinity is established. There was evidence of a continued reaction taking place, in the alkaline phase for up to four months after test initiation which can be seen in the form of effervescence at the liquid/solid interface of all the cores. These tests also showed the need to establish a method of continuous monitoring pH, especially in the initial stages of the immersion period. Subsequently, a set of concrete cores were immersed in acidic water with an initial pH value of 5. A 'Hanna pH Turtle' was used in conjunction with a laptop pc to enable continuous monitoring and data logging of the pH values. Prior to the test, a calibration using pH buffer solutions was carried out and constant temperature monitoring was performed and input to correct the pH values during the test. Figure 5.2.8 illustrates the test set up.

Figure 5.2.8: Data Logging Facility

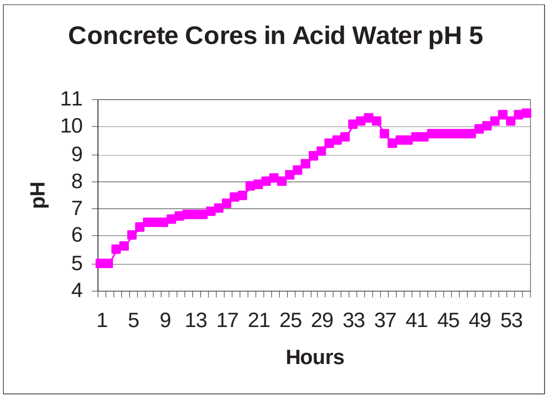


Figure 5.2.9: Graph of pH Versus Time

The monitoring software was set to sample on an hourly basis and a plot of pH versus time is shown in figure 5.2.9. It can be seen that this method is of importance in showing the rate of reaction which gives rise to a generally steady increase in pH to above 10 in the first 36 hour test period. This is followed by a sharp decline to pH 9.4 over a 3 hour period and then a steady increase towards a pH 11 at 60 hours.

Water chemistry and scanning electron micrograph and EDAX analysis of the concrete cores

After 9 months, all immersion tests were terminated and samples examined, dried and prepared for testing and analysis. The tests carried out were:

- Scanning Electron Microscope (SEM) surface analysis on concrete cores
- Uniaxial compressive strength (UCS) on concrete cores

Unsoaked concrete core (baseline sample)

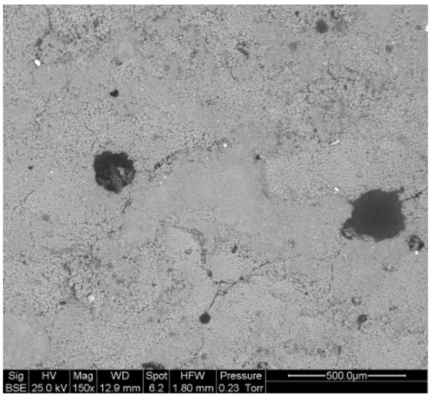


Figure 5.2.10: Unsoaked concrete core

The SEM (figure 5.2.10) shows the presence of two large macropores and some smaller pores in the concrete surface indicating that this core is likely to be susceptible to leaching reactions. Carbon is present indicating carbonates. The surface Ca:Si weight percentage ratio (given by EDAX analysis) is about 3.9 which is usual for a Portland Cement. There is an area of the surface covered in a white crystalline deposit located between the two macropores at the centre of the SEM, and also, the presence of a crystal in the macropore on the left-hand side of the SEM.

The chemical composition is complex as expected for concrete which is prepared via a complex precipitation reaction. This sample serves as the baseline to which all other samples are compared.

Concrete core soaked in deionised water

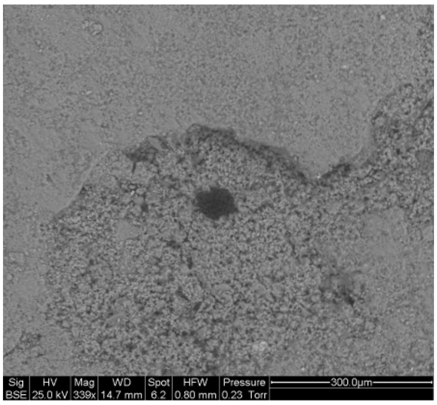


Figure 5.2.11: Concrete core soaked in deionised water

In this sample (figure 5.2.11) there is a smooth plateau area (top half of the SEM), a macropore (centre) and what appears to be an eroded area around the macropore (lower half). The actual pH of deionised water is slightly acidic due to absorption of CO_2 from the atmosphere. There are no ions initially in the water except for the hydronium ions (or protons) and OH^- which are not likely to be highly dissociated. There is a slight difference between the chemical compositions of the non-eroded and eroded surfaces as shown by EDAX. The apparent erosion has occurred around a surface macropore in the concrete and can be explained either by CO_2 bubble formation (from dissolution of carbonates in dilute acid solution) occurring near the macropore which might contribute to accelerated leaching of alkaline materials since CO_2 is a weak acid when in solution, or, the etching may be an artefact of the concrete preparation, possibly by deaeration and water-channelling during the drying/setting process of the concrete.

Analysis of the chemical formulae against that of the baseline concrete shows that there has been a complete loss of Na^+ and enrichment in Ca^{2+} which can only be due to leaching in deionised water. The loss of carbon atoms from the surface explains the bubble evolution from the surface of the concrete core observed during the experiment in terms of CO_2 formation. The increase in the calcium content at the surface is then probably due to early leaching of Ca from the dissolution of some of the $Ca(OH)_2$ and Na^+ from the concrete thus raising the pH of the solution, which causes later redeposition of the calcium as $CaCO_3$ and/or hydroxide, producing the final surface enrichment in calcium.

Concrete core soaked in tap water

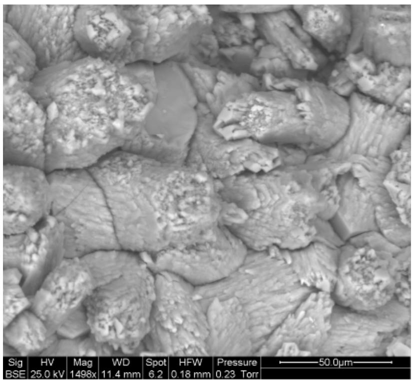


Figure 5.2.12: Concrete core soaked in tap water

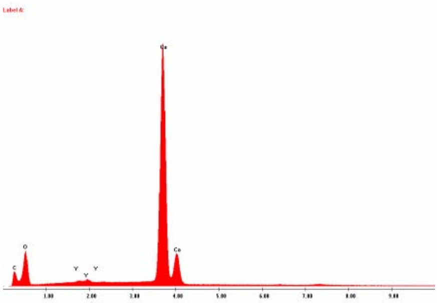


Figure 5.2.13: EDAX spectrum (tap water)

The SEM (figure 5.2.12) shows the presence of a layer of agglomerated, non-unidirectional crystals deposited on the concrete surface. The EDAX spectrum shown below in figure 5.2.13 shows only carbon, calcium and oxygen which strongly indicates that these crystals are calcite. The source of calcium for these calcite crystals is likely to be from the $Ca(OH)_2$ component of the cement as opposed to partial hydrolysis of any of the C-S-H phases and subsequent dissolution of Ca. It appears that the leaching is diffusion-controlled. The relatively soft tap water used is likely to have a 20-30 ppm Ca^{2+} content which will alter the dynamics of the dissolution of the $Ca(OH)_2$ phase slightly. However the tap water will be a good source of carbonate and bicarbonate ions for the calcite formation:

$$Ca(OH)_2 \leftrightarrow Ca^{2+} + 2OH^-$$

$$Ca^{2+} + 2OH^- + CO_2 \leftrightarrow CaCO_3(s) + H_2O$$

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \leftrightarrow CaCO_3(s)$$

Note also that:

$$Ca^{2+}(l) + 2HCO_3^-(aq) \leftrightarrow CaCO_3(s) + H_2O(l) + CO_2(aq)$$

$$Ca^{2+} + 2HCO_3^- + Ca(OH)_2 \leftrightarrow 2CaCO_3(s) + H_2O$$

Tap water has a pH of around 7. Ca^{2+} is leached from the concrete surface which causes the bulk solution pH to rise (especially at the solid-liquid interface region) and thus, facilitates the precipitation of $CaCO_3$ and/or seeded crystal growth. The system was open to the air and it is likely that CO_2 was being continually absorbed from the atmosphere. The results are in line with those of a Swedish study where mortar was exposed to drinking water over time and the mortar surface was found to contain a thick layer of calcite crystals. A closer examination of the SEM of the calcite crystals suggests that they could have started to erode, possibly due to the rise in pH and/or absorption of more atmospheric CO_2 and the presence of several dynamic chemical processes:

$$CaCO_3(s) + H_2O + CO_2 \leftrightarrow Ca^{2+} + 2HCO_3$$

As the pH becomes more alkaline, more CO_2 will be absorbed into the solution.

$$H_2O(l)+CO_2(aq)\leftrightarrow H_2CO_3(aq) \quad \text{and} \quad H_2O(l)+H_2CO_3(aq)\leftrightarrow H_3O^+(aq)+HCO_3^-(aq)$$

$$H_2O(l) + HCO_3^-(aq) \leftrightarrow H_3O^+(aq) + CO_3^{2-}(aq)$$

The yttrium was present already as a cement component mineral/compound in the starting mix materials as indicated by the EDAX analyses of the unsoaked concrete sample.

Actual acid mine water equilibrated with concrete cores

Table 5.2.2 shows the percentage ion content by weight of the acid mine water. The Langlier Index = +1.24 for this particular mine water sample is a measure of how chemically aggressive the water may be to a solid sample, and is a function of the temperature, water hardness and total alkalinity. The water is not acidically corrosive but is more likely to form an alkaline scale. The mine water shows a high ionic content: Cl^-, Na^+, free SO_3^{2-}, $CaCO_3$, free Ca^{2+}, Mg^{2+}, Fe (as solid), K^+ and residual solids. The composition and pH (7.2) resemble that of groundwater. Almost 10% of the solution contains free sulphate ions. The high chloride content of this solution is likely to pose problems with regards to cement deterioration akin to those found to pose construction material problems in the environment due to the use of de-icers on roads.

Table 5.2.2: Acid Mine Water Percentage Ion Content by Weight (pH 7.2)

Species	% ion by weight	Species	% ion by weight
Chloride	48.05	Fe (total)	0.44
Na	31.68	K	0.41
Sulphate	9.51	Nitrate	0.01
$CaCO_3$ (Alkaline upto pH=4.5)	4.81	N (ammoniacal)	0.01
Ca	3.26	Al (dissolved)	0.00
Mg	1.09	Mn	0.00
Solids (minus Fe solids)	0.73	Fe (dissolved)	0.00

The SEM (figure 5.2.14**)** shows that the proportion of the core surface analysed is mostly covered in monoclinic-type, needle-shaped crystals, some of which are arranged in dendritic groups. The EDAX data (figure 5.2.15) of this material indicates high sulphur, calcium and oxygen content. Both the crystal morphology and the empirical chemical formula suggest that this material mostly comprises $CaSO_4.2H_2O$ (gypsum). The empirical chemical formula calculated from the elemental weight percentage is Ca_{42} Y Fe Al Si_3 $S_{35.7}$ $O_{223.7}$.

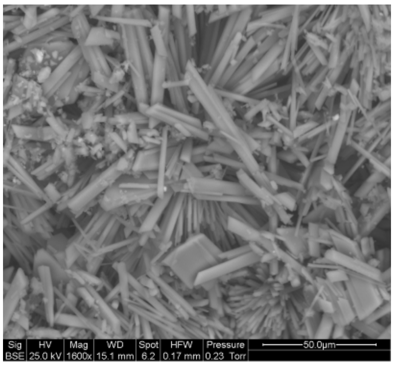


Figure 5.2.14: Mine water equilibrated (SEM)

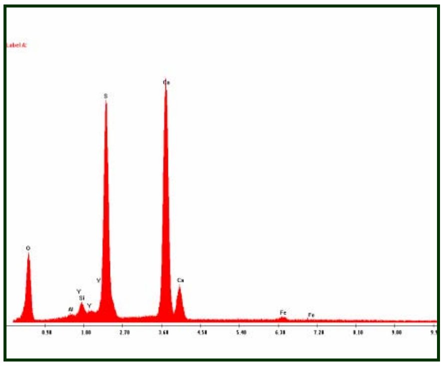


Figure 5.2.15: Mine water equilibrated (EDAX)

All elements for the formation of ettringite ($3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$) are present but the stoichiometry of the empirical formula which was calculated from the EDAX data indicates a very low content of Al (at only 0.4 weight %) whereas ettringite crystals should contain typically about 4 weight % Al. The calcium sulphate has been precipitated by reaction of the high free sulphate ion content (>1000 ppm) in the mine water with the Ca ions associated with OH^- anions by leaching of portlandite ($Ca(OH_2)$) at the surface of the concrete. At the cement/water interface the pH is considerably more alkaline (due to leached metal cations and OH^- anions) than that of the bulk solution which should serve to prevent leaching of $Ca(OH)_2$. However, the following reaction to produce the gypsum has occurred in the acid mine water containing a large proportion of Na cations:

$$Ca(OH)_2 + Na_2SO_4 + 2H_2O \leftrightarrow CaSO_4 \bullet 2H_2O + 2NaOH$$

Gypsum is a precursor for ettringite formation in concrete by the reaction:

$$3(CaSO_4 \bullet 2H_2O) + 3CaO \bullet Al_2O_3 \bullet 12H_2O + 14H_2O \rightarrow 3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$$

There is no carbon content in these crystals ruling out the possibility of any carbonate deposition or thaumasite presence. The reaction processes are extremely complex, highly pH-dependent and are in a dynamic state. As the pH increases, new chemical processes are being established and they are dynamic. CO_2 is being drawn in from the atmosphere as none of the systems were closed or manually degassed. In addition, the concrete casts are ‘young’ and possibly have some metastable calcium silicate hydrate phases within them that are not fully hydrated and can be reactive in acid mine water.

Concrete Cores Soaked in Sulphuric Acid Solution:

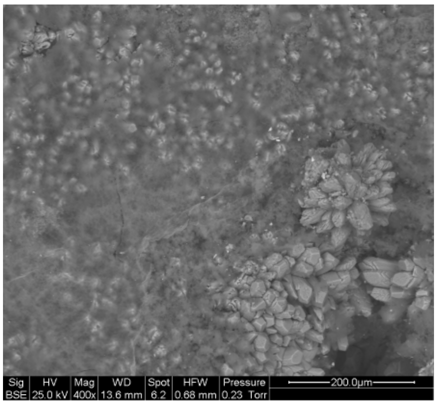


Figure 5.2.16: Concrete core soaked in sulphuric acid solution

The SEM (figure 5.2.16) of the surface of the concrete core soaked in dilute sulphuric acid solution at pH 4.8 shows nests of multi-directional white crystals deposited in the vicinity and inside the macropore, and an amorphous glassy material covering parts of the concrete surface and the surface of the macropore. The acid solution was made up in tap water. The results of concrete cores soaked in simple tap water (vide supra) clearly showed the precipitation of calcite crystals on the concrete core. In the case of the cores soaked in sulphuric acid made up with tap water, sulphate anions and carbonate/hydrogen carbonate anions are also present. The aqueous solution chemistry of these anions renders the carbonate anion to be more likely to precipitate out at the experimental pH. This appears to be verified by the EDAX analysis which shows no sulphur content in the crystals analysed at the perimeter of the macropore. There is no evidence of gypsum or ettringite formation on the analysed surface. In addition, at pH 4.8 in the simulated acidic water, there is considerably less SO_4^{2-} present in solution than for the actual acid mine water which contained over 1000 ppm sulphate ions, and consequently, there was no approach to the solution saturation value for precipitation of gypsum. The acid reaction has caused crystal formation to preferentially occur near a macropore as seen in the SEM. This is due to the fact that leaching of $Ca(OH)_2$ and metal cations has occurred in and around the pore and the solution in the pore has acquired a higher zonal pH thus causing preferential precipitation of minerals. The chemical composition of these crystals as given by the EDAX analysis is: $Na_2KCa_{17.3}Mg_{2.3}Al_5Si_{5.7}C_{15.3}O_{126.3}$.

The complex formula shows predominantly calcite with some mixed-metal aluminosilicates (zeolitic materials) and possibly calcium aluminates (which also have a fibrous needle morphology). There is also the presence of a covering of glassy amorphous material on the surface of the cement, on some of the crystals and covering the macropore, possibly due to acid attack of the cement paste/aggregates to leach out reactive silica into solution and which have then reacted with leached alkali metal cations to form the gel on the surface of the sample. This phase has deposited on the surface after the crystal formation as the pH continued to rise until the final pH equilibration. This material was not found in the other core samples contacted with various solutions and could be some form of amorphous siliceous gel. Note that this reaction has occurred in a low sulphate concentration. Above pH 9, it is expected that reactive (amorphous) silica may start to leach out from the concrete. A further analysis of this material needs to be performed before any firm conclusion can be made about its nature or origin, as it could be indicative of an alkali-silica reaction.

5.2.4.2. Effect of mine water on shaft fill materials

The two fill material types tested were granular crushed gritstone and coal measure tip material. The gritstone consisted of angular pieces of coarse grained yellow-grey material which appeared to be well cemented and very competent material. The coal measure tip material consisted of shales, mudstone, sandstone and some coal. The immersion test carried out on both sample types using pure water of pH 7 and acidic water of pH 5, consisted of the following:

- Long term immersion test to determine the reactive period using pure water and acidic water.
- Base line test using pure water and left unchanged which also simulates stagnant conditions.
- Base line test using pure water but changed on a monthly basis to simulate some level of flow.
- Acidic water test, left unchanged to simulate stagnant conditions.
- Acidic water test, where pH is re-established on a monthly basis to simulate some level of percolation through strata.
- Acidic water test, where acidic water is changed on a monthly basis to simulate some level of flow of acidic mine water.

After 9 months, all immersion tests were terminated and samples examined, dried and prepared for testing and analysis. The tests carried out were:

- SEM surface analysis on granular material
- Weight loss analysis on all immersion tested granular material

Examination of the material competency showed that, in every test case, the fractions of gritstone, under all test variations, maintained general competency. This also applied to gritstone fractions tested over several months.

