Modelling Minewater Flow and Quality Changes after Coalfield Closure.

Julia M. Sherwood

Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy, Department of Civil Engineering, University of Newcastle upon Tyne.

August 1997

Abstract

The changes that have taken place in the British Coal Industry over the last five years have meant that in many coalfields the last deep mines have closed. When a coalfield is abandoned and dewatering ceases groundwater levels rebound, threatening surface waters with polluting discharges. However, the sparse data sets available limit modelling with existing techniques.

A lumped parameter model GRAM (Groundwater Rebound in Abandoned Mineworkings) has been developed. This model conceptualises a coalfield as a group of 'ponds'. Each pond is an area of the coalfield that has been extensively worked and can be considered as a single hydraulic unit. The ponds are connected by pipes which represent major inter-connecting roadways along which flow is assumed to be turbulent. Discharge to the surface is also represented using pipes. Flow through the pipes can be calculated using either the Prandtl and Nikuradse or the Colebrook-White pipeflow equations. The storage coefficient can vary vertically to represent both worked Coal Measures and the intervening unworked strata. GRAM is able to predict the timing and volume of discharges. An iron component gives an indication of the water quality evolution of the discharges. Monte Carlo simulation allows the variables that have most error in their estimation to be represented by probability distributions.

The Dysart-Leven Coalfield in eastern Fife, Scotland has not been mined since 1985. However, dewatering has continued to protect the workings in the Frances colliery. In 1994 British Coal decided that Frances would never reopen, there is therefore no longer a need to continue dewatering. GRAM has been used to produce estimates of the quantity, timing and location of discharges from the Dysart-Leven Coalfield should pumping cease. MODFLOW has also been applied to the coalfield with less success. Water quality modelling was also attempted using GRAM's iron component, however, conclusive results will not be obtained until the three variables over which there is most uncertainty have been calibrated against existing discharges.

Acknowledgements

I would like to thank my supervisor Dr Paul Younger for his input and support. I am also indebted to Hendry Barbour at Bullen Consultants who involved us in the Frances and Michael Collieries Study for the Forth River Purification Board. Data was kindly provided by representatives of various agencies. In particular I would like to thank Bob Sargent, Richard Pennell, Sarah Thompson and Judy Proctor.

I am grateful to the Water Resources Group who have been a great help in many different ways. Particularly the PhD student seminar group who were a constant source of assistance and information. Russell Adams read the thesis and made useful comments and suggestions. Mick Riley provided comprehensive modelling advice. Dr Jean Clews and Dr Trevor Elliot made recommendations on a wide variety of issues.

On a more personal note, the following people deserve a special mention. Alice Hearne was my long suffering grammar consultant. Dr Tony Rex and Dr Shaun Salmon of Aspinwall gave me the courage of my convictions. Dr Sue White solved many logistical problems by making it possible for me to own a PC.

Finally I would like to thank my family and friends, who have been forced to live through these last few months with me.

"This island is made mainly of coal and surrounded by fish. Only an organising genius could produce a shortage of coal and fish at the same time."

Anuerin Bevan, Speech at Blackpool, 24th May 1945

"Coal's prospects have never been better."

Secretary of State for Energy, 1980, Speech on second reading of the Coal Industry Bill in the House of Commons, Hansard, 17 June, Col. 1377.

Table of Contents

List of Figures

List of Tables

List of Photographs

1 Introduction

1.1 Acid Mine Drainage

The problem of Acid Mine Drainage (AMD) has once again become topical in the UK over the last few years. On 13 October 1992 the closure of thirty one of the last fifty British Coal pits was announced. Twenty seven were to be closed permanently and four were to be put onto a 'care and maintenance' regime. By the end of 1992 the number of closures had been reduced to twenty one. However, the cuts were still of a sufficient size to have a large impact on the British Coal Industry.

Whilst one pit in a coalfield remains open the operators are forced to continue dewatering to protect the active workings from water inflow from adjacent abandoned workings. With the closures announced in 1992, some coalfields lost their last remaining pits. There was therefore no longer a need to continue dewatering. If dewatering is ceased the result is groundwater rebound, threatening surface water courses with discharges of AMD. In addition to polluting discharges the possible impacts of rising groundwater are erosion of subsurface infrastructure, methane emissions and leaching from landfills.

Operators of collieries closed prior to the end of 1999 are not legally responsible for polluting discharges resulting from the cessation of pumping. Until then, solutions to the problem will be the result of negotiation between the mining operator and the regulators (the Environment Agency / Scottish Environment Protection Agency and the Coal Authority).

Treatment techniques are land-intensive and dependent on the quality and quantity of discharges. This has meant that there has been increasing interest in modelling groundwater rebound, to predict the timing, location, quality and quantity of discharges. However, the type of data which are necessary for the application of standard groundwater modelling packages are not available, because the Coal Measures have generally not been saturated since the widespread development of permeability by mining.

Collection of appropriate data would mean allowing the groundwater to rise, without really knowing what the implications are. Even with appropriate hydrogeological data the assumptions implicit in standard modelling approaches would make modelling an unenviable task.