The Coal Measure tip material, under all test variations, turned to a mud layer at the base of each test container, with coal, sandstone and plant material remaining generally unchanged, after 24 hours. This was the case for both pure water and acidic water tests. The long term tests carried out on each material type, using both pure water and acidic water, have shown in all cases that after one month immersion period, all pH levels tended to neutral. Table 5.2.3 shows the pH values for each of the long term tests. The test reference numbers refer to the test method as follows:

Test 1 Immersion of gritstone in pure water

Test 2 Immersion of Coal Measure tip material in pure water

Test 3 Immersion of gritstone in acidic water

Test 4 Immersion of Coal Measure tip material in acidic water

Table 5.2.3: Change in pH with Time

Test	1h	6h	12h	1d	2d	4d	5d	7d	12d	1m	2m	3m	4m
1	7.0	6.9	6.8	6.7	6.8	6.9	6.9	6.9	6.9	7.0	7.0	7.1	7.1
2	7.0	6.9	6.8	6.8	6.8	6.8	6.9	6.9	6.9	6.9	7.0	7.0	7.1
3	5.1	5.4	5.7	5.9	5.8	6.0	6.1	6.4	6.8	6.9	7.0	7.0	7.3
4	5.1	5.2	5.7	5.8	6.1	6.5	6.4	6.6	6.9	7.0	7.1	7.1	7.2

Key: h = hour, d = day, m = month

The results also show that there is no alkaline phase and that the trend for immersion tests in pure water is generally to remain neutral and the acidic water immersion tests to develop neutrality. All the other immersion test variants also demonstrated the trend to neutrality towards a period of one month irrespective of the number of changes on a monthly basis (at 4 changes). Constant neutral conditions were achieved at 5 months and up to test termination at 9 months.

SEM and EDAX analysis on samples of granular shaft fill material soak tests

Samples of all test representations were scanned and analysed for indications of chemical attack. All the gritstone samples showed no evidence of surface change or deposition of material. Samples of coal measure material were scanned and analysed. Any logical analysis was not possible due to the complex nature of the material.

Weight analysis and general observation of the granular material

On termination of the soak tests of the various fractions of gritstone and Coal Measure material, all liquid from the containers was carefully removed with a suction pipette. All the samples were then allowed to air dry to constant weight. There were no major differences between the various test methods for the gritstone fractions and those of the Coal Measure material. The generalised results are summarised as follows:

- All tests demonstrate loss to solution & size reduction
- Gritstone – lost 2-3% weight
- Gritstone – showed material reduction to sand generally 4% by weight
- Coal Measure Material – 4-6% weight
- Coal measure material – total loss of void space

Loss of material to solution plus size reduction was expected with the coal measure material but was unexpected with competent gritstone. This is used as a standard shaft fill material. This also demonstrates the requirement for further studies in this area.

Scanning electron microscope tests did not show evidence of mineral change. A more detailed study is required with this and more types of material to obtain absolute assurance of material to withstand corrosive effects of mine waters.

5.2.4.3. Test results summary

The concrete core tests demonstrated that immersion tests in acidic water resulted in change through neutrality to an alkaline phase in days. Furthermore, reaction continued in the alkaline phase which was demonstrated by bubbles being formed at the solid/liquid interface. Cores immersed in pure water tended to alkalinity with similar maximum and end of reaction values as the acidic water immersion tests.

Both gritstone and Coal Measure tip material showed no alkaline phase during any of the immersion tests. All tests demonstrated a tendency to neutrality after one month.

Geochemical and SEM analysis of the concrete samples showed:

- Shaft linings with any form of cement will be subject to corrosive attack
- Attack will be instantaneous at a liquid solid interface
- Attack continues in both the acid and alkaline phase in stagnant and continuous flow conditions
- Formation of complex sulphates and silicates enhances attack in the alkaline phase

Geochemical and SEM analysis of coal measure shaft fill material showed:

- Chemical reactions are numerous and complex
- Material competency is reduced in days
- Volumetric reduction is approx 30%
- A high number of historical surface hazards result from settlement of this type

Geochemical and SEM analysis of gritstone shaft fill material showed:

- No evidence of surface chemical reactions or surface deposition
- Reduction in weight of granular material by 3% after soak period
- 3% conversion to fine sand – possibly due to weathering of gritstone.

5.2.5. Conclusions

The tests on concrete showed that there was a reactive process from acidic conditions through to the alkaline phase. Although these tests were not intended as a major research programme, indications are that any water flowing or in stagnant conditions will attack lime based materials such as concrete or mortar in brick lined shafts. Weathering will also have major detrimental effects on such shaft materials. Further work is required to give a wider analysis and to relate this work to actual field samples where possible. Methods of examining shaft lining competency especially in submerged/filled conditions are required. More work is required to investigate the relationship of these initial findings and the numbers of abandoned mine shaft collapses and crown holes at the surface, recorded in the UK.

Competent shaft fill materials are required to ensure that no voids form as a result of corrosion from mine water. Historical evidence has shown that coal mine waste material, used for shaft filling purposes has caused many problems due to void formation and surface subsidence resulting from settlement and loss of competency with contact to water. The tests on granular gritstone showed 3% loss of competency by weight. In a 1000 meter shaft, this may result in a considerable void space forming below the shaft cap. It is essential that careful choice of fill material is made to ensure void reduction and prevent potential lining and/or ground failure.

Further studies are required to determine competent fill materials and in-situ treatments to prevent corrosion of shaft linings, support, fill material and cappings.

5.3. Near surface aquifer impacts caused by deep hard coal mining and shallow lignite mining

5.3.1. Introduction

The potential contamination of an aquifer resulting from the mining of deep hard coal and shallow lignite is a problem that affects several European coalfields. The research undertaken focused on the potential effect from deep hard coal mining on the Permo-Triassic aquifers overlying the Durham and Nottinghamshire Coalfields in the UK and the Saar-Loraine Coalfield straddling the French German boarder and shallow lignite mining concentrated in two areas, the Megalopolis and Ptolemais fields, in Greece, both of which overlie Karstic Limestone aquifers.

In each of the mining areas the hydraulic connection between the mine workings and the aquifers were assessed and in the case of the shallow lignite fields the connection between surface water courses and backfilled voids or spoil heaps. Historic and current data was obtained on water quality in the mines, aquifers and surface water courses, including trials of in-situ chemical measurement probes. In the Durham Coalfield in the UK data was also obtained from an area where contamination of the Magnesian Limestone aquifer above an area of deep hard coal workings had previously occurred to help in assessing the mechanism involved and for comparisons with the results of modelling work carried out on the mixing of mine waters with aquifer water.

Modelling work was also undertaken in the Durham Coalfield on the development of layering within a mine of different mine water qualities and the impacts of this layering of varying rates of mine water pumping. The impacts of mine stability on the potential hydraulic connection between aquifers and mine workings water were also assessed.

5.3.2. Potential hydraulic connections and data acquisition

5.3.2.1. Durham and Nottinghamshire deep mined hard coal

Hydraulic connections

Previous studies of mine plans in the Durham and Nottinghamshire Coalfields had sub-divided the coalfields into either isolated areas or areas with limited hydraulic connections with adjacent blocks. The principal aims of this research were to assess the hydraulic connections between mine workings and the aquifers and to determine the quality of mine water that could flow through these connections.

The identified hydraulic connections in the Durham and Nottinghamshire Coalfields fell into three main categories:

- Direct Mining Connections via shafts or adits, underground drivages or areas of coal extraction connected to aquifers (very high permeability).
- Mining induced fracture permeability (intermediate permeability).
- Natural strata and fracture permeability (intermediate to very low permeability).

Examination of mine plans, water inflows to the mines and piezometric heads in the mine workings and aquifers identified the principal risk to aquifers in the Durham and Nottinghamshire coalfields as being from a combination of direct mining connections and post mining changes in piezometric heads together with the hydraulic gradients that develop in the mine workings and aquifers. Figure 5.3.1 shows and example from an area of Durham with existing aquifer contamination, of a direct mining connection between a longwall face and the Permian strata that subsequently provided a high permeability hydraulic pathway following recovery in the piezometric heads in both the aquifer and mine workings. Similar direct hydraulic connections between abandoned mine workings and overlying Permo-Triassic aquifers were found in areas where mine water levels are still recovering and where the future difference in piezometric head between the aquifer and the mine workings would ultimately result in a significant flow of mine water into the aquifer.

Water quality and inflow data

Data obtained on the quality and volumes of water flowing into previously defined mining blocks comprising the Durham and Nottinghamshire Coalfields showed considerable variation and flow even within a single mining area. The various mine waters identified fall into were:

- Type A. Shallow mine waters with low chloride level (< 1000 mg/L), low iron concentrations (< 10 mg/L) and correspondingly low sulphate concentrations (< 1000 mg/L).
- Type B. Shallow to Intermediate depth mine waters, containing relatively low chloride levels, generally below 5,000 mg/L, these waters are more acidic with variable iron concentrations, generally in the range of 10 to 100 mg/L with suphate levels related to the iron concentrations.
- Type C. Deep offshore saline mine waters in Durham with very high chloride levels in the range of 100,000 to 200,000 mg/L, generally low concentrations iron in the range of 1 to 50 mg/L and with high concentrations of sulphate, sodium and calcium.
- Type D. Deep inland saline mine waters in Nottinghamshire with chloride levels in the range 80,000 – 120,000 mg/L, generally low concentrations of iron in the range of 1 to 60 mg/L and with barium replacing sulphate.

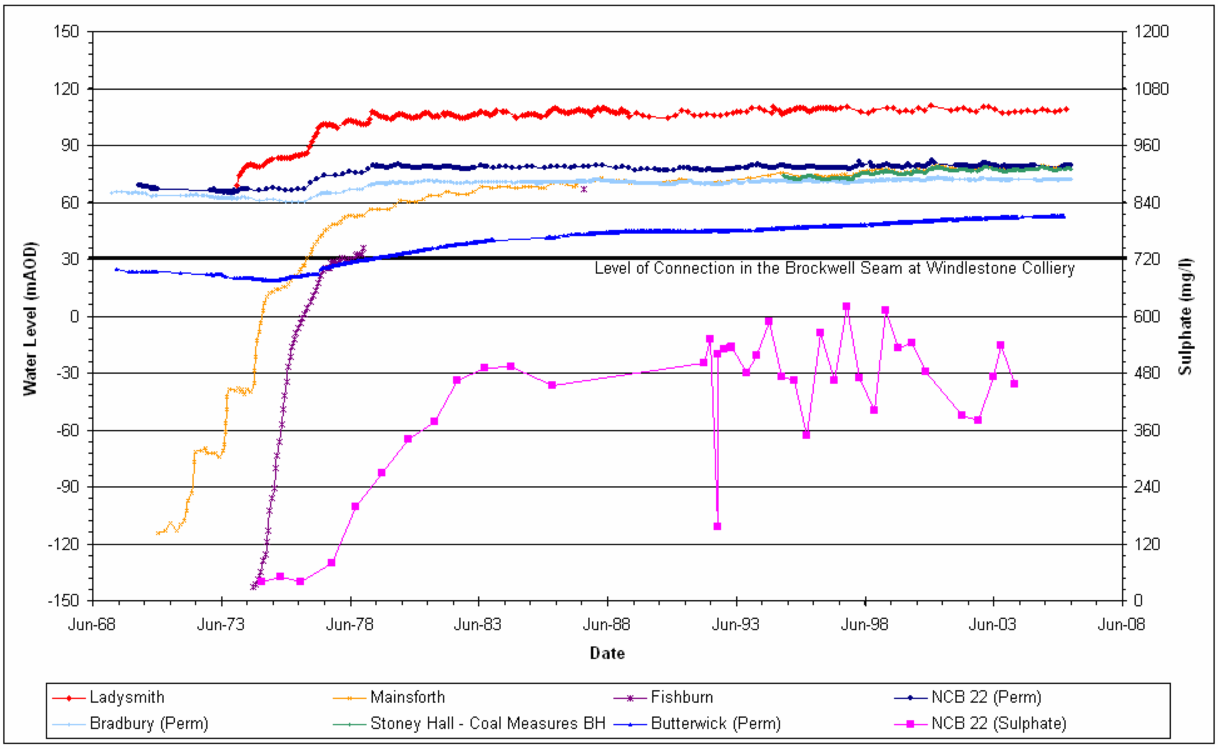


Figure 5.3.1: Mine water and Permian aquifer water levels showing the start of Permian aquifer contamination in the Butterknowle Area of the Durham Coalfield.

Mine water inflow rates were also very variable ranging from a few litres per second for the high salinity strata waters in the deepest Nottinghamshire mines to rates of over 100 L/s for the mine working under the evaporate deposits below the North Sea in Durham.

Historic data on the reported contamination of the Permo-Triassic aquifer in Nottinghamshire and the Permian Magnesium aquifer above mine workings in the Butterknowle area of Durham were also researched to determine the source of the contamination and to aid in the modelling of potential mine water contamination on coalfield areas still recovering. The aquifer waters in Nottinghamshire showed slightly elevated levels of chloride that were assessed as being caused by either surface discharge of pumped mine water prior to closure or surface use of salt. The aquifer waters in Durham showed clear indications of contamination by mine water, principally elevated levels of sulphate and calcium but with only slight increases in chloride and no significant increase in iron. Figure 5.3.1 shows the increase in sulphates in the Permian aquifer at NCB BH 22 following contamination by mine water.

5.3.2.2. Megalopolis and Ptolemais lignite fields

Hydraulic connections

Elevated concentrations of various parameters have been identified in both groundwater and the surface ponds associated with the Thoknia waste dump area (table 5.3.1). The main water bodies that may be affected by contaminated water from the ponds and the possible paths of contamination are:

- Direct discharge of the mine water of the ponds into the rivers
- Surface outflow into the rivers
- Hydraulic connection with aquifers developed in the sediments through permeable layers
- Creation of hydraulic connection through activation of sinkholes.

Water quality and inflow data

The water quality data obtained for the Megalopolis lignite area is summarised in table 5.3.1 below.

Table 5.3.1: Statistical analysis of surface and ground water chemistry in the Megalopolis Area

TABLE 1. STATISTICAL ANALYSIS OF GROUND AND SURFACE WATER IN MEGALOPOLIS AREA.

	Sample ID	pH	EC µS/cm	TDS mg/l	Ca ppm	Mg ppm	SO4 ppm	Mn ppb	Ba ppb	Mo ppb
RIVERS	MIN	7.64	250	180	6.4	4.65	19.5	2	24	2.08
	MAX	8.42	1300	1010	229	25.1	573	64	70.3	583
	AVERAGE	8.04	638.04	415.87	94.04	14.43	134.67	11.90	46.87	242.74
PONDS I-II IN THOKNIA	MIN	6.9	840	570	118	10.9	308	2	50.8	730
	MAX	8	4370	3120	684	64.3	1807	2154	113	11110
	AVERAGE	7.58	2113.85	1733.85	350.77	34.31	1050.77	434.42	86.25	4487.33
PONDS IN OTHER MINES	MIN	6.85	430	102	5.8	1.49	82	2	18	5
	MAX	11	3660	2810	580	129	1650	2090	205	547
	AVERAGE	7.77	1815.72	1273.90	299.71	52.59	728.00	472.50	80.90	104.96
KARSTIC AQUIFERS	MIN	7.65	380	230	75	8.39	16.1	2.2	20	10
	MAX	8.1	550	330	87.8	17	37.3	112	65.3	12.6
	AVERAGE	7.99	487.00	293.33	81.88	14.45	29.58	46.90	34.40	10.98
DEEP AQUIFER IN THOKNIA	MIN	7.2	570	360	34.8	12.1	4.9	4.1	52.4	5
	MAX	8.1	1130	730	210	20	228	538	503	32.5
	AVERAGE	7.63	882.00	582.00	148.68	15.97	97.86	158.07	209.12	18.78
GROUNDWATER ARROUND WASTE DUMP	MIN	6.60	540.00	450.00	11.80	11.60	0.39	59.00	0.12	5.00
	MAX	8.90	2940.00	1710.00	506.00	91.70	1181.00	5082.00	884.00	97.70
	AVERAGE	7.65	1504.11	950.77	186.71	29.44	180.94	687.04	242.73	31.64
GROUNDWATER IN WASTE DUMP	MIN	6.41	870.00	580.00	115.00	0.30	86.70	14.00	4.00	5.00
	MAX	9.40	4980.00	3200.00	1030.00	167.00	2080.00	4792.00	250.00	5800.00
	AVERAGE	7.46	2587.91	1959.80	459.94	73.22	1224.23	772.51	39.94	616.94

The maximum average value

The second maximum average value

Minimum average value

The second minimum average value

5.3.2.3. In-situ measurements of quality water

The areas of mining in the UK studied for potential contamination of aquifer had been abandoned for a number of years and the only access to the mining void was via open shafts or boreholes. Therefore, in-situ measurement of water quality had to rely on either sensors connected by cable to surface, or discrete water samples taken either from pumped water or sampled as part of the shaft or borehole wire line logging operations. Initial risk assessments identified chloride in the East of Wear area in Durham as having the highest impact on the overlying aquifer and the use of in situ measurement of chloride and other associated parameters was investigated. Four commercially available multi-function probes for in-situ water chemistry analysis were identified (table 5.3.2). However all had limits to the depths of water in which they would operate and in the range and type of sensors. The probe with the greatest range of sensors and the greatest operating depth below water (70 m) for chloride measurement was the Troll 9000. Three Troll 9000 in-situ sensors were purchased and sited in the East of Wear area, one in the mine shaft to be pumped at Horden, one in a Northumbrian Water abstraction borehole in the aquifer (Hawthorn Pumping Station) and one in an Environment Agency aquifer water quality monitoring borehole. The probes used measured pH, oxidation reduction potential (ORP), conductivity dissolved oxygen, chloride, temperature and water pressure.

In all the open mine shafts in the area of potential aquifer contamination in Durham, and the shafts where aquifer contamination had previously occurred fluid conductivity and temperature logs together with discrete sampling of the water column was carried out at regular intervals to check on the quality and layering and for comparison with the in-situ probes.

Table 5.3.2: In situ chemical monitoring probes, the parameters measured and their advantages and disadvantages

Instrument	Parameters	Advantages	Disadvantages
Minitroll	Water level Temperature	- 11.5 yrs of Power - Samples from 20 min to 1 sec intervals - Data logging with 1 MB memory - Onboard power - Quick Connect cable - Monitors water level changes as small as 1mm with 15 PSI sensor.	- Only a maximum 30m length of cable - Only measures water level & temperature
Troll 9000	PH/ORP or ISE D.O Turbidity Conductivity Salinity Nitrate Ammonium Chloride Depth Temperature Barometric pressure	- 4 MB memory - Stores more than 1 million data points the sensor remembers calibration settings - It has several key parameter options - Designed for extra long-life & minimise external interferences - Operates up to a depth of 70m for Chloride - Has a maximum depth range of 211m	- More expensive than the Minitroll - The nitrate and ammonium probes only work to a depth of 14m.
Multi – Tech	Depth Temperature Conductivity D.O PH Turbidity Salinity	- It is portable - Ion selective electrode (ISE) can be fitted. - Can programme sampling for 5 sec intervals up to 99 hrs.	- Only operates up to a maximum depth of 20m - Only a 30 day life – time on a fully charged battery (when logging at 15 min intervals)
YSI 556 Multiprobe System	Depth Temperature Conductivity D.O PH/ORP Turbidity Salinity TDS Barometer	- Stores 49,000 Data sets - Simultaneously measures D.O, pH, conductivity, temperature and ORP - Field replaceable electrodes - Records calibration data in memory	- Only operates up to a maximum depth of 20m

5.3.3. Modelling of chemical reactions resulting from mine water mixing and pumping

5.3.3.1. Mine water quality layering

The layering of mine water qualities has been recorded in several UK coalfields where mine water levels have recovered to surface discharge or near surface. The layers of mine water reflect the different origins of the water entering the mine, the amount of mixing of these inflow waters and the degree of contamination of the waters from within the mine. The layers are observed in open mine shafts with the boundaries of the layers generally being coincident with insets in the mine shafts, reflecting the flow paths within the mine and the origins of the various mine waters.