Standard groundwater modelling approaches apply Darcy's Law, which assumes a simple porous media in which flow is laminar. Flow through roadways in the mineworkings is likely to be turbulent, bearing more similarity to channel flow than laminar groundwater flow.

One approach used in fracture flow modelling is to represent fractured strata as an Equivalent Porous Medium (EPM). Effective parameters are assigned which produce a volumetric flow pattern similar to that in the fractured strata. However, due to the limitations inherent in assigning effective parameters, this type of model is able to reproduce regional rather than local conditions. Other approaches used in fracture flow modelling such as Discrete Fracture models, require vast amounts of detailed structural data. However, this may be overcome using a stochastic approach.

Analytical models of water in mineworkings, such as the Deep Mine Model (Ricca and Hemmerich, 1978) require vast amounts of data. Rogoz (1994) has developed a model that represents the rise in water level, in abandoned mineworkings, without the need for excessive amounts of data. However, the model assumes that at least one mine in a coalfield is working and that once rebound reaches a point at which it flows into active workings, it is pumped away. The limitations of existing modelling techniques means that a new approach is required to model groundwater rebound and predict surface discharges of AMD.

1.2 Aims of Project

The main aim of this study was to develop a new approach for modelling groundwater rebound through abandoned mineworkings by producing a simple conceptual model of the mineworking environment. The model must not be data intensive and should make allowances for the accuracy of the data which are available. The model should be able to predict the timing, location and quantity of discharges.

The model will be verified by application to a case study (the Dysart-Leven Coalfield). Standard groundwater modelling software will also be applied to the case study. Comparison of the different methods, should illustrate the strengths and weaknesses of both approaches.

A method of predicting the quality of AMD discharges would significantly improve the value of the flow modelling. The results of any water quality predictions should be compared with those produced by existing geochemical modelling codes.

1.1 Summary of Thesis

Chapter 2 consists of a literature review which provides a context for the modelling work. The literature is divided into six sections. The first section describes the generation and chemistry of AMD. The second section lists the potential impacts of AMD, illustrating these with the Durham Coalfield case study. The third section discusses solutions to the problem of AMD. These include, conventional (active) treatment, passive (wetland) treatment, and continued pumping to prevent the generation of AMD. The fourth section covers the UK Coal Industry, its history and the legal situation regarding pollution. The fifth section characterises the hydrogeology of worked Coal Measures and the final section outlines models that have been applied to water in mineworkings.

Chapter 3 describes the development of GRAM (**G**roundwater **R**ebound in **A**bandoned **M**ineworkings) which is a semi-distributed, lumped parameter model. GRAM's conceptual model represents a coalfield as a series of 'ponds' connected by pipes. Flow modelling of the Dysart-Leven Coalfield using both GRAM and MODFLOW is described in Chapter 4. In Chapter 5, water quality modelling is addressed. This consists of the development of an iron component for GRAM and its application to the Dysart-Leven Coalfield. Chapter 6 comprises the conclusions. This summarises the work done in this study and makes recommendations for further work.

2 Literature Review

2.1 Acid Mine Drainage

2.1.1 The Generation of Acid Mine Drainage

Acid Mine Drainage (AMD) is a specific type of water pollution associated with the mining of coal or metalliferous deposits. Typically AMD has a low pH and a high metal content (particularly iron). However, the nature of discharges is diverse (see Section 2.1.3). In England and Wales 200 km of waters are currently affected by AMD, most of these discharges are from abandoned coal mines (NRA, 1994). AMD can be generated in surface spoil heaps, opencast or deep mines.

The creation of AMD in deep mines occurs in three stages. First, when the groundwater is pumped to allow mining, pyrite (FeS_2) is exposed to air. It is oxidised forming sulphates and iron oxides. Prior to pumping pyrite oxidation only occurs on a small scale, therefore water quality is generally not a problem. Mining results in physical changes in the coal measures strata such as fissuring and bed separation, this allows air to enter the strata and circulate freely oxidising any pyrite present (Henton, 1979).

Second, if the sulphates and iron oxides come into contact with water they are dissolved into solution. This occurs on a small scale with pumped discharges; however, in general pumped discharges from mines are of reasonable quality (Glover, 1983). Harper and Olyphant (1993) indicate that recharge to groundwater in coalfields flows to the water table through a few well washed pathways. These pathways have already had the iron oxides and sulphates dissolved. Since the groundwater level is largely stationary it does not encounter large quantities of sulphates and iron oxides. Large scale hydrolysis of the sulphates and iron oxides only occurs when the groundwater level rebounds with the cessation of pumping.

Finally, when waters rich in ferrous iron (Fe^{2+}) emerge at the surface there is a rapid oxidation to ferric iron (Fe^{3+}), which then hydrolyses and forms FeOOH or $Fe(OH)_3$.

This precipitates as an orange ochre that coats the stream bed and banks. AMD may also contain other dissolved metals which will precipitate as oxides or hydroxides, such as manganese which produces a black deposit and aluminium that forms a white hydroxide (Hedin *et al*, 1994).