The denser, more highly contaminated mine waters are generally observed towards the bottom of the water column with the less contaminated waters near surface. Figure 5.3.2 shows an example of the fluid conductivity and temperature logs together with the results of the discrete sampling for iron showing the mine water layering in Dawdon Colliery Theresa Shaft. The development sustainability of layers of mine water with less contaminated mine water at surface has significant implications both to the risk of aquifer contamination and use of pumping to lower piezometric heads in the mine workings to prevent aquifer contamination.

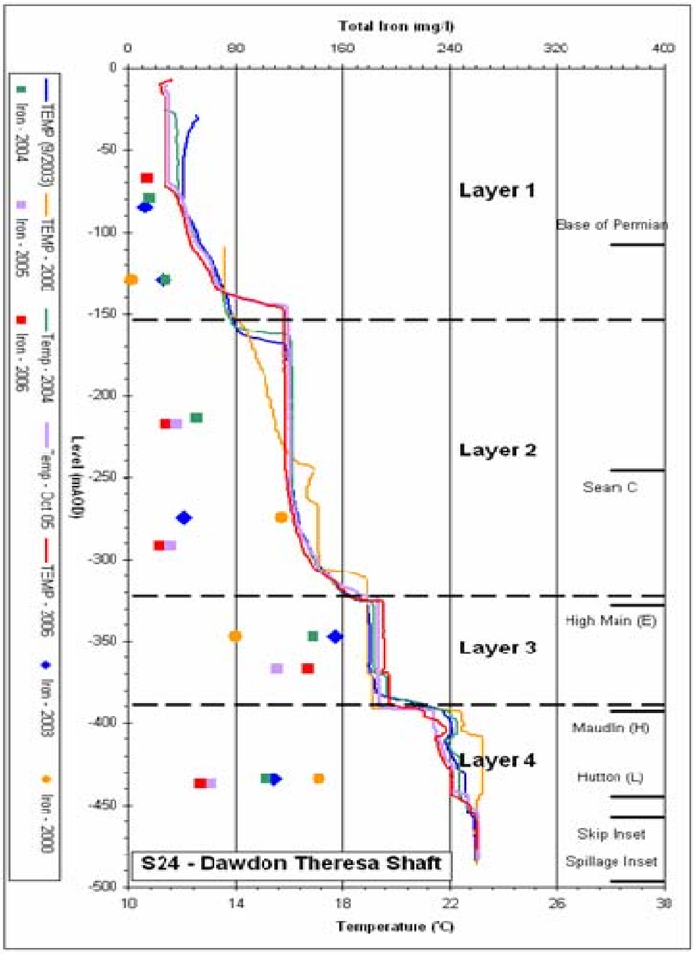


Figure 5.3.2: A Graph showing the temperature logs of Dawdon Theresa shaft water over time and the total iron concentrations from the discrete water samples

The East of Wear area in Durham (UK)

The East of Wear area I Durham is an isolated block of mine workings that dips east from surface outcrop under the Permian aquifer and out under the North Sea and the Permian evaporite deposits. The hydraulic gradients in both the aquifer and the mine workings are generally east towards the coast. The mine water recovery and quality is monitored at several shafts including four deep coastal shafts, Horden, Easington, Dawdon and Hawthorn (figure 5.3.3). Water enters the mine workings from four separate sources with varying piezometric heads.

- Surface watercourses and superficial deposits above shallow mine workings. Piezometric head approximately 50 to 100 m above sea level (ASL).
- Permian Magnesian Limestone principally via shafts. Piezometric head approximately 0 to 20 m ASL.
- Coal Measure aquifers via natural or mining induced fractures. Piezometric heads are very variable.
- Permian evaporite deposits via mining induced fractures. Piezometric head approximately sea level.

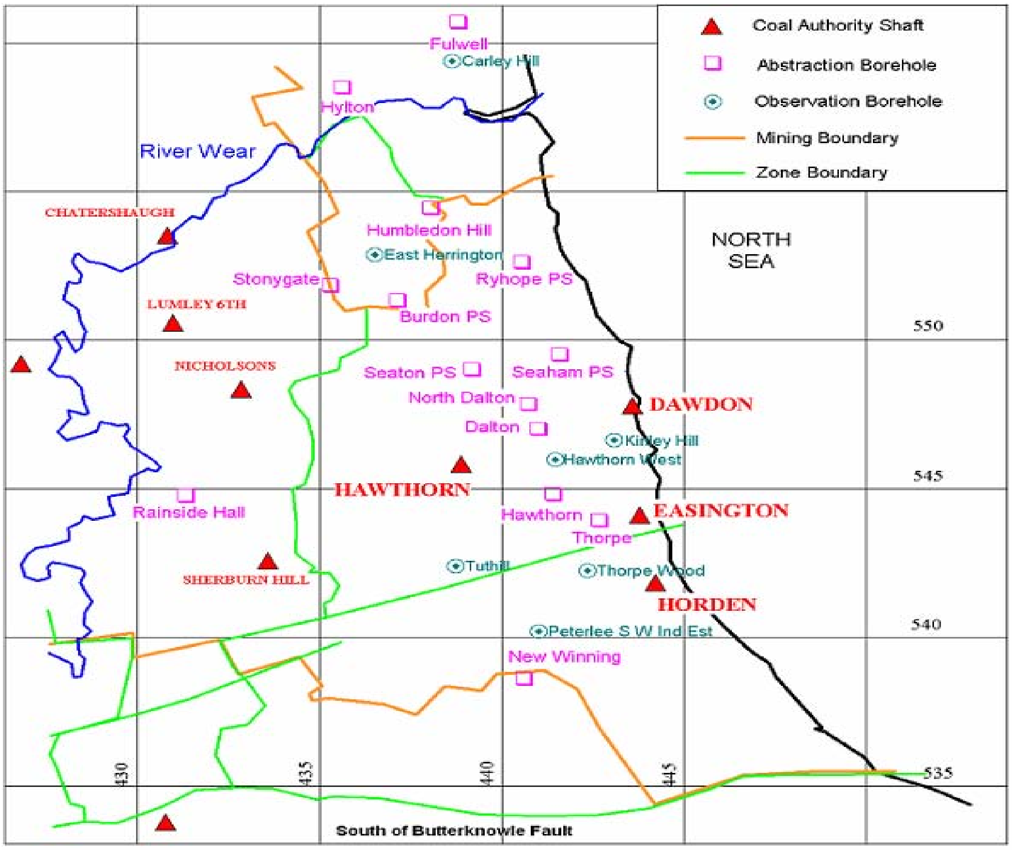


Figure 5.3.3: Plan of Durham Coalfield (East of Wear) showing the mining areas, Coal Authority open shafts, Environment Agency monitoring sites and Northumbrian Water abstraction wells.

These inflows gave rise to types A, B and C types of mine water noted in section 5.3.2.1. The mine water quality layering during recovery in the East of Wear area was made up of a shallow layer principally derived from the Permian, then intermediate layers with gradually increasing amounts of types B and C, with principally type C at the base of the shafts. The sources of mine water were known and their piezometric heads but the flow paths through the workings and percentage of flow from the various sources were conjectural due the presence of dams and the age of the mine workings.

To reduce the inflow of the high chloride mine water which poses both a risk to the aquifer and limits the mine water treatment options, the water level in the mine workings had to be raised as near as possible to sea level but still below the piezometric head in the aquifer. To control the mine water in the workings below to sea level and assess the impact on the mine water layering an extended pumping test was carried out with stepped increases in abstraction. The impacts of the pumping on the mine water quality layers were monitored at the open shafts and modelling of the mine water quality undertaken to assess the percentage of the different mine water types in the water abstracted at the different flow rates and determine the likely flow paths.

5.3.3.2. Impacts of mine water pumping on mine water quality layering

The extended mine water pumping test was undertaken at Horden Colliery using two 75 L/s submersible pumps on separate rising mains to give a range of abstraction rates between 50 and 150 L/s. The pump inlets are situated at 107 and 112 metres below surface. The mine water abstracted is treated to remove all iron by means of a temporary active treatment plant and then discharged directly to the sea. To date the pumping has been carried out at 35 to 50, 60 to 75 and about 125 L/s, although in each step operational problems resulted the pumping having to be temporarily stopped or the abstraction rate reduced. In addition to the mine water quality temperature logs were used to aid in the interpretation of flow paths. The effects of the mine water pumping at Horden on the concentrations of iron and chloride at the open shafts at Easington, Dawdon and Hawthorn are shown in table 5.3.3. The overall impact of pumping was to cause a marked increase in iron and chloride concentrations at Horden when the pumping rate was increased above 50 L/s. The pumping also resulted in the flushing of high salinity mine waters from the inland workings below the aquifer as represented by the changes at Hawthorn.

Table 5.3.3: Concentrations of Iron and Chloride within the mine water layering at Horden, Easington, Dawdon and Hawthorn Mine Shafts during different Abstraction Rates at Horden.

		Pre-Pumping 2000-2003		**35-50 l/sec 2003-2004**		**60-75 l/sec 2005**		**125 l/sec 2006**		**Comments**
Horden PS	5. Layers	Fe	Cl	Fe	Cl	Fe	Cl	Fe	Cl	Significant increase in Fe and Cl when pumping raised above 50 l/sec. Marked temperature change (inflow) at Low Main inset.
	1.	0.2	355	N/S		N/S		N/S		
	2.	3.16	3,500	17.1	3,570	157	12,100	148	18,000	
	3.	E30	E4,500	33.5	4,480	177	35,900	171	34,600	
	4.	56.7	5,060	73.4	7,600	136	33,300	108	39,400	
	5.	27.1	45,500	N/S	N/S	N/S	N/S	N/S		
Easington	5. Layers									Little change in water quality with pumping. Mine water by-passing Easington.
	1.	Fluid				1.6	E1,100	0.8	1,100	
	2.	Conductivity				99	30,900	102	30,100	
	3.	and		N/S		111	31,200	134	37,700	
	4.	Temperature				157	41,400	151	41,300	
	5.	Logs only				33	46,200	64	48,100	
Dawdon	4. Layers									Reductions in both iron and chloride concentrations over time in lower layers. Inflow of shallow waters.
	1.	11.8	2,910	14.3	2,370	E15	E2,400	13.3	2,380	
	2.	41.4	3,580	50.5	29,700	33.5	25,100	27.2	23,500	
	3.	155	38,800	137	40,300	111	37,600	133	31,900	
	4.	109	65,200	102	69,800	61.3	65,000	52.9	23,900	
Hawthorn	5. Layers									Marked reduction in chloride concentration and slight reductions in iron. Changing to two layer system related to main roadway.
	1.	0.98	54	0.25	43	E1.0	E50	0.17	138	
	2.	192	31,600	134	30,000	E160	E10,000	E130	7,940	
	3.	191	46,900	136	38,600	162	12,100	131	8,630	
	4.	44.9	57,800	13	37,700	156	19,200	139	E8,630	
	5.	N/S	N/S	N/S	N/S	N/S	N/S	19.3	38,000	

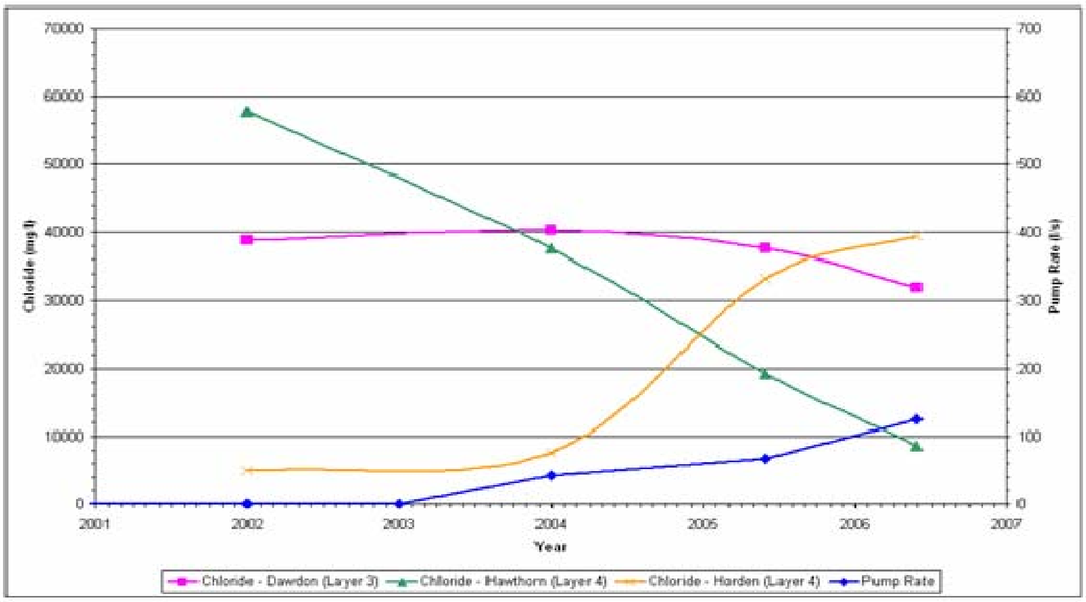


Figure 5.3.4: Changes in chloride concentrations within mine water layers at Dawdon, Hawthorn and Horden with increasing pumping rates at Horden Pumping Shaft.

5.3.3.3. Modelling of water quality mixing using PHREEQC

The PHREEQC geochemical modelling has been used both to investigate the potential impact of various mine waters on aquifers and surface waters (Megalopolis, Ptolemais and Durham) and to assess the proportions and sources of mine water in mine water quality layering (Durhan East of Wear Area). The latter work being linked to the DSK/DMT modelling of mine water chemistry changes during recovery.

The PHREEQC program (Parkhurst et al 1995) was designed to investigate geochemical processes in aquatic systems. It is capable of simulating a wide range of geochemical reactions including the mixing of waters, addition of net irreversible reactions to solution, and dissolving and precipitating phases to achieve equilibrium with the aqueous phase. The model is able to consider the irreversible dissolution of solid phases under unsaturated conditions. It is also able to use the concept of partial equilibrium to maintain the solutes at saturation with respect to any secondary phases.

The PHREEQC model uses recorded, solution ion concentration data to determine saturation indices for the soluble solution ions. From this information PHREEQC is able to determine the potential for any precipitation of secondary mineral and amorphous phases from within the original solution chemistry under any specified environmental conditions. In order to do this, the model has to balance the chemistry between the secondary, aqueous and gaseous phases taking place by using a series of geochemical reactions.

Megalopolis and Ptolemais lignite fields.

In the Megalopolis Lignite area the PHREEQC modelling was designed to:-

1. To predict the water quality of the lake that will be formed in the final void after the end of the exploitation.
2. To investigate the influence of the current contaminated water in the ponds of the dumping area on :-
    - Deeper aquifer in the permeable sediments below the bottom of the mine
    - The main karstic aquifer which forms the basement of the basin
    - The River Alfios which flows adjacent to the dumping area

The modelling methodology at Megalopolis was to use the water found in Ponds IA and Pond II where the highest values in SO_4^-, Ca^{++}, Mg^{++} and the trace elements, mostly in Mo^+, were observed, and mix these waters with the water from the deeper aquifer, the karstic aquifer and the River Afios. In each case the result of mixing of water type A with water type B at different proportions was investigated. Both samples were equilibrated with CO_2 and O_2 and the value of redox calculated because of the shallow open nature of the system. The concentrations of most ground water samples in Megalopolis have high values of Ca^{++}, Mg^{++} supporting the above assumption. The impact of the reaction of calcite and dolomite in the mixing water was also investigated and the effect of the kinetic reactants on dispersion. Also calculated was the composition of the water in Pond1A resulting from the mixing of rainfall with the surface water of the pond.

- Firstly the water from the deeper aquifer was mixed with water from the ponds at varying rates (95% : 5%, 97% : 3% and 99% : 1%). Only a small percentage of contaminated water was used because there is no obvious hydraulic connection between these two types of water. The composition of the new mixture is similar to the initial solution sample at monitoring site YGB. Some of the elements as Ca and Mg, had increased, as would be expected, as the sample was equilibrated with calcite and dolomite. An increase in the concentration of N(5) was also observed. A higher value in pH was observed, which is an indication of the alkaline environment
- Secondly, water from Alfios River was mixed with water from the ponds and the main karstic aquifer at different rates (90%:5%:5% and 95%:4%:1%). The results gave water similar to the initial river quality before mixing with only very small variations, the water is still very good quality with a pH value of 7.4 and the main anions and cations have similar concentrations with the initial water. Only the concentrations of Zn, Mn, and Na have higher values.
- The general conclusion from the modelling is that there are no significant impacts in the waters of the Ponds on the Alfios River or on the karstic and deep aquifers.

In the Ptolemais area, the aim of the modelling was to assess the influence of the coal mines on the quality of the water in the River Soulou. The River Soulou flows through the mining area from south to north. The water in the stream comes mostly from the mines. The quality of the Soulou water was examined where it comes into the mining area in the South field. In this region the River Soulou flows over carbonate strata, mainly marls and clays, and these elements were taken into consideration for the modelling. In the Ptolomais area the main pollution problems are the concentrations of $NO^-_{3,}$ NO^-_2 and NH_4^+ resulting from the agricultural activities in the area.

In the Ptolemais area the PHREEQC modelling involved the mixing of three samples with equal ratio (33%÷33%÷33%), the samples used were from one of two pumping stations, one of the ponds of the mines and the River Soulou. The percentages used reflected the approximate proportions of the different waters in the river downstream of the mines. The results of the modelling were:-

- The water in the River Soulou remained very good quality with a pH value of 7.35.
- After the modelling the River Soulou has lower concentrations of Ca, Mg, Na, S, Si than in the initial river water.
- The concentrations of N and Cl are higher values than in the chemistry of the initial river water.

The general conclusion is that there are no significant impacts from the mine water in the ponds on the ground water or even to the surface waters of Soulou or Alfios Rivers when the mine water is directly discharged.