2.1.2 The Nature and Source of Pyrite

The oxidation of pyrite is the first step in the generation of AMD. Pyrite occurs in two basic forms, organic and inorganic; the latter is the type more common in coal measures. It is generally found in the form of iron disulphide, either as marcasite or more frequently as pyrite. Pyrite is usually found in high concentrations in the upper 300 - 450 millimetres of the coal seam and in the overlying shales. It is found as nodules, streaks and disseminated crystals (Cairney and Frost, 1975; Caruccio and Ferm, 1974; Casagrande, 1987; Emrich and Merritt, 1969).

Williams and Keith (1963) concluded that the presence of marine waters during or soon after deposition is one of the determining factors influencing the variation of pyrite content within coal measures. It was statistically proven that a regional variation in sulphur content was associated with the presence of marine-deposited overburden.

Caruccio (1970) reports that the amount of pyrite present in a sample is not always proportional to the amount of acidity produced and concludes that fine grained framboidal pyrite is significantly more reactive than euhedral pyrite. It is therefore the nature of pyrite rather than the pyrite content of the strata that determines the polluting nature of AMD. Caruccio and Ferm (1974) argue that mapping the different environments of coal deposition results in a predictive map for framboidal pyrite and hence potential AMD production. However, Morrison *et al* (1990) cite studies where no relationship has been found between framboidal pyrite and acid generation, though relationships with both grain size and marine depositional environments were found.

The natural concentrations of pyrite are often augmented by mining. In order to conform to sulphur dioxide emission standards, coal with a high sulphur content has to be treated. Therefore, coal which has high sulphur levels is less economically attractive. For this reason, coal that has a high pyrite content is more likely to be left in the mine or in spoil heaps. This material will be highly fragmented resulting in a large surface area being available for pyrite oxidation.

2.1.3 Typical Chemical Characteristics of AMD

Caruccio and Ferm (1974) describe typical AMD discharges with a pH of around 2, acidities in the form of H^+ of 4 - 20 mg/l, sulphate content of 500 - 12000 mg/l and ferrous iron content of 50 - 500 mg/l. However, Henton (1979) shows that where coal measures are rich in pyrite the iron content of AMD can reach 2000 mg/l.

Subsequent work has shown a greater diversity in the nature of AMD, when it discharges at the surface. For example, AMD can have a near neutral pH if it has passed through strata (such as limestone) which will result in a high level of alkalinity from carbonate dissolution (Cairney and Frost, 1975; NRA, 1994).

Younger and Bradley (1994) studied the hydrochemistry of five discharges in the Durham area that varied widely in nature. (See Table 2.1 and Figure 2.1.) Three of the discharges have a near neutral pH.

It seems reasonable to accept that it is carbonate dissolution creating alkalinity at the St Helens where there is substantial groundwater inflow from the Magnesian Limestone (Younger and Bradley, 1994). However, Broken Banks and Stoney Heap are not close to such an obvious source of bicarbonate, neither is the chemistry consistent with this explanation (Younger and Bradley, 1994).

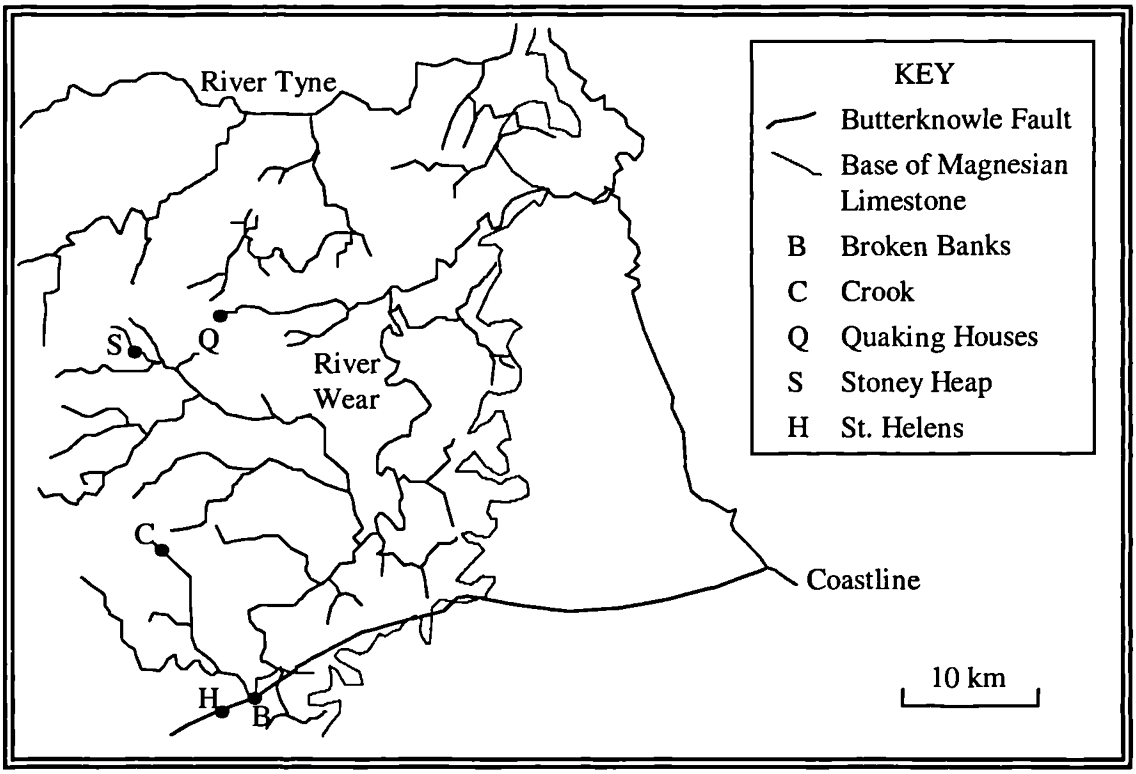
Another explanation is indicated by the comparatively low sulphate concentrations and Eh values of the discharges and the presence of hydrogen sulphide at both sites. These observations suggest that the alkalinity is being generated by microbial sulphate reduction close to the point of discharge (Younger and Bradley, 1994).

Table 2.1: Hydrochemistry of Durham AMD Discharges at First Emergence.

Site Grid Ref:	Broken Banks NZ 197295	Crook NZ 185356	Quaking Houses NZ 178509	Stoney Heap NZ 147515	St Helens NZ 197269
Flow rate (m^3/s) (on 15/4/1994)	0.1328	0.00194	0.0067	0.0256	0.01
Calcium (mg/l)	100.70	185.29	255.20	83.58	262
Magnesium(mg/l)	61.232	93.15	102.79	49.69	107
Sodium (mg/l)	26.86	21.52	463.62	27.87	80
Potassium (mg/l)	10.69	6.78	57.04	6.7	13
Iron (total) (mg/l)	1.76	79.84	17.96	26.32	1.84
Manganese (mg/l)	0.998	6.97	4.78	1.2	1.68
Aluminium(mg/l)	0.261	4.18	12.94	0.156	0.0413
Zinc (mg/l)	0.023	0.045	0.04	0.022	0.0184
Copper (mg/l)	0.110	0.230	0.228	0.097	0.0110
Alkalinity (mg/l as $CaCO_3$)	364.0	0	0	188.0	357.0
Sulphate (mg/l)	137.0	810.0	1358.0	325.0	890.0
Chloride (mg/l)	60.0	65.0	1012.0	102.0	75
pH	6.5	4.8	4.1	6.3	6.4
Temperature (°C)	10.9	11.8	11.2	10.3	12.0
Eh (mV)	39	264	327	36	-50
Conductivity	1177	1563	3560	1134	2360

After: Younger and Bradley (1994)

Figure 2.1: Location of Uncontrolled Discharges of AMD in the Durham Coalfield Identified by Younger and Bradley (1994).



After: Younger and Bradley (1994)

2.1.4 The Chemistry of AMD

The overall chemistry of AMD formation can be simply described by Equation 2.1.

$FeS_2 + {}^{15}/_4O_2 + {}^{7}/_2H_2O$ ------> $Fe(OH)_3 + 2SO_4^{2-} + 4H^+$ **Eqn: 2.1**

The following equations describe the most common process of pyrite oxidation and hydration in coal mines. The first two reactions occur when the water level is lowered by pumping. Initially the crystalline pyrite is oxidised to form ferrous iron as in Equation 2.2.

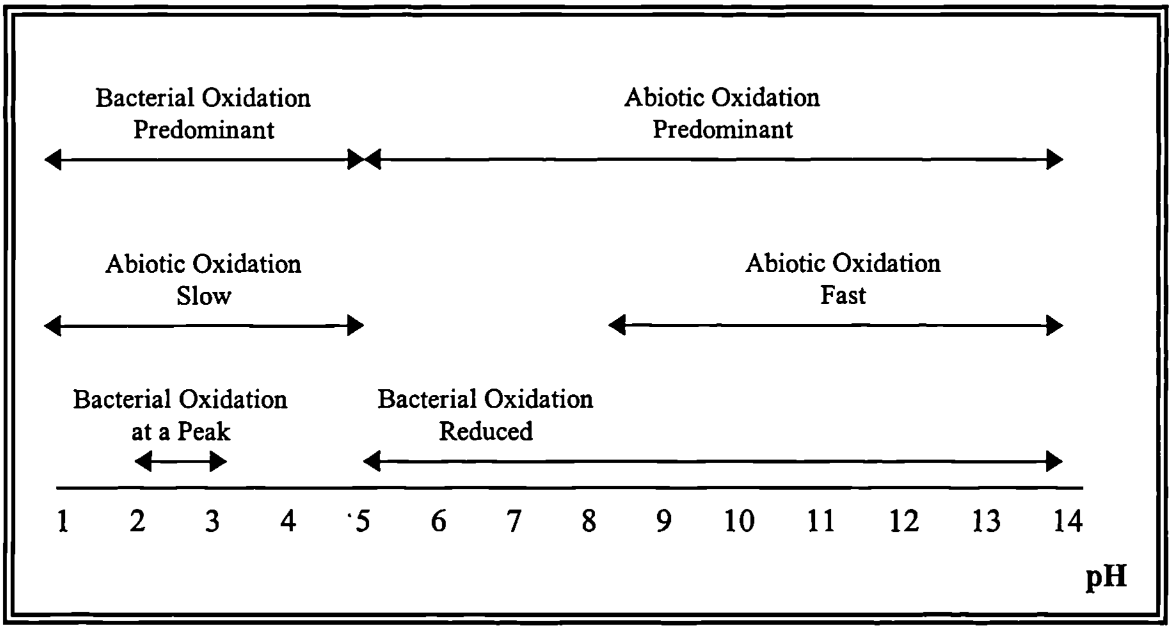
$FeS_2 + {}^{7}/_2O_2 + H_2O$ ------> $Fe^{2+} + 2SO_4^{2-} + 2H^+$ **Eqn: 2.2**

This ferrous iron then undergoes oxidation to become ferric iron. Singer and Stumm (1970) note that the oxidation of ferrous iron is the rate determining step. This is represented in Equation 2.3.