The Durham coalfield East of Wear Area

The pumping of mine water to control the piezometric head in the workings below that of the overlying Permian aquifer was expected to have an impact on the mine water quality layering developed within the East of Wear area. To determine the optimum site or sites for pumping and treatment the potential long term changes in mine water quality and in particular chloride and acidity levels needed to be assessed. Modelling using PHREEQC and the mine water qualities observed in the various mine water layers prior to pumping showed that a simple proportioning of mine water qualities from the various layers within Horden Shaft only worked at low flows (35-50 L/s). As soon as the flows increased above 50 l/s the modelling of the various layers at any of the monitored shafts could not be used to replicate the quality of the mine water that was being pumped. At this stage the modelling always produced a water with too high a salinity and too low a concentration of iron. Therefore, the pumping had to have induced an increased flow into the pumped shaft (Horden) from a source with a water quality that was different to the initial mine water layers at Horden and from the initial and post pumping layers at Easington, Dawdon and Hawthorn. The type of water flowing to Horden shaft had to be type B water from intermediate depth with low salinity but with moderate to high iron concentration.

The geophysical logging and discrete sampling of the layered mine waters had shown that the greatest impact on the mine water layering was at Hawthorn the shaft farthest away (a 7 km) from the pumping shaft at Horden. At Hawthorn the chloride levels in the mine water layers had been significantly reduced (see section 5.3.3.2) following the start of pumping at Horden and there was a slight initial reduction in iron concentration. Therefore, it is assumed that a significant proportion of the mine water pumped during the test at Horden is originating in the Hawthorn area of mine workings. By a process of testing of various combinations of water from the mine water layers and the addition of a mine water pumped at Murton Colliery (part of the Hawthorn complex) during production a mine water of very similar to the mine water abstracted at Horden during the pumping test was produced. This water comprised a combination of deep mine water from the Hutton inset at Horden (1%), Permian water from Horden (9%), Hawthorn layered mine water (55%) and the Murton mine water (35%). Based on an abstraction of say 100 L/s this would infer that only about 1 L/s of the water is originating from the offshore waters associated with the evaporate deposits (Type C), 90 L/sec of mine water are originating from the shallow or intermediate mine waters (Type B) and about 9 L/s is originating via direct connections with the Permian aquifer.

5.3.3.4. PHREEQC modelling of the contamination of the Permian aquifer by mine water

The mixing of mine water of varying types and at varying rates with Permian aquifer water was undertaken to assess the impacts on water from the potable Permian Magnesian Limestone aquifer. In addition studies were carried out in an area of the Durham Coalfield south of the Butterknowle Fault which was identified as an area of already contaminated aquifer to determine if the quality and volume of mine water entering the aquifer could be determined from the levels of contamination currently found in the aquifer water.

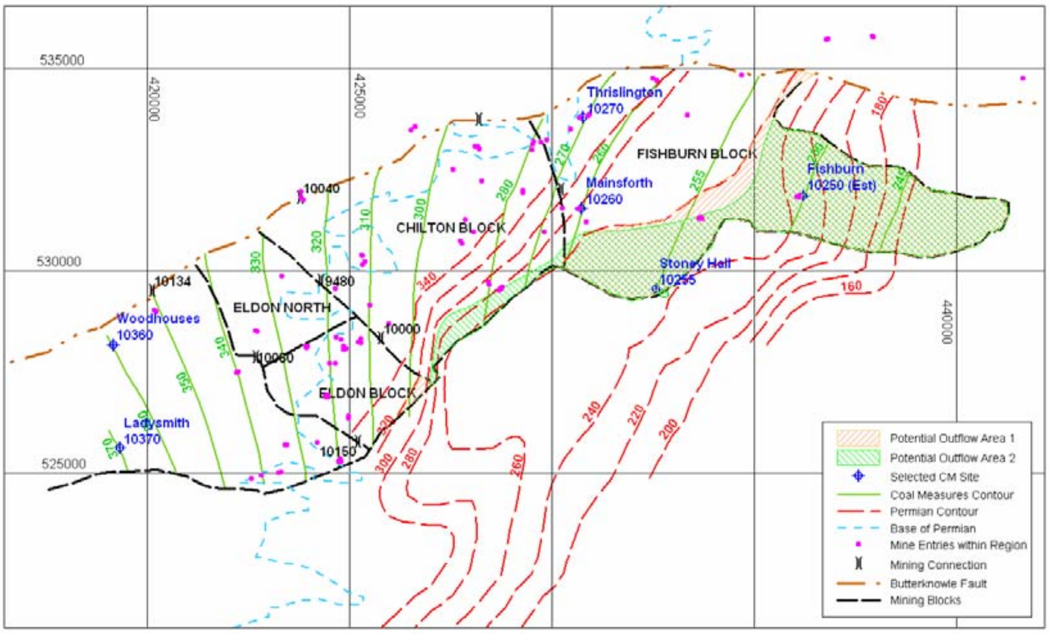


Figure 5.3.5: The Butterknowle Area of Durham showing the mining areas, the main monitoring sites, the mine water outflow area and the hydraulic gradients in the mine workings and aquifer.

Mine waters flowing into the contaminated area of aquifer south of the Butterknowle Fault were sampled from Mainsforth Shaft and Stoney Hall Borehole (see figure 5.3.5). Laboratory analyses of these samples showed mine water with moderate levels of iron (20 to 30 mg/L), sulphate (1000 to 1300 mg/L) and chloride (70 to 130 mg/L). Modelling of the mixing of these waters with uncontaminated Permian strata gave good correlation with three samples showing significant levels of contamination of the aquifer water when the ratio of mixing was about 2 to 4 % of mine water to aquifer water. In many cases away from the initial inflow points the levels of contamination are much lower The modelling has confirmed that the principal contaminant resulting from the mixing is sulphate and that the iron is precipitating out and not contaminating the aquifer water. Based on the mine water levels and quantities of mine water that were pumped in the Butterknowle area in the 1970's and the maximum piezometric head in the mine workings it is estimated that the current total flow of mine water into the aquifer is in the order of 100 L/s. The transmissivity of the Magnesian Limestone aquifer in the area has been estimated as normally being between 60 and 800 m^2/day (Younger 2007) and the mine water inflow of 100 L/s occurs over a contact zone with small discrete areas of flow of unknown hydraulic conductivity that extends along the incrop of the Coal Measure over a length of around 10 to15 km. Assuming the estimated flow from the mine workings is correct and the mixing ratio is about 4% then the total flow in the aquifer across the area of contamination would be around 8,600 m^3/day over a 10 km zone (see figure 5.3.5).

The modelling of the outcome of mixing of mine waters and Permian aquifer in the East of Wear area show that if similar levels of inflow of mine occurred (4%) then the impact would be significantly greater due to the more acidic nature of the mine water and the significantly higher iron and chloride concentrations within the mine water, figure 5.3.6 shows the chloride and iron concentrations in the aquifer increasing with the percentage of mine water mixing making the aquifer water unsuitable for drinking without treatment. The modelling confirms that prevention of flow of mine into the aquifer is essential in the East of Wear area.

5.3.4. Applications

5.3.4.1. Durham and Nottingham coalfields

In the area of the Durham Coalfield East of the River Wear the results of the investigations have shown that contamination of the overlying Permian aquifer will occur if mine water levels are allowed to the levels where there are direct open mining connections between mine shafts and the aquifer above ground water levels (0-20 m a.s.l.) The aquifer in this area provides 36,000 ^{m3} per day of potable water requiring no additional treatment.

A programme of mine water pumping and treatment is now planned based on the results of the modelling, pumping test and monitoring undertaken. The results have shown that by pumping at Horden the percentage of high chloride water from the offshore workings is relatively small and that at low pumping rates the chloride levels should be such that passive mine water treatment including an aerobic wetland should be possible. It is also clear that the pumping at Horden has significantly reduced the concentration chlorides in the upper mine water layers in the mine workings below the aquifer inland as a result of flushing by lower chloride but iron rich mine waters from nearer to outcrop or below the aquifer. However, the pumping test and monitoring has also shown that there is apparently less mine water flow through the other two collieries on the coast, Easington and Dawdon even though there is apparently good hydraulic connection. There remains a risk of high chloride levels in the upper mine water layers below the aquifer at these mines. Therefore a second mine water pumping station is to be established at Dawdon Shaft that will used to try and balance the various flows into the mine workings and maximize the quality of the mine water needing to be pumped to hold the mine water at the required levels and thereby minimize treatment costs. The mine water treatment a Dawdon will be an active plant using caustic soda, flocculent, lamellar plates and a centrifuge to remove the ochre sludge.

The Dawdon and Horden pumping stations are expected to continue to flush the high salinity mine waters from the upper mine quality layers resulting in a gradual improvement in mine water quality, a reduction in risk to the overlying aquifer and the potential for all both mine water pumping stations to use passive mine water treatment with aerobic wetlands.

In the Nottingham Coalfield mine water recovery is still at an early stage a there is no immediate risk of contamination of the overlying Permo-Triassic aquifer. However, the aquifer will ultimately be at risk and further monitoring and will be required as the mine water gradually recovers.

5.3.4.2. Megalopolis and Ptolemais lignite fields

As a result of the water quality measurements undertaken during this project and from long-term measurements (10 years) at the mine pumping stations that in normal conditions of pumping without the use of a centrifuge, the concentration of TDS is very low (4mg/l). However, when the discharge is high and the water has only a short retention time in the pumping station lagoon the TDS concentrations are high (>70 mg/l). This value is over the discharge limit of 30 mg/l.

To increase retention time at the pumping stations from between a few hours (5-10 hours) to 24 hours, 3 additional open reservoirs for precipitation were constructed (150m x 80 m x 5 m). The gravity flow of the mine water through the three additional lagoons resulted in a high precipitation (95%) of suspended soils, again without the use of a centrifuge.

To decrease the concentration of TDS and EC several techniques were tried, reverse osmosis, desalinization and the use of calgon. The results were satisfactory but expensive.

An additional method adopted to minimize contamination of aquifers was the use of an impermeable layer (10^{-9} m/s) on the sides of the lagoons to prevent the mine water in the lagoons from coming into direct contact with the underlying sediments and entering permeable layers within those sediments.

5.3.4.3. Saar-Lorraine coalfield (DSK/DMT)

The box model developed by DSK and DMT has been applied to a risk assessment to identify preventive measures to minimise aquifer contamination of an important drinking water resource in the French German border area of Lorraine and Saarland (figure 5.3.6). The aim of this modelling exercise is to couple the model of the Lower Triassic Sandstones (LTS) aquifer with the box model of the mining reservoir (Centre-East sector) so as to provide answers to the important hydrogeological issues arising as a result of the planned mine closures and the resultant flooding. The technical reason for doing this is the fact that no uniform water level will be established in the mining reservoir. This implies that the behaviour of the flooding volume flows between the mining concessions is highly complex and can no longer be estimated by means of simple analytical evaluations.

Experience was obtained during this project on mine water quality developments at partial flooding of Lorraine coal mines. These data were used to calibrate the water quality calculations using the newly generated geochemical features integrated into the BoxModel. The intention was to obtain the best forecast possible on mine water quality developments (iron, sulphate, chloride) and potential impact on groundwater and surface water quality. The subsequent figure 5.3.7 and figure 5.3.8 represent two alternatives for the development of mine water quality (parameters selected are iron, sulphate and chloride) at expected points of overflow resp. points of discharge.

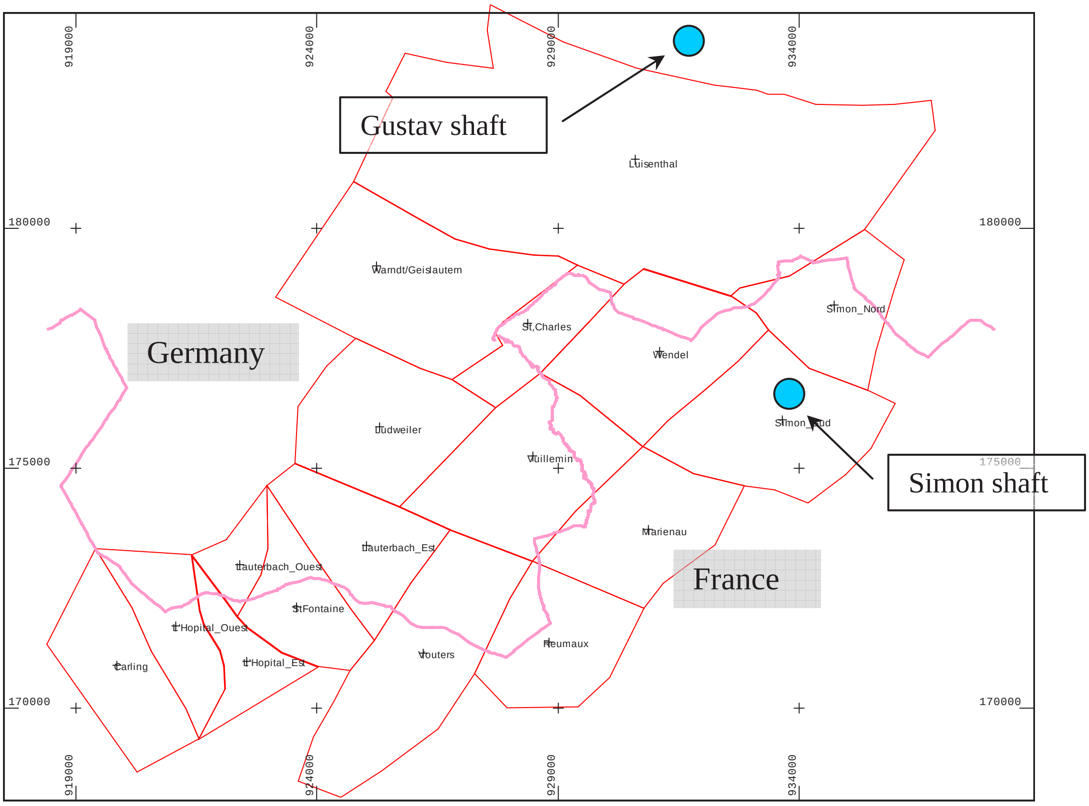


Figure 5.3.6: Box model French Lorraine Coal Basin and neighbouring German coal mines.

The Gustav shaft of the German Warndt mine is the discharge point of the whole mine field. The development of selected mine water quality parameters as calculated with the geochemical model is represented in figure 5.3.7. In this Alternative 1 the mine water inflow from the French mines is not controlled by any pumping but is hydraulically forced to pass the low levels of the mines in order to rise up again and to finally discharge at surface in approx. 2022. While iron and sulphate will follow more or less the expected exponential decline in concentration levels, chloride originating from deep geogenic inflow will accumulate at the deeper portion of the mines until the increasing hydraulic head will throttle the inflow.

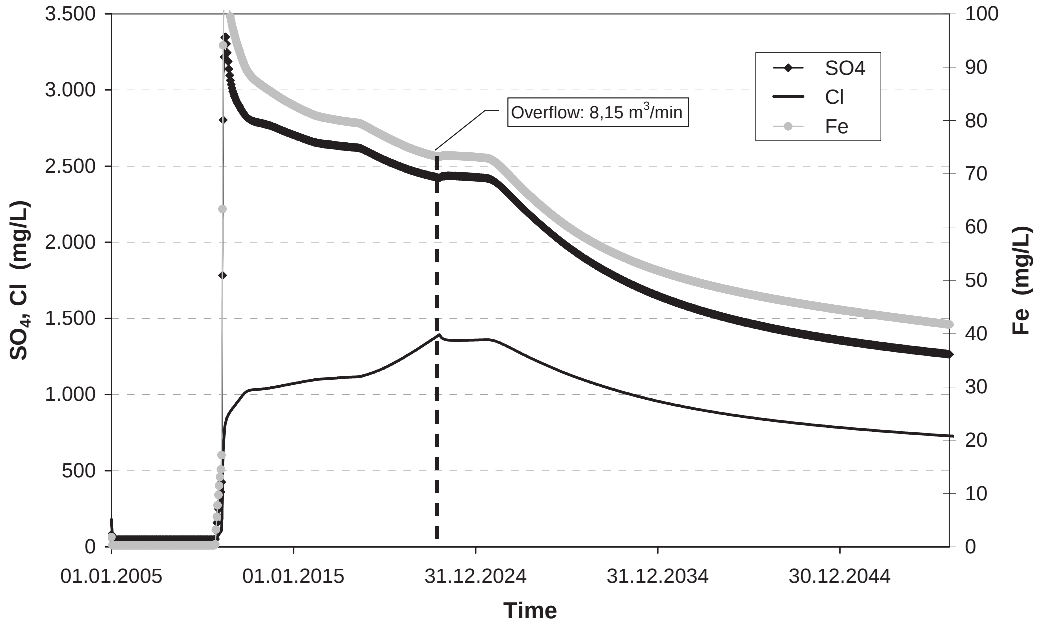


Figure 5.3.7: Development of concentrations at Gustav Shaft in case of overflow through deep mine levels into Germany (Alternative 1).

The Alternative 2 calculated by the geochemical model provides for pumping at several French mine shafts controlling the mine water levels and reducing the potential overflow at the Gustav shaft to practically zero. Figure 5.3.8 shows the mine water quality development when pumping out of the Simon shaft as an example. Initial concentration levels are relatively low due to dilution of mine water from the overlying Buntsandstein aquifer. When pumping commences in about 2022, concentration levels are expected to increase again due to upward movement of mine water with higher concentration levels.

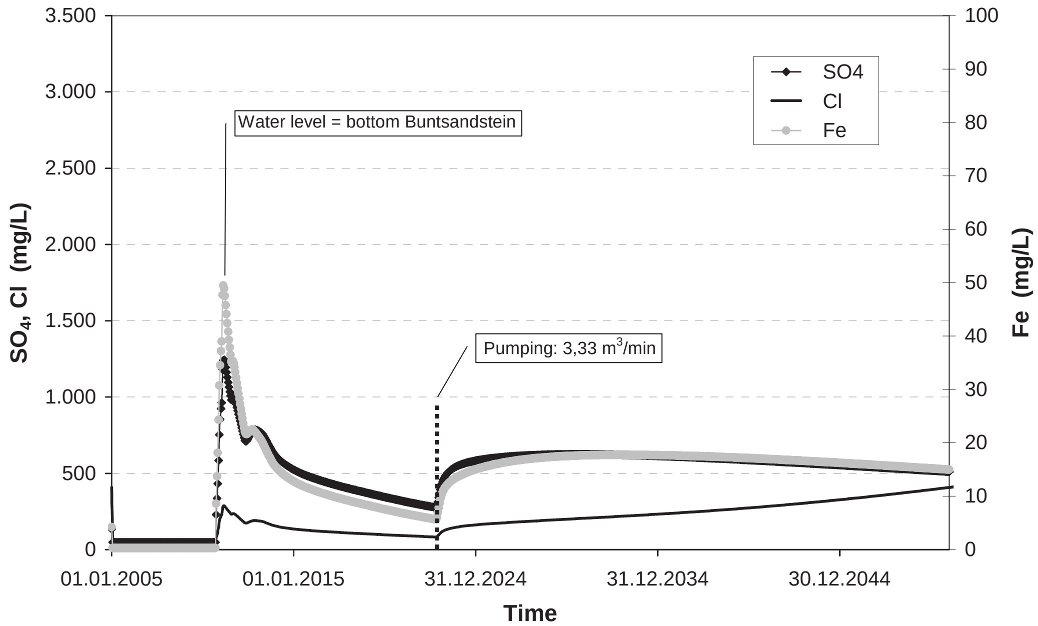


Figure 5.3.8: Development of concentrations at Simon pumping station in case of pumping in France (Alternative 2).