$Fe^{2+} + {}^{1}/_{4}O_2 + H^+$ ------> $Fe^{3+} + {}^{1}/_{2}H_2O$ **Eqn: 2.3**

Ferrous iron oxidation occurs both abiotically and as a result of bacterial activity. Abiotic iron oxidation is dependent on pH when oxygen is not limiting. It slows a hundred fold for every unit decrease in pH. The rate of the abiotic oxidation is fast when the pH is greater than 8, but slow when it is less than 5. Bacterial oxidation of ferrous iron is at an optimum between a pH of 2 and 3 and is reduced at a pH greater than 5 (Hedin, *et al* 1994). Therefore at pH above 5 abiotic oxidation predominates and at pH below 5 bacterial oxidation is the primary process (see Figure 2.2).

Figure 2.2: Relative Rates of Bacterial and Abiotic Iron Oxidation.



The iron bacteria *Thiobacillus ferrooxidans* and *Ferrobacillus ferrooxidans* are significant in the oxidation of pyrite (Norton, 1983; Robb, 1992). Initially pyrite oxidation is slow and proceeds by both air oxidation and bacterial catalyst. When the pH is lowered to 4.5, *Thiobacillus ferrooxidans* has on additional role, accelerating iron oxidation (Barton, 1978). At approximately pH 4.2 *Ferrobacillus ferrooxidans* achieves rapid rates of iron oxidation (Silverman *et al*, 1963). As the pH is lowered the acceleration in oxidation rate caused by bacteria increases. *Thiobacillus ferrooxidans* has been shown to accelerate the oxidation of iron by more than a million fold at pH values less than 3.5 (Barton, 1978). However, if the pH approaches 2.5 the oxidation rate begins to reduce again (Silverman *et al*, 1963).

Bryner *et al* (1967) studied the effect of temperature on pyrite oxidation. For the biological oxidation of pyrite the optimum temperature was found to be near 35 °C and a minimum amount of oxidation was observed at 65 °C.

As ferrous iron is oxidised to form ferric iron, it is subject to hydrolysis reactions that can precipitate it as a hydroxide, as in Equations 2.4 a and b.

$Fe^{3+} + 2H_2O$ -------> $FeOOH + 3H^+$ **Eqn: 2.4a**

$Fe^{3+} + 3H_2O$ ------> $Fe(OH)_3 + 3H^+$ **Eqn: 2.4b**

This occurs abiotically and is dependent on pH. With a pH of less than 2.5 there will be negligible dissolved ferric iron; however, if the pH is more, significant amounts may be in the minewater (Hedin *et al*, 1994). Singer and Stumm (1970) propose a relationship with pH, which suggests that ferric iron hydrolysis processes change from being very rapid in rate at pH greater than 3 to very slow at pH less than 2.5. The precipitation of FeOOH depresses the pH further.

When the groundwater rebounds the hydrolysis of ferric iron produces ferric hydroxide and also lowers the pH. When the pH reaches 2.5 the kinetics of iron hydrolysis slow so that ferric iron remains in solution. Ferric oxidation of pyrite then occurs. This is a fast reaction and results in an exponential increase in acid production which is dependent upon the bacterial oxidation of ferrous iron (Kleinmann, 1981).

Ferric iron is reduced by pyrite, producing ferrous iron (see Equation 2.5). The ferrous iron re-enters the cycle at the second reaction (Equation 2.3) (Ahmad, 1974; Robb, 1992; Stumm and Morgan, 1981).

$FeS_2 + 14Fe^{3+} + 8H_2O$ -----> $15Fe^{2+} + 2SO_4^{2-} + 16H^+$ **Eqn: 2.5**

Ferric hydroxide is the orange deposit observed when AMD pollutes surface waters. The AMD may be clear when it reaches the surface; because if there is little oxygen underground the iron will remain in solution. However, when it reaches the surface it mixes with air and the iron rapidly oxidises to the ferric form and precipitates out as an orange deposit as in Equations 2.4 a and b (NRA, 1994).

To summarise, the factors that influence the rate and extent of the oxidation include oxygen availability, pH, pyrite grain size, temperature, bacteria activity and the presence of water.

Details of the Bacterial Oxidation of Pyrite

Atkins and Singh (1982) describe the biochemical reactions responsible for the bacterial oxidation of pyrite. The extent of the influence of bacteria is dependent on biochemical conditions, such as temperature and pH. Bacterial oxidation of pyrite can be divided into direct and indirect mechanisms.

The direct mechanism involves the bacteria using the sulphur, ferrous ions or sulphide ions as an energy source. This is expressed by Equation 2.6.

$4FeS_2 + 15O_2 + 2H_2O$ ----Bacteria----> $2Fe_2(SO_4)_3 + 2H_2SO_4$ **Eqn: 2.6**

This may occur in two stages with ferrous iron being produced at the intermediate stage. See Equations 2.7 and 2.8.

$2FeS_2 + 2H_2O + 7O_2$ ----Bacteria----> $2FeSO_4 + 2H_2SO_4$ **Eqn: 2.7**

$4FeSO_4 + O_2 + 2H_2SO_4$ ----Bacteria----> $2Fe_2(SO_4)_3 + 2H_2O$ **Eqn: 2.8**

The indirect mechanism involves the ferric ions being the primary oxidant, producing a metal sulphide and reducing itself to the ferrous state (see Equation 2.9). Bacteria oxidise the ferrous ions to the ferric state (see Equation 2.10) regenerating the cycle (Atkins and Singh, 1982).

$FeS_2 + 7Fe_2(SO_4) + 8H_2O$ ----> $15FeSO_4 + 8H_2SO_4$ **Eqn: 2.9**

$2FeSO_4 + H_2SO_4 + {}^1/_2O_2$ ----Bacteria----> $Fe_2(SO_4)_3 + H_2O$ **Eqn: 2.10**

2.1.5 Classification of AMD

Glover (1973) defined a scheme of classifying minewaters in working mines. It relies on pH and iron content as defining parameters. The categories are as follows:

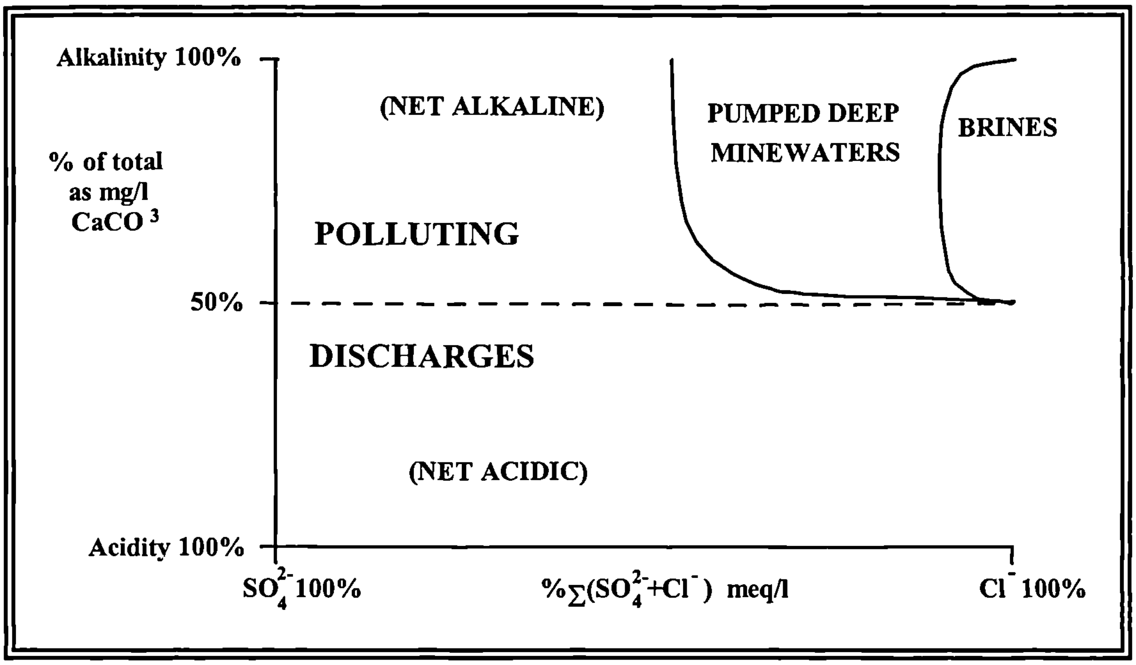
1. acidic with low total iron concentration
2. acidic with high ferric iron concentration
3. acidic with high ferrous iron concentration
4. neutral with high ferrous iron concentration
5. suspended ferric hydroxide (with dissolved ferric or ferrous iron)

This classification was evolved for water from working mines which is significantly different in nature from AMD associated with abandoned mines. The chemical information this classification provides is sparse making it limited when choosing a method of treatment.

A method of classification that was developed specifically for this purpose is defined by Hedin *et al* (1994). It divides AMD into net alkaline and net acidic categories. In the case of AMD, alkalinity is predominantly a measure of the bicarbonate content. Acidity is not only a measure of the proton activity expressed by pH, but also the mineral acidity and organic acidity. In AMD organic acidity tends to be negligible. Hence the acidity of AMD is a measure of the proton activity and the mineral acidity from dissolved iron, manganese and aluminium (Hedin *et al*, 1994). This classification covers virtually all the major elements of AMD neglecting only the sulphate and chloride content (Younger, 1995).