This example demonstrates the use of combined flow and reaction models for mine water quality prognosis in large complex mining areas. The manifold interference factors and the multiple mixing and precipitation processes can not be simulated by one dimensional calculation. Particularly in case of the interference of two overlying aquifers, the hydraulic effects of the water table and the numerous flow connections between the coal fields and levels have to be considered. It is obvious that an optimised pumping regime forming the essential basis for improved mine water discharge can be derived from sophisticated model application.

After evaluating the model results conclusions were drawn in a French-German meeting held in Forbach, France, on 14 October 2005, under the presidency of the Sous-Préfet Mr. Guy Tardieu, participating:

- Charbonnages de France (CdF)
- Deutsche Steinkohle AG (DSK)
- DRIRE Lorraine (French mining authority)
- Oberbergamt für das Saarland (OBA) (German Mining authority)
- Ministerium für Umwelt (German Provincial Ministry of Environment)
- Landesamt für Umwelt und Arbeitsschutz (German Regional Department of Environment and Workers Health and Safety)

and the participating engineering companies ANTEA, CESAME and DMT.

The agreement is formally documented in a protocol distributed with letter dated 23 November 2005 by the Sous-Préfet to all participants and the French and German authorities in charge.

5.3.4.4. Butterknowle area of Durham

The water quality data, monitoring and modelling undertaken in this area has detailed the pathways through which mine water can enter an aquifer and the impacts the contamination is having on the aquifer. The data is currently being used to target with monitoring boreholes the direct hydraulic connections between the mine workings and the aquifer identified as having the highest flows to confirm the piezometric heads in the mine workings and check the estimated mine water qualities.

5.3.5. Conclusions

- The modelling of the mixing of mine waters and aquifer waters using PHREEQC can be used to assess the degree and type of contamination of the aquifer that will result. In areas where previous contamination of an aquifer by mine water inflow has taken place the modelling can be used to determine the proportion and quality of the mine water entering the aquifer.
- The modelling of the mixing of mine waters combined with an extended pumping test and the monitoring of changes to mine water layering can be used to indicate flow paths and the sources of water pumped at the different abstraction rates.
- The BoxModel integrating a geochemical reaction model proved to be a very appropriate tool in simulating mine water rebound effects and impact on mine water discharge quality in large coal mine fields.
- The data obtained from modelling, monitoring and pumping can be used to determine if mine water level control by pumping is required to prevent contamination of an aquifer. The data can also be used to determine the optimum site or sites and abstraction rates required together with the most cost effective method of mine water treatment.
- In the Megalopolis Lignite area while there is some contamination of the surface water by sulphate originating from waste dumps. However, the main source of pollution of the surface water is waste water from the town of Megalopolis. There is no significant contamination of the karstic aquifer or the sediments below the lignite deposit.
- Investigations undertaken in the Ptolemais Lignite area have shown that there is a moderate increase in mineralization of both surface and groundwater related to mining. However, the contamination is not at a level that will that create any serious environmental problems to the

River Soulou or other surface and ground waters. The main contaminants in the surface water are iron, manganese, nitrates, ammonia, boron and chlorides. In the ground water concentrations near to permitted limits for drinking water have been found for cadmium and mercury.

References:

A Neyermeyer, R.T. Williams and P.L.Younger. Migration of polluted mine water in a public supply aquifer. Q.J.Eng. Geology. Vol 40 Part 1, Feb 2007

PARKHURST, D.L. (1995), User´s guide to PHREEQC - a computer program for speciation, reaction-path, advective-transport and inverse geochemical calculations, U.S. Geological Survey, Water-Recources Investigations Report 95-4227, 143 p.. Lakewood, Colorado.

5.4. Experimental underground plug construction by shotcrete technique

5.4.1. Introduction

Ever since coal has been mined, problems connected with controlling mine water have been among the most important ones faced by miners and mining companies. The present RFCS (Research Fund for Coal and Steel) project pretends to reduce such problems by developing several research lines.

For instance, the abandonment of zones in underground coal mines, in which galleries connect with other productive areas, produce an increase in pumping costs in the operational parts of the mine, being one solution to this problem the construction of underground barriers to control or confine water (many times generating high pressure) in galleries. Although underground barrier construction for mines has been known for long time, there are still a number of problems to be solved.

In this sense, the research work is intended to determine how to seal mines or parts of the mines that are left abandoned, in a safe and efficient way, by studying alternative designs and techniques for the construction of underground plugs and dams, investigating novel approaches for the construction of barriers (fast plugs), developing and testing methods to check and improve the quality of plugs, and finally carrying out tests in particular applications to trial the performance of underground sealing plugs.

5.4.2. Objectives

The objectives of the work are to improve the methodologies to construct the underground plugging systems required to protect actives areas of the mines from water coming from abandoned areas, including:

- The study of the state of the art in underground sealing solutions, and in particular the different designs and techniques for the constructions of the underground plugs.
- The assessment of the hydrogeological framework of potential areas in order to select a suitable site for the plugs.
- The development and testing of a detailed plug design including both its components and the constructive technique.
- The construction of underground test plugs according to the design developed in order to check their behaviour

5.4.3. Work carried out

5.4.3.1. Review of documentation, state-of-the-art and analyses of construction alternatives

5.4.3.1.1. Search and review of documentation

The first work carried out has been the review and evaluation of existing data, literature and in general available information on existing experiences of underground dam construction (plugging systems) to separate flooded areas, and its associated problems. These include among others:

- Experiences about plug construction published by specialised firms
- Studies on methods of plug design and construction from particulars or from government's institutions
- Analyses and studies on specific problems as the acid rock drainage
- Other uses of plugs or barriers as those constructed to retain tailings stocked in galleries closed to work, to obtain water-and-gas-tight sealing of underground stocks of gas, or sealing in underground repositories of high level radioactive waste.

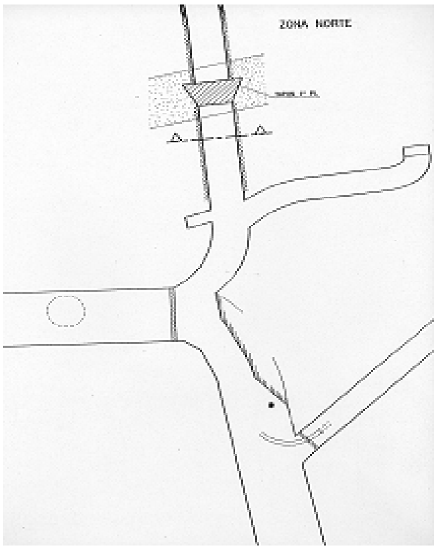
Many studies have been done so far about underground barriers construction in mines. For instance, already in the 50's, W.S. Garret and L.T. Campbell [1] studied methods of plug design and construction. After them, other studies have followed from particulars or from government's institutions, like the chamber of mines of South Africa [2] that gave some recommendations for mass concrete plug construction.

Moreover, experiences about plug constructions have been published, by specialised firms [3] or by the mine contractors after a flood and its sealing [4, 5 & 6], or about the closure of galleries of coal mines [7, 8 & 9] to share the knowledge acquired within the world mine community in different applications.

Barriers are also used in abandoned mines since the leakage of water from a mine can generate great ecological problems if this water has become acidic after its reaction with minerals [10]. This problem is known as acid rock drainage (ARD). A solution is to seal and inundate the galleries where this reaction has been produced, given that the lack of air prevents this reaction and reduces the acidity of the water [11].

Besides, other mine barriers are constructed to retain tailings stocked in galleries closed to work [12]. In a different context, barriers are used to seal and to obtain water and gas tightness in stocks of gas [13 & 14] or they are in study for underground repositories of high level radioactive waste [15, 16, 17 & 18].

In some cases, as in the case of HUNOSA's abandoned mine of San José in Valle Turón (Asturias, Spain), an unsuccessful sealing experience has been studied, specially as this mine was initially considered as a possible investigation/application area for the project. Several mass concrete plugs had been constructed a few years ago to separate the abandoned areas from the working areas in order to prevent the flooding (figure 5.4.1). The sealing with these plugs was unsuccessful and the plugs could never be put in operation to support hydraulic pressure.



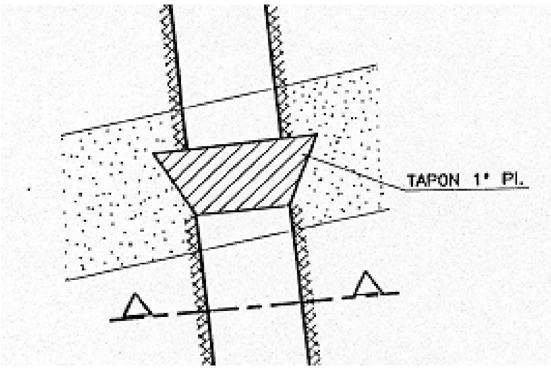


Figure 5.4.1: Unsuccessful sealing experience in San José Mine (HUNOSA).

With regard to the hydrogeology, in a first stage a compilation of general bibliography on the main issues related with the groundwater and coalmines was obtained: groundwater flow and water quality, groundwater rebound in abandoned mines, groundwater monitoring, etc. In a second stage, a recompilation of specific documentation from the selected investigation sites was carried out.

5.4.3.1.2. Construction alternatives

All the information compiled on underground plugging was organised, sorted and summarised in a technical report with useful information as a sorting of different types of underground barriers, alternatives on plug construction with pros and cons, and an overview of the different stages to be accomplished in order to perform a successful construction, including guidelines and recommendations on the key aspects to be taken into account on each stage.

Most of the available studies are referred to plugs construction, although these structures must be differenced from other underground barrier types.

- Dams: generally used in underground mines to store water for drilling purposes or for settling sumps. They are generally constructed of concrete but can also be made of timber or sand/cement filled sandbags and measure typically no more than a couple of metres in height and are free to overflow if the water height exceeds the height of the dam.
- Fill-Retaining Barricades: normally used for retaining backfill in mine stopes and in other cases to increase ore recovery. These structures use water heads not exceeding 100 kPa (about 10 metres of water or 5 metres of liquefied tailings), and can be constructed of waste rock, shotcrete, timber, cable slings and wire mesh, or a combination of them.
- Bulkheads: the main difference between these and the plugs may be that bulkheads are intended to last for less years than plugs [3], although many times no distinction is made between them. They can be constructed of waste rock, shotcrete, concrete, timber, cable slings, or a combination of them.
- Plugs: used to impound water or tailings at pressures exceeding 100 kPa (10 m of water). As underground plugs are intended to be permanent structures (for instance, more than 20 years), they will normally incorporate higher factors of safety and meet more rigorous quality control and quality assurance specifications during construction than bulkheads. Plugs can be constructed as monolithic plugs or hollow core plugs, used in large diameter tunnels, to favour heat dissipation where the heat from cement hydration is high (see figure 5.4.2).

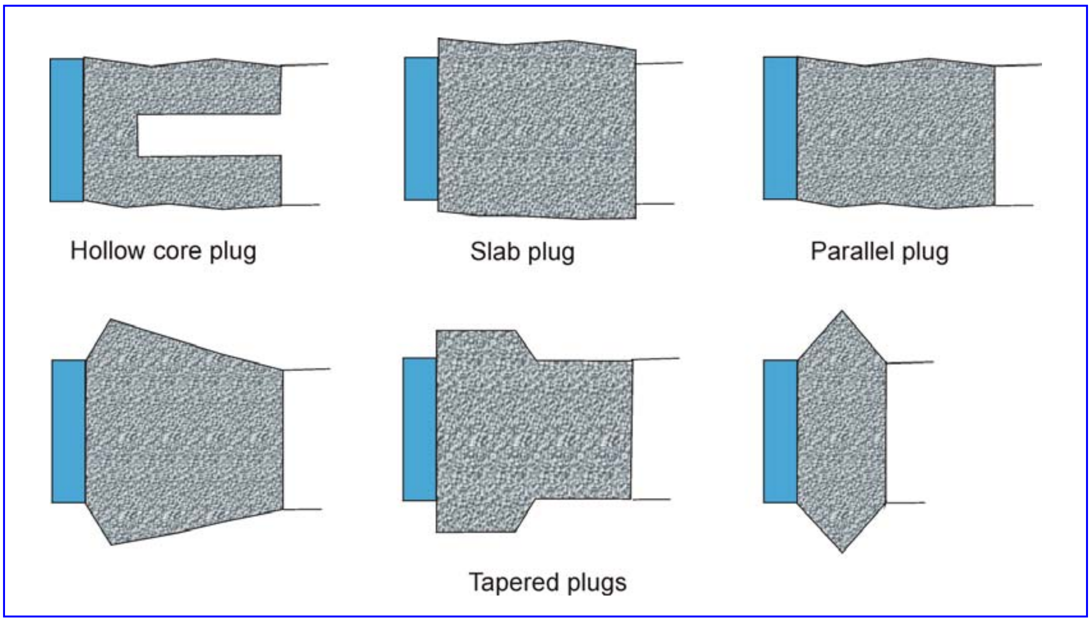


Figure 5.4.2: Different plug configurations.

As one of the objectives of the work is to seal a part of a mine in the safest way and for the longest time possible, in what follows, only underground concrete plugs are considered.

Two basic construction methods can be used: mass concrete and shotcrete, and a third possibility is to use a combination of both, perhaps including other material too:

- <u>Mass concrete</u>: this method has been the most used since the first plugs were constructed to seal tunnels (middle of the 20th century). The plug is casted into forms (generally constructed in timber) where the concrete is poured by gravity displacement in successive vertical layers of a given thickness. This thickness is determined by the dimensions of the gallery and by the hydration heat of the concrete. Voids due to a concrete shrinkage while curing and to improper concrete placement, remain usually in the crown of the batch, so normally a contact grouting is necessary afterwards to prevent seepage along this concrete-strata interface.
- Specific codes like the “Guide for the design and construction of water impounding plugs in work mines”[19] or"1983 Code of practice for the construction of underground plugs and bulkhead doors using grout intrusion concrete" [2] have been drawn up as guides for plug construction. The latter introduces a difference in the method, where aggregates (75-300 mm

diameter) are placed between the forms and later the grout is added (less viscous than concrete and easier to pump due to the lack of aggregates).

- Shotcrete or sprayed concrete is a basis cementations mix projected pneumatically at high velocity onto a surface to produce a dense homogeneous mass compacted by its own momentum.

  Shotcreting provides a very good contact between concrete and rock, filling all voids and holes, even at the roof part. In addition, a good quality shotcrete has a lower porosity and permeability than standard concrete, and can be easily reinforced using fibres. Another practical advantage is that forms are not needed, and therefore the plug construction is very fast.

  On the other hand, shotcrete is used in thinner layers (max. 30 - 40 cm) than mass concrete method, to allow the release of the hydration heat of the concrete. The construction of a plug measuring several meters in length requires a careful consideration of aspects such as construction time, cohesion between layers and the thermal effects during setting.

  A few experiences of plugs constructed by this method can be found:

  - Underground gas storage of Pribam - Háje (Czech Republic) [13]: four sealing taper plugs, measuring 10 m. in length each, were built with steel fibres reinforced shotcrete.
  - Chandler Tunnel Colorado plug [3] was constructed with a length of 2 m using dry mix shotcrete with steel reinforcement on the upstream and downstream ends of the plug.
  - A plug measuring 3 m. in length was constructed by shotcreting technique in the Febex gallery [15] at the Grimsel Test Site (Switzerland). This plug must support pressures up to 6 MPa due to bentonite swelling at the upstream side of the plug and should provide water and gas tightness.

- Concrete combined with other materials: a low-permeability bentonite/soil mixture can be an alternate design to lengthen a plug at a lower cost than concrete and grouting. Bentonite clay provides the low permeability needed in the plug and its swelling properties can improve the contact at the crown of the tunnel, which is often hard to fill with mass concrete. Swelling of the bentonite/sand mixture upon contact with water precludes the need for expensive contact grouting. A filter zone surrounding the bentonite/sand core provides confinement as the bentonite is hydrated and also protects the core from erosion.

  Earth-plugs are analogous to earth-dams, except they are constructed underground. Similar to an earth-dam, which is built with an impermeable clay core, filter zones and shells, the underground earth plug consists of a sand/bentonite clay core, and a graded earth filter zone downstream. A good example of this type of plugs is the Millennium Plug (see figure 5.4.3), a Canadian project to stop a toxic run-off from a mine [10].

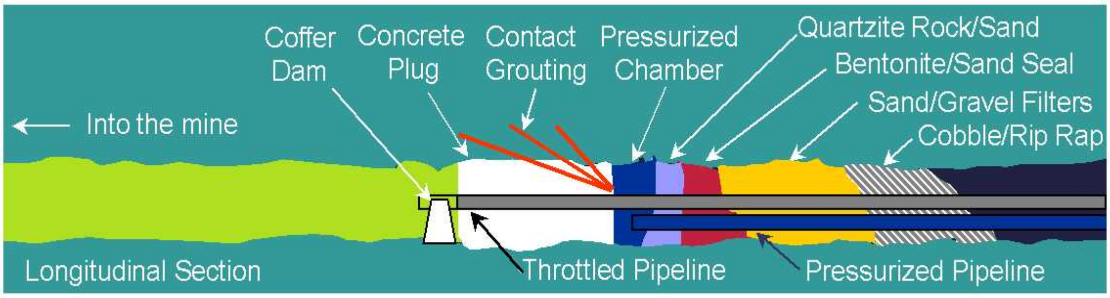


Figure 5.4.3: Millennium Plug.

In view of the advantages of the shotcrete technique for the specific objectives foreseen in terms of fast construction, and good contact with the rock to provide a better hydraulic sealing, this technique was selected for the underground test plugs to be constructed.

5.4.3.2. Selection of test and hydrogeological outlines

5.4.3.2.1. Investigation and selection of sites

This investigation area is located in the central sector of Asturias (North of Spain), to approximately 20 km SE of the city of Oviedo. The zone has an extension of approximately 1.000 km^2 and is known as Caudal basin coal field.