Younger (1995) has progressed from this point by plotting the alkalinity / acidity percentage against the sulphate to chloride ratio. By this method a discharge can be defined by its location on the graph, (see Figure 2.3). For example, if a discharge has a high level of alkalinity, the source of this alkalinity can be inferred by its displacement along the x-axis. If the source of alkalinity is carbonate dissolution it will be placed closer to the y-axis than if it is microbial sulphate reduction.

Figure 2.3: Classification of AMD by Plotting Alkalinity / Acidity Percentage Against the Sulphate to Chloride Ratio.



From: Younger (1995)

2.1.6 AMD Discharge at the Surface

As the level of groundwater in abandoned mines rises it reaches a point where it can discharge at the surface. There are two routes by which AMD may enter surface waters. It may augment the baseflow of water courses on, or adjacent to, the coalfield. Discharges may also occur through old springs or the products of mining such as shafts, adits, boreholes, or points of weakness caused by subsidence (Henton, 1979; Forth River Purification Board, 1981; Puente and Atkins, 1989; Wilkinson and Brassington, 1991; Whitelaw, 1993).

2.2 The Impacts of AMD

2.2.1 Groundwater Pollution

Pollution in a coal measures aquifer, can lead to the pollution of adjacent aquifers and their loss as a water resource. One aspect of the serious nature of groundwater pollution is that it is a long-term problem (Fetter, 1992).

2.2.2 Surface Water Pollution

When AMD discharges into streams and rivers the iron oxidises to the ferric form and precipitates out as an orange ochre deposit, as described in Sections 2.1.1 and 2.1.6. This orange discharge coats the banks and bottoms of polluted water courses, immediately reducing their amenity value. The National Rivers Authority (NRA) compiled a list of length of water course affected in England and Wales (NRA, 1994). These are shown in Table 2.2.

Table 2.2: AMD Discharges in England and Wales

NRA Region	No. of discharges from underground mines	km affected by AMD
Northumbria	15	18
North West	14	57
Severn Trent	4	19
Welsh	21	54
Yorkshire	most of the total 36 discharges	50
Total	100	198

The Impact on the Economic Use of a Water Course

AMD discharge into surface waters can result in the imposition of restrictions on users of the water course. It becomes unsuitable for irrigation, livestock watering and potable or industrial water supply. There may also be significant consequences for shell fisheries, conservation areas, recreation and tourism (NRA, 1994). If the water contains more than 300 mg/l of sulphate, it is harmful to crops and if water with a high sulphate content is used in domestic supply it can act as a laxative (Lemon, 1991). Warner (1973) reports a case of cattle who drank AMD getting gastric ulcers.

The Impact on Surface Water Flow

When groundwater is pumped to facilitate mining it is usually discharged into a nearby water course. The artificially low level of groundwater generally means that the surface waters receive no baseflow. Therefore whilst groundwater rebound occurs, after pumping ceases, the flow in the water course will be depleted. If the pumped discharge is being used to dilute sewage effluent, the dilution ratio will be reduced.

The Impact on the Aquatic Environment

AMD is not only unsightly but also extremely detrimental to the water course ecology. After a discharge has occurred, even if it possible to divert it, it can take a long time for natural conditions to return. Turnpenny *et al* (1987) in a study of upland streams in England and Wales showed that fish communities in streams with a low pH are less diverse and prolific than those in streams with a neutral pH.

The ferric hydroxide coats the bed and banks in an orange ochre that blankets the habitat of benthic organisms that provide food for fish. The turbid nature of the water cuts down the amount of light available. In extreme cases this can deplete plant life and fish are driven out of the stream (Forth River Purification Board, 1981).

Heavy metals are dissolved into the acidic conditions of stream water which is polluted by AMD. These conditions can be highly toxic to fish; the high metal content can cause gill disease and low pH results in fish deaths. There may also be deposition of iron on the perivitelline membrane covering their eggs (Barton, 1978). AMD ruins the spawning gravels for fish by occluding the interstices of the gravels with fine sediment. Natural game fish, salmon, sea trout and trout are particularly susceptible to such pollution.

Scullion and Edwards (1980) report on the effect of AMD on the River Taff in South Wales. Downstream of the discharge, brown trout occurred at very low densities due to impoverished food supply rather than the direct effect of toxicity. It was also noted that reaches which were subject to AMD had egg mortalities in excess of 80 %.

Warner (1973) describes a stream affected by AMD in West Virginia. Stretches with a pH between 2.8 and 3.8 were inhabited by low diversities of benthic invertebrates (3 - 12 taxa) and 10 - 19 species of attached algae. Stream reaches with a median pH of 4.5 supported larger communities of 25 taxa or more of invertebrates and over 30 species of attached algae. High concentrations of acidity, iron, sulphate, hardness, calcium and aluminium produce an intricate and changing environment. The toxicity of AMD to aquatic organisms is a function of a variety of factors. However, pH provides a measure of the effect of AMD on aquatic life.

Jarvis (1994) found that the dominant influences on biotic diversity and abundance were acidity and iron concentrations. However, with distance downstream from a discharge acidity becomes the prevailing factor.