The San José Mine, located in this area, was preliminary proposed by Hunosa as experimental site. This abandon mine is being pumped to avoid the flooding of other actives mines located in the area (Figaredo, Santa Bárbara, Barredo and Santiago).

In San José Mine they were constructed some years ago several concrete plugs in galleries at different levels to avoid the flooding of Figaredo Mine. The plugs never worked as it was foreseen due to different problems probably related with the geological and hydrogeological characteristics of the place where they were sited. The accessibility of the drifts and the lack of detailed geological information —there is not a detailed scale geological map and the galleries are grouted—, makes very difficult to conduct the project in this site and it was finally discarded and a new site was selected.

The new site proposed by Hunosa was Santiago Mine, close to San José Mine. Santiago is an active mine connected to San José through a gallery at the third level of the mine. This mine was selected to locate the plug because it remains active while the others two mines connected to San José (Figaredo and Barredo) are already abandoned (Barredo) or would be abandoned during the project (Figaredo).

The construction of concrete plug in Santiago Mine, as it had been planned, it didn't be viable due to Hunosa logistics problems. Then, Hunosa started to consider the possibility of constructing the experimental plug in another site (Barredo or Figaredo mines).

Meanwhile, the abandoned mine of Lumajo (León) was studied by Aitemin as a new possibility. Lumajo is a mountain coalmine that from the 30s was exploited by MSP (Minero Siderúrgica de Ponferrada) in the northeastern part of the coal deposit of Laciana's Valley. The mining activities were abandoned in December, 2004 and the mine is closed now. This mine had two main accesses, one in Villablino town (at 977 m a.s.l.), named "Tranversal de Villablino", and other one in "El Castro" at 1138 m .a.s.l. (see figure 5.4.4).

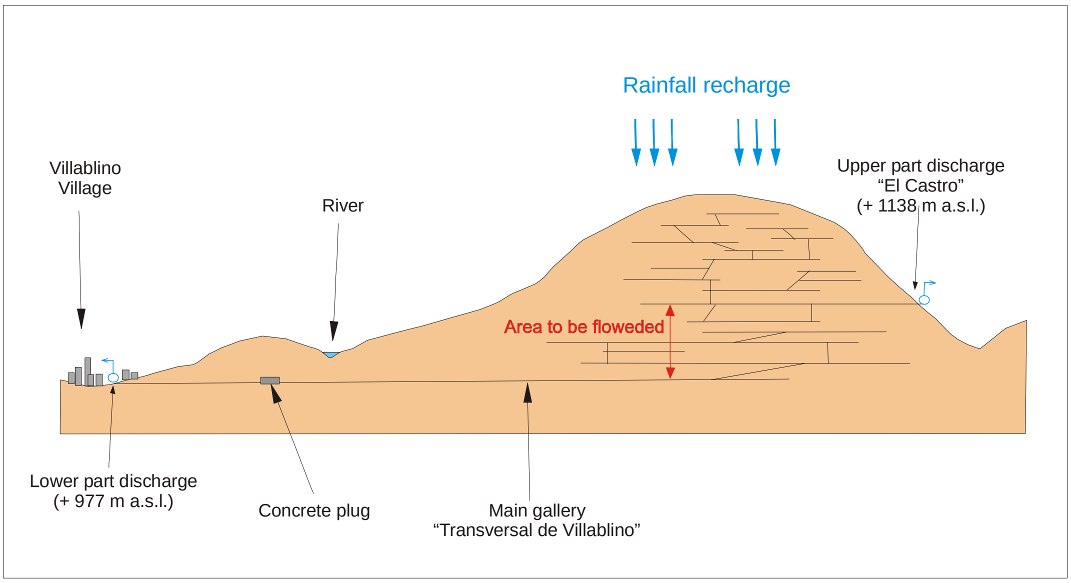


Figure 5.4.4: General scheme of Lumajo Mine and plug location.

The structure of this mine is based on a single gallery at the lowest level (Transversal de Villablino) to access to the working areas in the upper levels. This main gallery is connected to Calderón Mine, located to the west of Lumajo Mine (see figure 5.4.5). The mine drains a big hydrographic basin through the mining works to the main gallery. Thus a plug located in the main gallery would serve to store the water collected in upper galleries isolating the active zones of Calderón Mine. Thanks to the plug it would be possible to evaluate the possibility of using the water stored in the upper galleries to produce electricity.

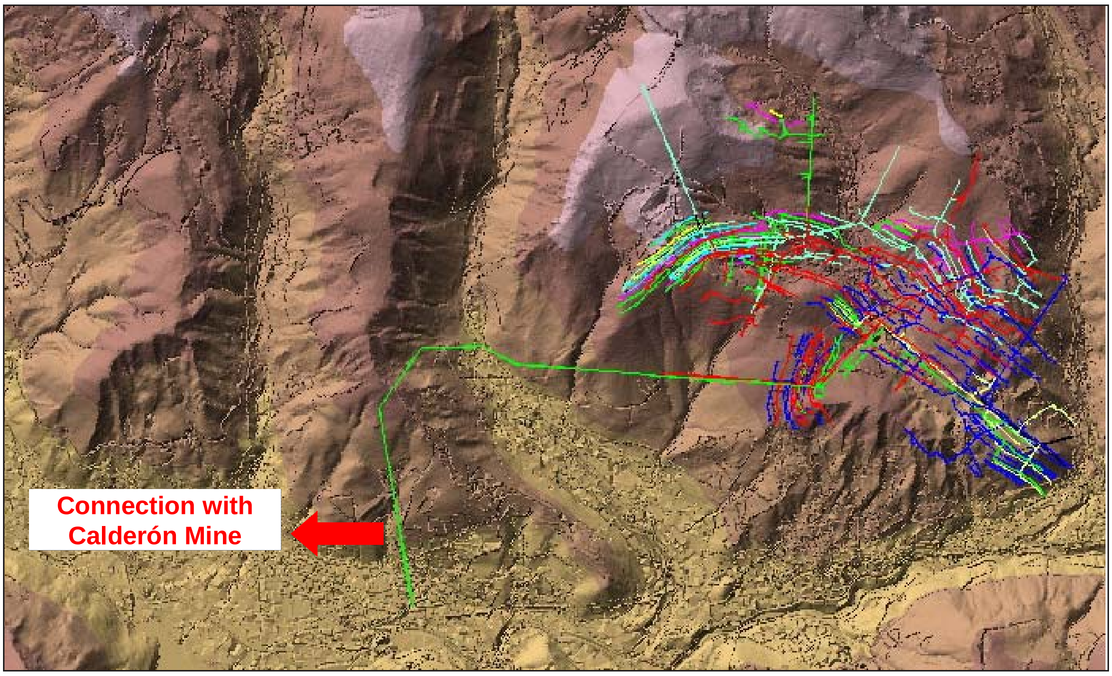


Figure 5.4.5: Plan view of Lumajo Mine and the connection with Caderón Mine.

The abandoned mine structure would work as a big reservoir in which the water would reach a maximum level of 1138 m a.s.l. (base of the 1st floor of Lumajo or Castro level), contained by the plug located in the main gallery at 977 m a.s.l. (Transversal de Villablino).

Many important aspects have been controlled inside and outside of the mine in order to define a hydrogeological conceptual model. This aspects have been; geological characteristics of the area (lithology; structure, fractures and joints, stratification, etc); hydrogeological characteristics (permeability of the materials, discharge and recharge areas, water well inventory, groundwater flow; natural mine drainage, output and input flows); water quality (electrical conductivity, pH, temperature, iron and sulphates content); seismic risk, etc.

Nevertheless, after of this works carried out, the geotechnical characteristics analysed in the rock mass were not appropriate to work in this area (low stability, many fractures, high collapse risk, etc) and therefore was necessary to change the site.

Finally, Figaredo mine was selected as the most suitable area for the construction of the real case demonstrator plug. This mine is located between San José and Barredo mines in Turon valley and has been active until the end 2006, although the site selected for the construction of the plug is located in an abandoned gallery.

In parallel it was decided to construct another underground plug in the Laciana school-mine of Foundation Santa Barbara, in order to perform a specific test under higher hydraulic pressure.

5.4.3.2.2. Hydrogeological outlines

The following aspects have been considered to establish the hydrogeological conceptual model of the Caudal basin coal field:

- Climatologic data: rain and temperature data from meteorological stations.

  The rainfall data have been requested to the National Institute of Meteorology in order to characterize the meteorological regime of the zone. The obtained information is reflected in the figure 5.4.6. Most of the rainfall data series that have been collected aren't long enough to establish an average regime. Nevertheless, the Santa Cruz de Mieres meteorological station, that has the longest rainfall sequence, has been used to estimate the pluviometry. This meteorological station provides information on the total monthly rainfall (Pm) and the daily average temperature (Td).

- Surface water data.

  In order to estimate the water balance in the area of study there has been compiled the information on main rivers discharges (see figure 5.4.6). The discharge data are from Nalón, Caudal and Ayer rivers.

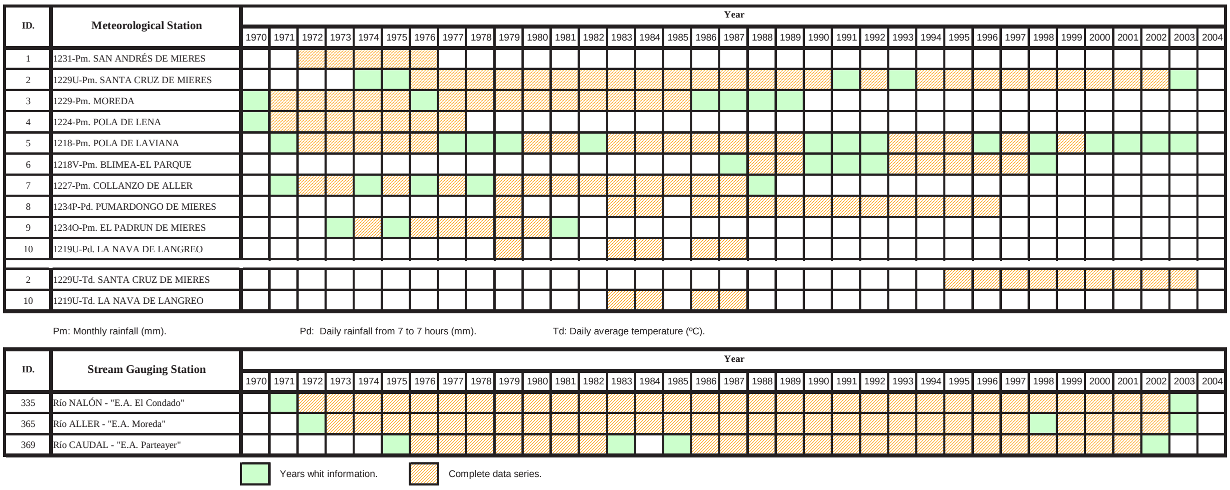


Figure 5.4.6: Meteorological stations and river gauging stations.

- Geological information.

  It has been reviewed all the existing information about the mining activities and about the geological characteristics of the site. The main sources of geological information have been Hunosa and the Geological Survey of Spain (Instituto Gelológico y Minero de España). The main exploited coal units can be seen in figure 5.4.7 which shows the site geological map at -100 m a.s.l.

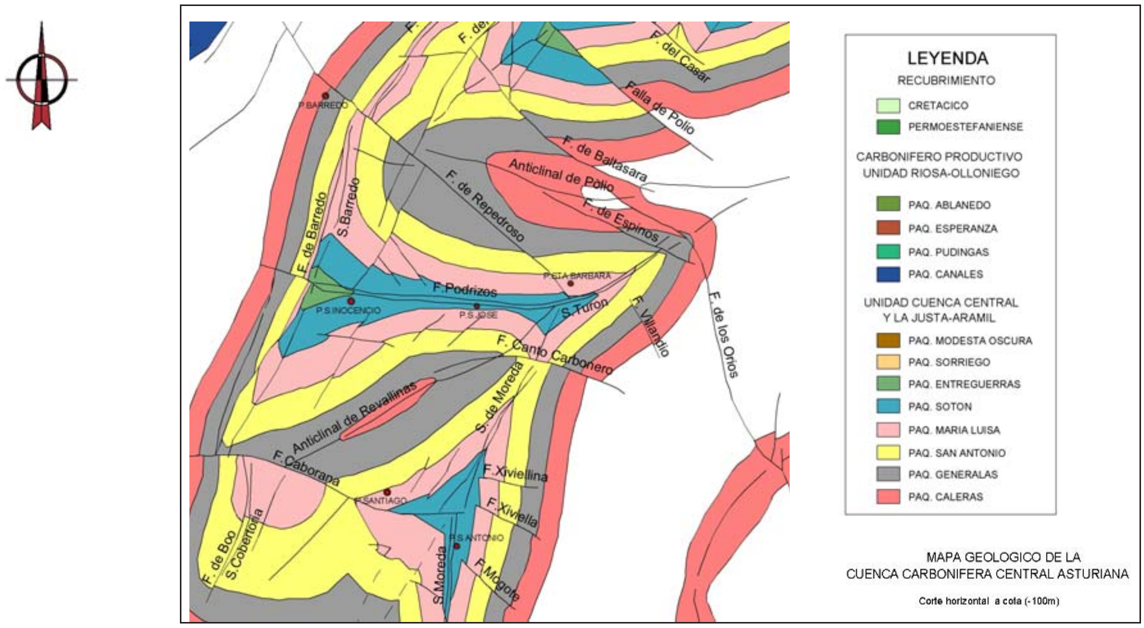


Figure 5.4.7: Geological map (elevation -100 m a.s.l.).

The profile of the figure 5.4.8 shows the complicated geological framework in the area with strong folds and faults. All the layers shown correspond to carboniferous deposits. In this profile is easy to check the different elevation between shafts.

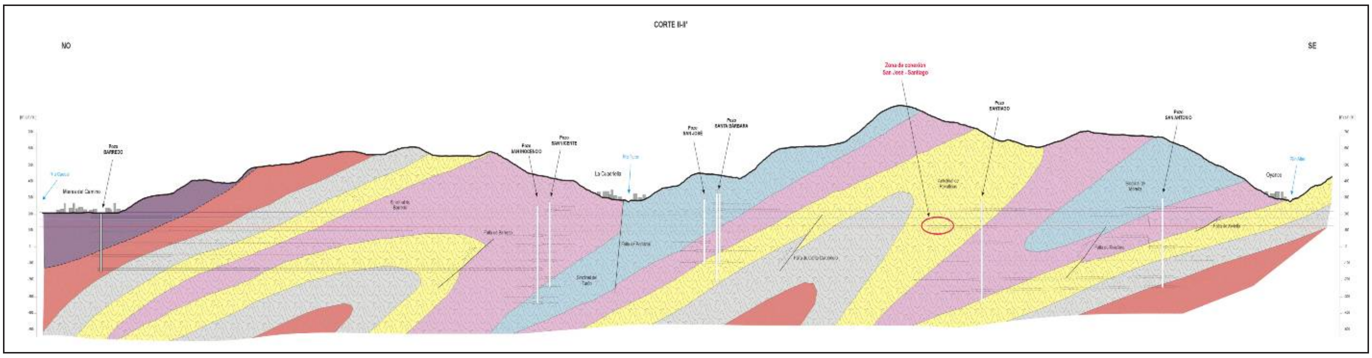


Figure 5.4.8: Geological cross section.

- Regional hydrogeological framework

  The area of study is partially occupied by the hydrogeological unit of Oviedo-Cangas de Onis that, in some areas, is used for groundwater extraction for domestic and industrial water supply. This hydrogeological unit is constituted by sands, silts and clays. Its average thickness changes between 50 and 400 meters depending on the sector, and provides water of good quality both for irrigation and for supply.

  The rest of the zone of study is occupied by the coal formation, which is until 6.000 meters thick. Tow sets of materials can be distinguished: the lower one is about 3.500 m thick and the upper one is 2.800 m thick. As a whole, these formations constitute a fractured medium with very low permeability where they are not altered by the mining activities.

- Water well inventory around the investigation area: springs, dug wells and drilled wells.

  In order to prepare the conceptual hydrogeological model of the investigation site have been gathered the information about dug wells, drilled wells and, spring. Around the site investigation there are 57 springs, 7 drainage galleries and 1 drilled well. Most of the springs have data about their discharge and water quality.

A sketch of the hydrogeological framework of the area is show in figure 5.4.9. The zone has been delimited following geological and hydrographic criteria. An inverse fault of great entity and Caudal river limit the area by W, whereas the different watersheds (locals and regional) limit the zone of study by the East and South. The northern limit is the Nalón river.

In figure 5.4.9 has been included the location of the main mining activities, the meteorological stations and the existing river output gauging stations in the zone. Also, water wells and springs have been represented.

From the hydrographic point of view, between the courses of the rivers Nalón and Caudal, the zone of study is crossed by three rivers: San Juan, Turón and Aller. Most of the mining shafts are located near to the rivers Turón and Aller.

Regional groundwater flow is supposed towards the Caudal River while intermediate and local groundwater flow should be towards smaller rivers and creeks.

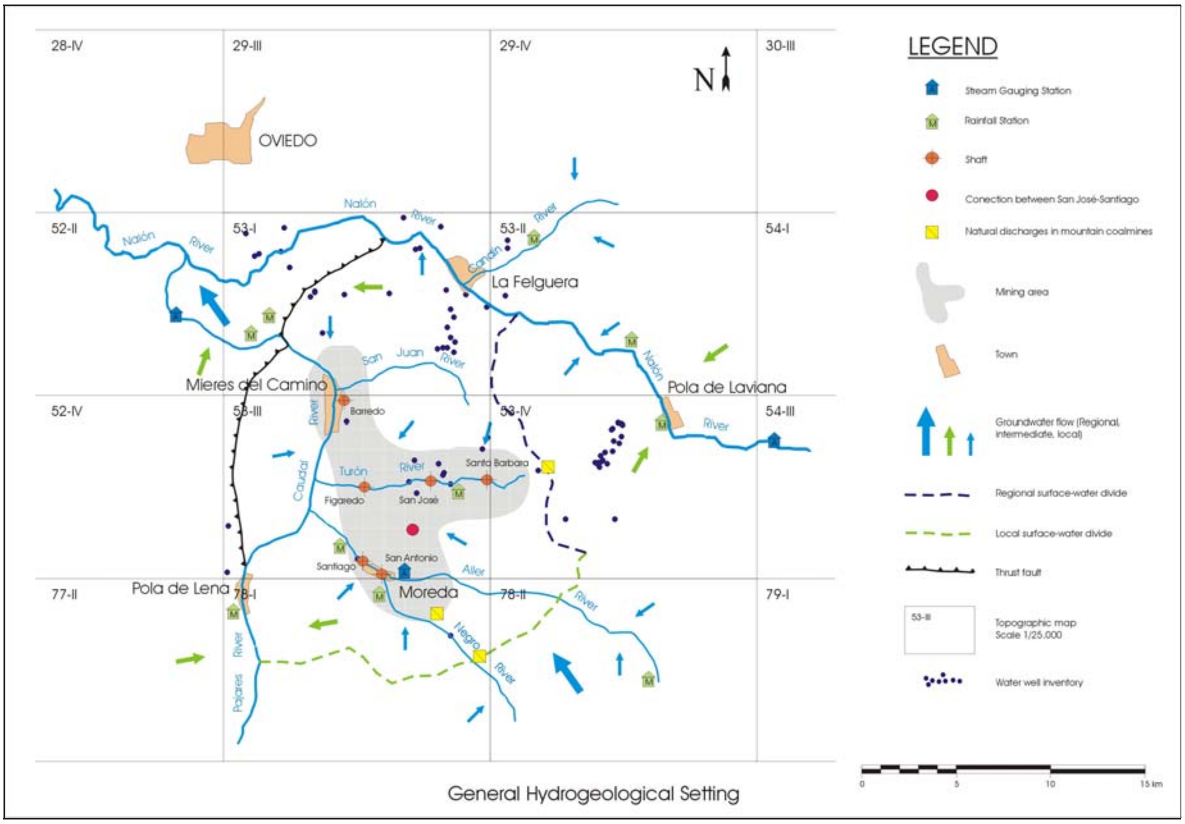
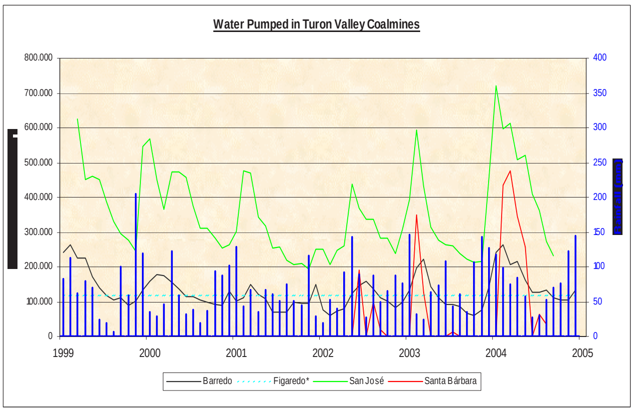


Figure 5.4.9: Gathered information in the Asturian coal basin.

In order to estimate the infiltration in the zone, in the figure 5.4.10 it is show a comparison between the monthly volume of water pumped in the main mines and the monthly rainfall in Santa Cruz de Mieres Meteorological Station (from 1999 until the end of the year 2004). It is possible to observe that a clear relation exists between both records. This suggests a rapid infiltration, owed probably to old mining activities near the surface, which facilitate the direct infiltration of the rain.

HUNOSA has a continuous control of the water drainage in the main shafts of the area (Barredo, Figaredo, San José and Santa Bárbara) since 1999 approximately. In the next figure can be seen the total water pumped between 1999 and 2005 in each mine per year.



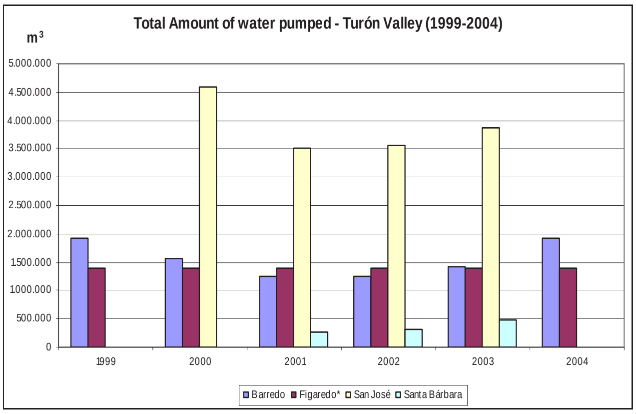


Figure 5.4.10: Rainfall and total amount of water pumped.

Figure 5.4.11: Water drainage in the main shafts of Turón coal field.

Around 7 millions cubic meters are pumped per year (figure 5.4.11). San José Mine is the main point of drainage. As it can be seen, there are a very good relationship between the rainfall and the water pumped; the delay between both (rainfall and increase of pumping) isn't very large it is possible to estimate a quick infiltration in the zone.

Also, the water discharge was controlled in three abandoned mountain coalmines (Urbiés, Pontones and Canales mines). These points are natural discharges and they are located in the limits of the study area (see figure 5.4.12).

Figure 5.4.12: Urbiés, Pontones and Canales mountain coalmines.

During the field works Aitemin installed pressure probes to control the evolution of the piezometric levels and these could provide indirect data about the possible fluctuation of water level in the test area. Also have been studied the data obtained by HUNOSA (in daily basis) from December 2004 to May 2005 (see figure 5.4.13).

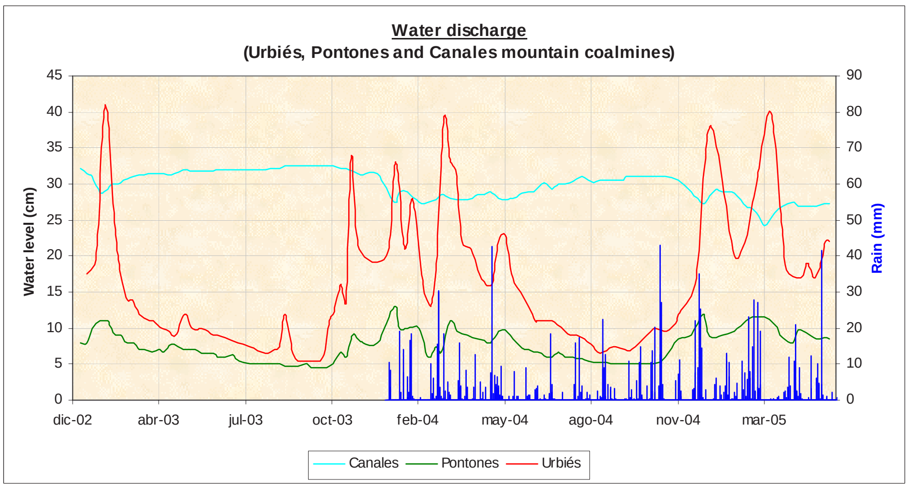


Figure 5.4.13: Water discharge measured by HUNOSA in the three abandoned mountain coalmines.

It is possible to observe that the evolution levels are very similar, with big changes of level in Urbiés mine and hardly variation in the other points. These data confirm that the infiltration of the rainfall is very quick, probably because there are a lot of mountain coalmine abandoned in the zone and the altered area of mining works are very near to the surface.

Furthermore, in order to check the water quality in the area, some measurements of electrical conductivity, pH, temperature, total iron and sulphates content have been made in the water discharge of the mines. The most interesting results obtained are shown in figure 5.4.14, figure 5.4.15 and figure 5.4.16.

The electrical conductivity values change between 1.053 and 2.120 µS/cm in open mines and between 499 and 1.862 µS/cm in closed mines. The mean value is around 1.367 µS/cm.

Electric Conductivity (µS / cm)

Active Mines

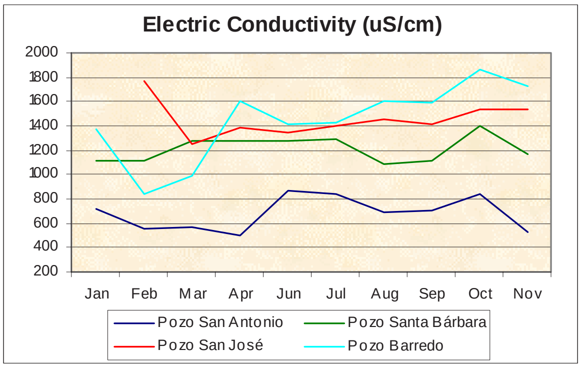
Mine	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Pozo Santiago	1.671	1.725	1.694	1.715	1.718	1.748	1.735	1.799	1.665	1.659
Pozo Figaredo	1.053	1.473	1.614	1.321	1.614	2.030	2.120	2.010	1.901	1.821

Abandoned Mines

Mine	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Pozo San Antonio	713	556	567	499	869	840	695	701	835	521
Pozo Santa Bárbara	1.111	1.110	1.279	1.276	1.282	1.287	1.086	1.113	1.394	1.169
Pozo San José		1.770	1.252	1.391	1.347	1.396	1.457	1.414	1.541	1.542
Pozo Barredo	1.377	840	990	1.610	1.418	1.431	1.602	1.585	1.862	1.721

Max. Min.

Abandoned Mines



Active Mines

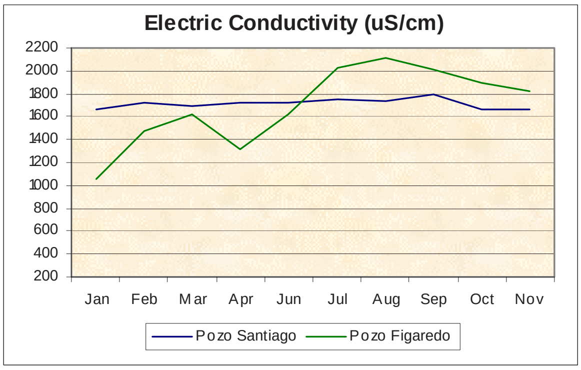


Figure 5.4.14: Electric conductivity values measured during 2004 in active and inactive mines.

Iron (mg/l)

Active Mines

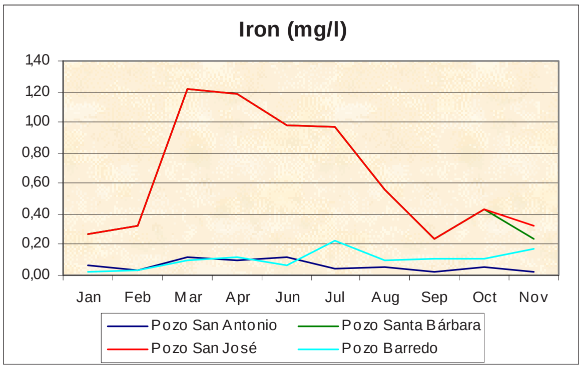
Mine	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Pozo Santiago	0,395	0,338	0,171	0,379	0,366	0,209	0,184	0,327	0,400	0,122
Pozo Figaredo	0,092	0,215	0,027	0,159	0,217	0,155	0,315	0,226	0,040	0,186

Abandoned Mines

Mine	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Pozo San Antonio	0,062	0,031	0,121	0,096	0,115	0,041	0,053	0,023	0,054	0,023
Pozo Santa Bárbara	0,270	0,320	1,216	1,188	0,977	0,964	0,557	0,236	0,433	0,233
Pozo San José	0,270	0,320	1,216	1,188	0,977	0,964	0,557	0,236	0,433	0,319
Pozo Barredo	0,025	0,027	0,093	0,123	0,068	0,226	0,092	0,105	0,103	0,167

Max. Min.

Abandoned Mines



Active Mines

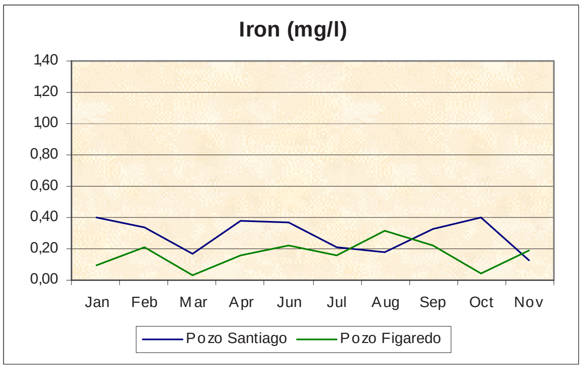


Figure 5.4.15: Iron concentrations during 2004 in active and inactive mines.

pH

Active Mines

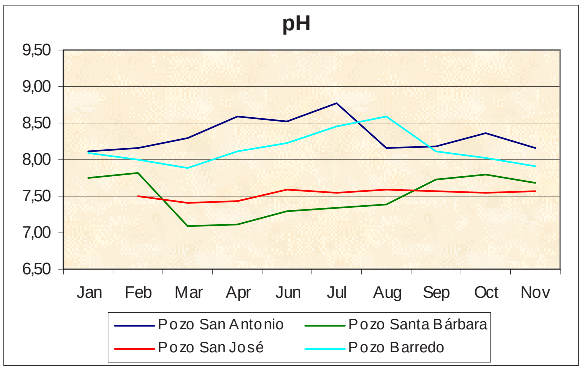
Mine	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Pozo Santiago	8,44	8,90	9,05	8,51	8,48	8,63	8,62	8,69	8,73	8,62
Pozo Figaredo	7,88	8,33	8,25	8,46	8,83	8,64	8,49	8,41	8,45	8,51

Abandoned Mines

Mine	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Pozo San Antonio	8,11	8,17	8,30	8,60	8,52	8,77	8,16	8,18	8,36	8,17
Pozo Santa Bárbara	7,74	7,82	7,08	7,12	7,30	7,35	7,39	7,73	7,79	7,68
Pozo San José		7,50	7,41	7,44	7,58	7,54	7,60	7,56	7,54	7,56
Pozo Barredo	8,10	8,00	7,89	8,12	8,23	8,46	8,60	8,12	8,02	7,91

Max. Min.

Abandoned Mines



Active Mines

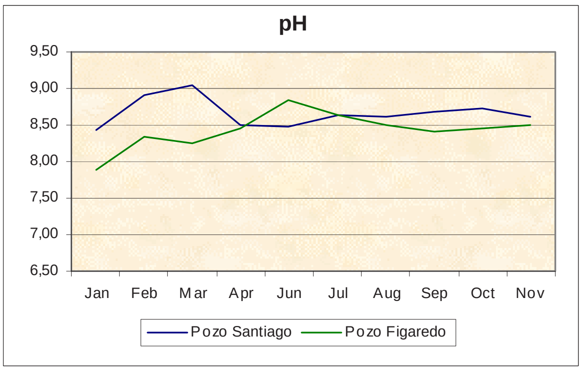


Figure 5.4.16: pH values measured during 2004 in active and inactive mines.

The iron concentration is always below 0,75 mg/l except in two cases, Santa Bárbara and San José mines whose drainage was together during the spring months. In these months were detected values around 1mg/l.

The pH is usually around 8, probably due to the fact that in the local geological sedimentary sequence below the coal layers there is always a limestone bed.

As it can be observed, the electrical conductivity and the pH are greater in the active mines than the inactive mines but the iron concentration is greater in the second case.

About the waters analyzed in surface points (springs, fountain, etc)., it can be observed that the springs in the mining area have low conductivity values, around 100 μS/cm. The pH is similar to measured inside the mine, with values around 7.6. The iron and sulphates concentrations are very low in all cases (below 0.05 mg/l).

Therefore, the water quality in the area is generally good and the effects that the substances dissolved in the mine water will have on the plug are supposed to be negligible. Anyway it is quite possible that the water quality could change in the long term because of the increase of the transit time of groundwater after the construction of the plug.

5.4.3.3. Plug design

5.4.3.3.1. Concrete formulation

Once that the Figaredo site has been selected and the shotcrete technique has been chosen for the construction of the plug, the key aspects to be taken into account on its design are the concrete formulation and the length.

A standard concrete formulation was developed, based on standard Ordinary Portland Cement (OPC), with limestone filler as an inert part of the binder. The amount of cement was thus reduced so to obtain a concrete with low heat of reaction, negligible shrinkage, a Young modulus below 25 GPa, and a low compressive strength, between 10 and 20 MPa. No special requirements were set for the OPC and filler other than they were easy to obtain in the market, so both components were selected from standard manufacturers The formulation was completed with off-the-shelf additives from a well known manufacturer and a standard aggregate with a 0 - 12 mm grading curve. The grading curve was obtained from adapting the standard 0-16 mm curve from the Standard Concrete Association. The coarse size was reduced in order to improve the pumpability.

The aim was to obtain a shotcrete plug fast and safe, well casted in the rock (good adherence) and with a certain degree of “elasticity”. A plug of this type constructed in an underground mine will undergo a certain rock-concrete deformation under the expected hydraulic load on the upstream side. This deformation will transmit the hydraulic load throughout the plug mass to the host rock, producing a better sealing of the joint rock-concrete and increasing the total strength of the plug. Given that the pressure applied in the upstream side is hydraulic, another aspect to be taken into account for the plug performance is the hydraulic conductivity of the concrete, which should not be higher than that of the housing rock.

5.4.3.3.2. Preliminary tests

A series of tests were carried out in the Bierzo school-mine of Foundation Santa Barbara in order to check the behaviour of the formulation developed and to assure the feasibility of the plug construction operation in different working conditions with said formulation.

In first place it was considered one of the main operative problems that can arise when tackling the construction of a plug into an underground mine: the case that a concrete plant is not available reasonably close to the plug installation site, or that it is difficult to transport the concrete to the site. In this case, two solutions can be implemented (or a combination of them). In first place, the transport of concrete to the site with low-profile underground mixers, and in second place the on-site manual preweighing and mixing of the required amounts of concrete in mobile mixer. A manual mixing test was carried out and the concrete obtained was compared with the same concrete produced in an automatic mixing plant. No variations were found between the two batches of concrete, but the manual pre-weighing and mixing resulted in quite a laborious and time consuming operation.

The second case considered was that, due to constrained space or to restrain access, it is not possible to install the concrete pump close to the site, or that even if this is possible, there is no suitable access for a standard mobile concrete mixer or for a low-profile underground mixer to feed it. In this case, it is necessary to perform a long distance pumping of concrete from the closest suitable area for mixing and pumping, to the application point. A test was carried out simulating this situation by placing the concrete pump at a certain distance, over 90 m, from the application point. The concrete was pumped along a steel pipe with curves without problems.

Finally, a manual shotcrete test was carried out over wooden panels located into tunnel to tackle different aspects that could result problematic during the plug construction: feasibility of shotcreting without robot due to space constraints, potential heterogeneity of the concrete in the edges close to the rock, caused by a local rebound effect, and potential appearance of retraction cracks during the first hours of hardening caused by an excess of generated heat. The operator could perform the manual shotcreting without problems, obtaining a uniform thickness throughout the panel (see figure 5.4.17). The shotcrete obtained showed good adherence, little rebound, and an homogeneous appearance. The temperature of the shotcrete during hardening was below 26 ºC, and the analyses of samples carried out after 28 days of hardening yielded the expected results on compressive strength, between 10 MPa and 20 MPa, elastic modulus below 25 GPa, and hydraulic conductivity obtaining a value in the order of 1E-10 m/s.

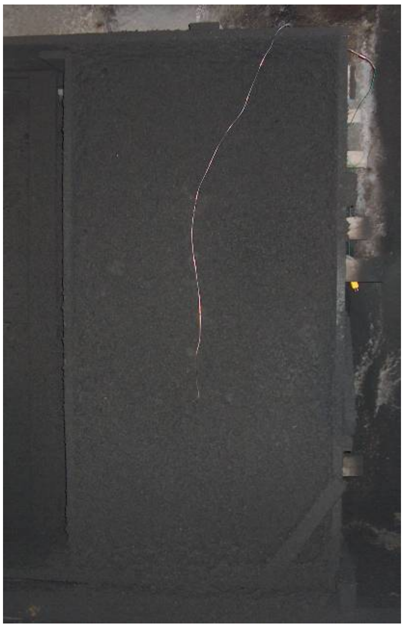


Figure 5.4.17: Shotcrete panel with temperature measure.

5.4.3.3.3. Plug calculation

In order to define the length of the plug, the reviewed bibliography recommends two ways to perform a manual calculation, according to the mechanical and to the hydraulic requirements that the plug is intended to fulfill. The length will be the longest of the two values obtained.

From W.S. Garrett and Campbell Pitt studies [1], in most cases the length is determined more by the leakage (hydraulic) than by the structural strength (mechanic). For this reason they recommend parallel plugs better than tapered ones, because the extra site preparation, with its subsequent increased rock de-stressing, time and cost, could not be justified. Given that the objectives pursued imply the construction of a plug in a fast way, a parallel plug has been considered for the project following those recommendations.

In this case, instead of performing a manual calculation, a numeric model was developed based upon the results obtained from analyses of samples. In order to simplify the calculation, instead of simulating the horseshoe shaped gallery of Figaredo, a 2D axisymetric model was considered for a cylindrical plug shape with a diameter of 3.5 m and a length of 4 m, having a vaulted upstream side, in order to help distributing the pressure against the host rock (figure 5.4.18). According to this model a pressure of 23 bar would be sustained without problems even in the event of total failure of the previous impermeabilisation. Given the approximate linearity of the relation plug length/pressure sustained, a plug of 1.6 m would sustain a pressure over 9 bar, which for the Figaredo mine provides a safety factor over 4, as the expected pressure would not exceed 2 bar in principle, and for the experimental test plug in Laciana school-mine of Foundation Santa Barbara would allow, with a length in the same order, a certain margin to check the behaviour of the plug at different pressures.

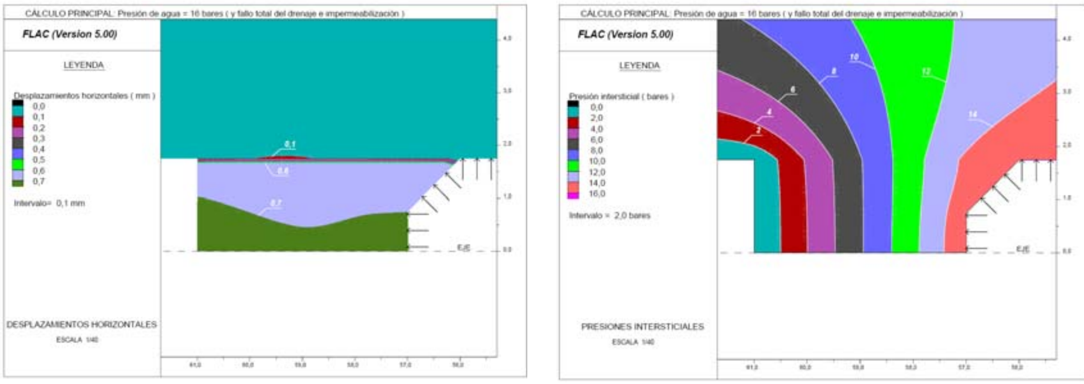


Figure 5.4.18: Numeric model developed.

5.4.3.3.4. Monitoring system

The monitoring of performance could be an essential component for a successful construction and operation of a plug in some cases. Instrumentation is used to determine the initial conditions at plug site, to survey the conditions during construction, and to carry out a long-term performance of the plug during its operation. Thus, the different elements and alternatives for monitoring systems for underground sealing plugs where studied and the information was compiled into a technical report.

This report included the recommended instrumentation for a wide range of plug performance supervisions, which effectively depend on the type of plug constructed and the functions to be fulfilled by the monitoring system.

The basic parameters to be monitored to assess the plug performance are:

- Pressures
- Movements and displacement
- Temperature
- Seepages
- Pressure release

The basic criteria for adequate instrument selection are:

- Use of off-the-shelf components as much as possible, seeking for availability.
- Reliability of measurements (range, resolution, accuracy, repeatability).
- Long-term stability and instrument longevity.
- Environmental conditions such temperature and humidity.
- Ease of automation for real time monitoring and efficient data management.

Other parameters to be controlled in some cases are the air quality (environmental measures): concentration of methane, CO and CO_2 in the gallery to avoid explosive atmosphere or poisonous and asphyxiating gases.

A general scheme of the instrumentation for a complete supervision of plug performance is shown in figure 5.4.19.

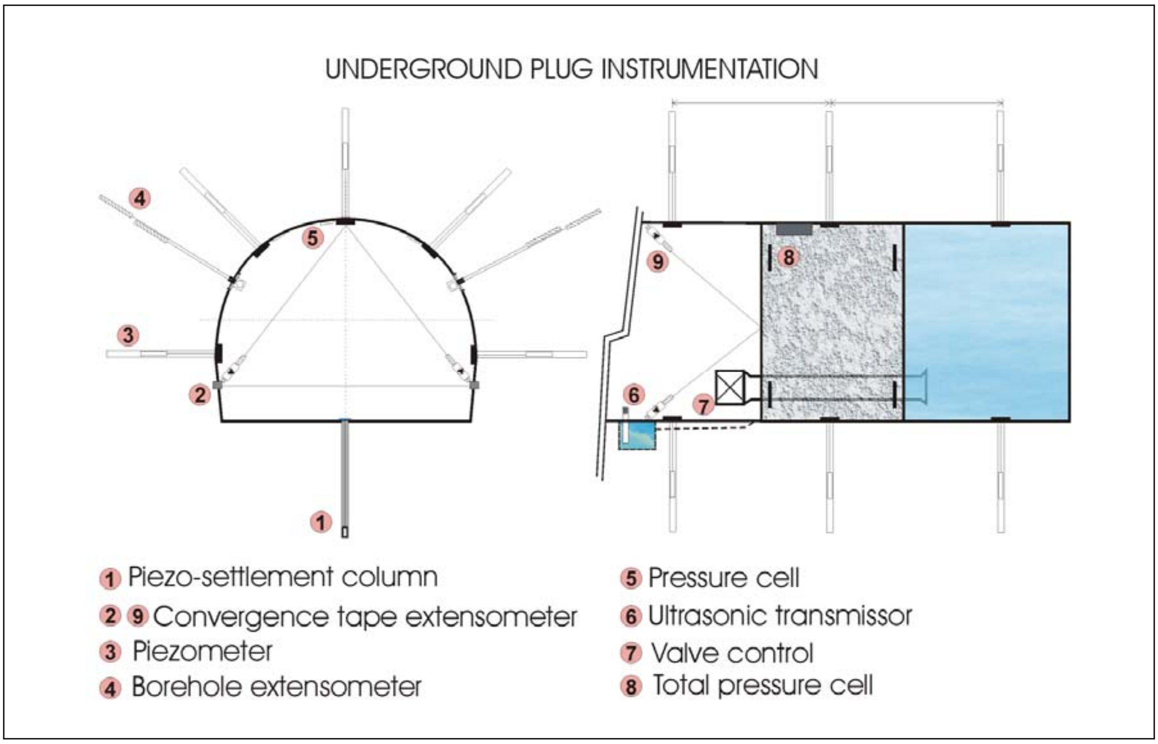


Figure 5.4.19: General scheme of instrumentation for a complete monitoring of an underground plug.

In the Laciana school-mine test plug, a pressure injection system was foreseen for the specific test under hydraulic pressure planned, consisting of a high flow, high pressure water pump with the necessary valves, connections and manometer to control and monitor the hydraulic pressure applied. Displacement sensors where foreseen too in the plug front to measure potential movements of the plug.

For the Figaredo mine plug, given the low requirement on hydraulic pressure sustained, only a measure of hydraulic pressure in the upstream side was foreseen.

5.4.3.4. Construction of underground test plugs

5.4.3.4.1. Test plug in Laciana school-mine

The experimental plug in the Laciana school-mine of Foundation Santa Barbara was constructed in January 2007. It was constructed into a dead end mine gallery wit horseshoe shaped section, leaving a short chamber in the rear end (figure 5.4.20). The plan was to inject water into that chamber, so to learn the behaviour of the plug under different hydraulic pressures. The following steps were taken for the construction:

1. The rock wall at the end of the gallery was first sprayed with a watertight membrane, in order to avoid the injected water flooding into the host rock, what would make difficult to increase the water pressure into the chamber.
2. The existing metallic supports were eliminated in the length of the plug. In this case, scaling was practically not necessary as the rock in that zone was quite intact, but it was necessary to remove the backfilled ground down to reach the intact rock ground.
3. Injection and deaireation tubes were installed, the latter finishing as high as possible in the water chamber to allow the maximum deaireation possible.
4. A wooden wall was constructed as a support for the first layer of shotcrete
5. The plug measuring 2 m in length was constructed by shotcreting in parallel layers with a thickness between 20 and 30 cm, leaving the chamber ready for water injection after a hard-

ening period of at least four weeks. The successive layers were shaped with certain concavity by spraying shotcrete first perpendicularly to the rock around the full edge of the layer and then continuing towards the centre of the section. In this way, the contact between concrete and rock was the best possible through the plug length, which is critical for the correct behaviour of the plug from the mechanical and hydraulic point of view.

6.

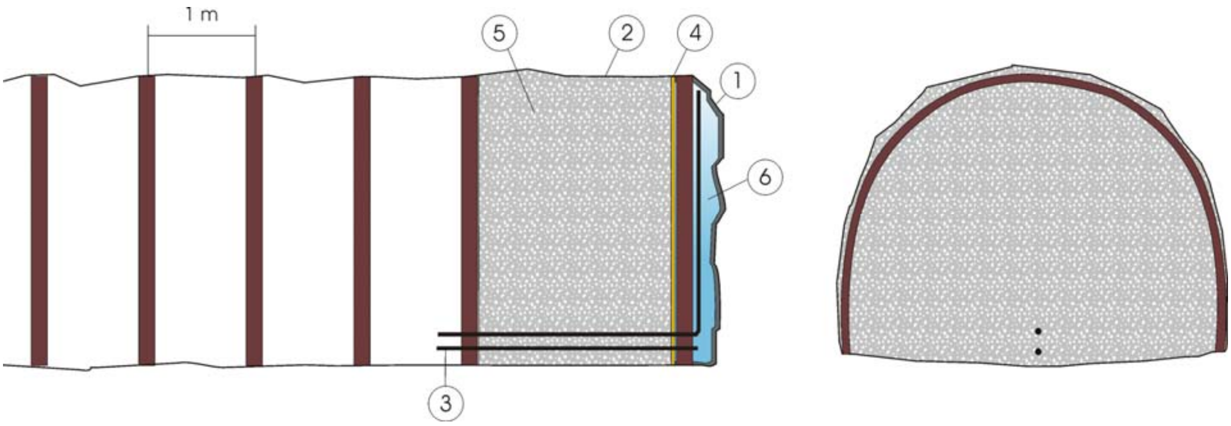


Figure 5.4.20: Experimental plug in the Laciana school-mine of Foundation Santa Barbara.

For the construction of the plug, the concrete was mixed in this case in a plant available in the same school-mine. The concrete was transported with a standard mobile mixer from the plant to the mine entrance, where it was transferred to an underground low-profile mixer. This run over trucks up to the construction site, where the concrete was loaded into the pump with a conveyor belt (figure 5.4.21).

Figure 5.4.21: Operative sequence for the underground plug construction in Laciana.

5.4.3.4.2. Test plug in Figaredo mine

The site selected in the Figaredo mine for the demonstration plug was the 7th floor, close to the operation loop where the pumping station and the access pit are located (figure 5.4.22). The characteristics of the gallery are: section 2UA, horseshoe shape, width aprox 3.5 m, height aprox 2.9 m and irregular surface.

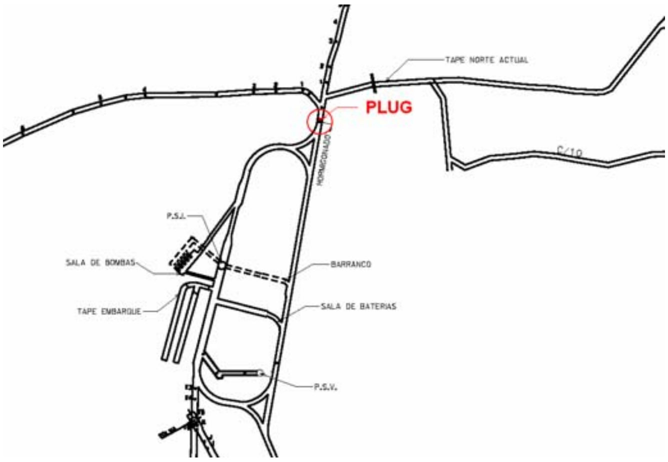


Figure 5.4.22: Plug location in 7th floor of Figaredo mine.

The plug constructed in this location allows the flooding of the north works up to the 6th floor. The water flows from 4th to 5th floor through an existing ventilation pit, and from this to 6th and then to 7th through two boreholes especially excavated. It also receives water from Barredo mine through a connection in the 5th floor (figure 5.4.23).

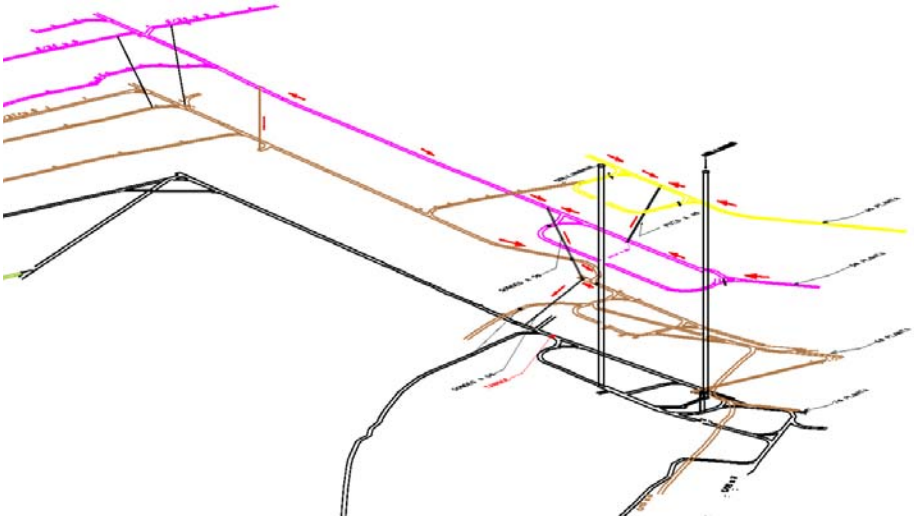


Figure 5.4.23: Water flowpaths in Figaredo mine.

After the preparation works in Figaredo mine, comprising deinstallation of rock support, rock scaling and cleaning, supply of ventilation, power and compressed air, and waterproofing of the rock in the upstream side, a plug measuring 1.6 m in length was constructed in February 2007. First a support was constructed at the upstream side, with tubes provided with the necessary valves passing through the plug for water pressure control, and afterwards the plug was done by shotcreting, again in parallel layers with a thickness of around 30 cm as already mentioned for the Laciana plug. The operative sequence was similar to that described for the Laciana plug. Desinstalar

Given the difficulties found to select the site, and the subsequent delay accumulated for the construction phase, the monitoring phase could not be started within the Project lifetime. With regard to the plug in the Laciana school-mine, the test under water pressure could neither be carried out for the same reason.

5.4.4. Results and conclusions

The main objectives of the work have been achieved: a comprehensive search on different underground sealing experiences around the world has been carried out, including the hydrogeological aspects involved, obtaining useful information that has been sorted, organised, and compiled. A thorough and difficult investigation of different potential sites has been carried out up to obtain a suitable site where to carry out a real case demonstrator of underground plug, in HUNOSA's Figaredo mine. Unfortunately the difficulties found have delayed the completion of this phase more that expected. The hydrogeology of the area has been studied and several conclusions have been extracted from this study. The plug has been designed and tests have been carried out to verify the feasibility of the construction from the point of view of the concrete formulation developed and the shotcrete technique selected. Finally, the plug has been constructed, and another additional plug has been constructed in a different underground site, in Laciana school-mine, to carry out a specific hydraulic pressure test in order to acquire additional knowledge on the behaviour of this type of plugs under different pressures.

The main conclusions drawn up from the work performed and the results obtained, both from the hydrogeological and from the constructive point of view, are listed hereafter.

According to the hydrogeology in the Figaredo test site, several conclusions have been obtained. They apply in particular to this area, although some of them can be extrapolated in general to other similar mining areas:

- Due to the existence of many mountain coalmines abandoned in Figaredo area, the infiltration of the rainfall into the mine is very fast and an important pumping is necessary in order to protect active areas of the mines from water coming from abandoned areas.
- The lag-time between rainfall and mine water discharge is very short, around two days in some cases.
- Nowadays, the coal basin is totally modified by the mining which one constitutes a catchment of underground water of big dimensions and complex geometry that changes notably the hydrodynamic system.
- In general, the mine water quality in the area is acceptable with electrical conductivity values around 850 µS/cm, pH slightly basic and very low iron content. For this reason, the effect that the water quality will have on the plug doesn't seem important. Nevertheless, it is quite possible that the characteristics of water would change in the long term due to a longer contact between groundwater and rock.
- According to the experience of San José Mine plugs, it is important to avoid possible preferential pathways open during the mining activities in order to guarantee the correct performance of the plugs.

With regard to the construction of underground sealing plugs, the main conclusions obtained are the following:

- The construction of underground plugs with shotcrete technique supposes a safe, fast and reliable method to seal abandoned mines, it is feasible even in difficult conditions or when the time factor is essential, and offers new advantages with regard to mass concrete plug construction, not only in terms of time and cost saving, but providing as well an improved sealing in the contact with the rock.
- The main operative problem found is the supply of concrete on site, but two different feasible ways to tackle it have been tested: the use of underground mixers and the in situ mixing.
- The length of the plug is determined upon the allowable hydraulic gradient and the shear strength of the concrete and surrounding rock mass
- A thorough geotechnical and hydrogeological assessment is recommended for any permanent plug in order to avoid preferential pathways and to guarantee the tightness of the plug.
- Instrumentation of the plug is recommended, and its monitoring will depend on the plug features, security design and expected service lifetime

After the hardening time of the plugs is completed, which will happen after the completion of the Project lifetime given the mentioned delay accumulated during the selection of site, the two plugs constructed will provide valuable information during the following months.

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