2.2.3 Geotechnical Impacts

Infrastructure

When groundwater rebound occurs it is often the case that the water level has previously been established at a lower level for centuries. Therefore, much of the infrastructure and construction over the area has been built under the tacit assumption that the depressed level is the norm. Wilkinson and Brassington (1991) cite examples of basements, foundations, sewers, water pipes and tunnels for both transport and cables, which have all been built during periods of depressed water table which are actually below the level at which the groundwater would rest without pumping. When rising groundwater intercepts sewers, the risk of pollution is augmented due to an increase in storm water overflows (Turner, 1993). There can also be problems at sewage treatment works, which are unprepared for water that has been polluted by AMD.

The high sulphate content of AMD is a particular problem where inundation of infrastructure is concerned. Sulphates in solution react with tricalcium aluminate within Portland Cement causing expansion, which leads to the breakdown of concrete and brickwork constructions (NCB, 1975). In addition, the movement of groundwater will replenish the sulphates removed by the reaction thereby maintaining the attack (Building Research Establishment, 1977).

Subsidence

In the long term inundation of abandoned workings is regarded as having a beneficial effect on the stability of workings, by adding buoyancy and reducing the total stress taken by the supporting pillar and walls (Henton, 1974; NCB, 1975; Whittaker and Reddish, 1989; Turner, 1993). Henton (1974) argues that we know very little about the effect of rising groundwater on the geology itself. Inundation of workings can cause an acceleration of the weathering of the material (Taylor and Spears, 1970). Norton (1983) describes the settlement of backfill as water rises through it, causing void migration and crownhole development leading to subsidence. Denby *et al* (1982) argue that water can significantly reduce the shear strength of coal measure rocks. With the water being of poor quality we know little of the detrimental effect it will have on the stability of the geology.

Partial extraction (bord and pillar) workings are likely to be more vulnerable to subsidence caused by the rising groundwater than more modern methods of extraction such as longwall mining. The NCB (1975) describe how in bord and pillar workings pillars can be forced through a soft floor particularly if it is wet. The most likely sites for subsidence are the entries to shafts and adits and the roadway junctions in bord and pillar workings all of which are likely to be close to the surface (Turner, 1993). These sites are the oldest which are therefore likely to be unmapped and abandoned in the absence of decommissioning guidelines. Smith and Colls (1996) working on the

Leicestershire Coalfield found that the earliest shallow mines were not recorded in plan, but in many seams were connected to later deeper workings.

Slope Stability

An increase in water content in both drift and rock slopes can lead to failure. Thus slope instability will be associated with groundwater rebound, particularly at mine openings (Turner, 1993).

2.2.4 Methane Emissions

Methane emissions from coal measures disturbed by mining have long been a problem. At concentrations in the air of 5 - 15 % it is explosive (Curl, 1978). Between 1851 and 1980 there were 186 major explosions caused by methane in British coal mines (Creedy, 1991). Whilst a colliery is active it is ventilated and the methane is controlled. However, with the closure of collieries, rising groundwater can displace the gas causing it to be emitted unchecked at the surface (Reeves, G., University of Newcastle upon Tyne, Personal Communication, 1993). Alternatively should it form trapped pockets in the voids left by mining there would be an increased risk of explosions (Turner, 1993).

2.2.5 Leaching from Landfills

Jackson (1993) cites three main impacts of rising minewater on landfill sites. If the rising minewater reaches a level at which it inundates a landfill, the result will be an increase in the rate of leachate production. This water will also displace air and cause anaerobic conditions which leads to the production of landfill gas. Finally the low pH of the minewater will result in the mobilisation of heavy metals and in consequence the leachate will contain increased concentrations of these metals.

2.2.6 Durham Coalfield Case Study

The Durham Coalfield in the north-east of England is 500 km^2 in size extending from the River Wear in the north to where the Brockwell seam outcrops (beyond Bishop

Auckland) in the south. (See Figures 2.2 and 3.1.) The area has a long history of coal mining. An early example of deep mining using the bord and pillar method dates from the early fifteenth century (Atkinson, 1966). However, it was not until the invention of the Newcomen pumping engine in the early eighteenth century that deep mining became widespread and the lowering of the groundwater levels began throughout the coalfield.

When Michael Heseltine announced the closure of 31 pits in October 1992 these included the last two remaining pits in County Durham. Whilst Easington and Vane Tempest continued to operate, the main hydrologically linked part of the coalfield had to be pumped to protect them from water inflow. Due to local political pressure the inland pumping stations continue to operate despite the closures. Ceasing to pump would lead to groundwater rebound throughout the coalfield and generation of AMD on a large scale. This will potentially have an impact on the ground and surface waters and lead to geotechnical problems.

Groundwater Pollution

The Permian Basal Sands and the Magnesian Limestone are important aquifers which provide a large proportion of County Durham's water. They supply Hartlepool and a third of Sunderland (Minett, 1987; Younger, 1993). The limestone is the more important aquifer and generally produces good quality water. This water typically has a neutral pH, a total hardness of 500 mg/l and a total dissolved solids concentration of 700 mg/l (Younger, 1993). The water from the limestone will therefore buffer the pH of polluted water from the Coal Measures. Consequently inflow from the coal measures will increase the storage of the aquifer. However, the water in the Basal Permian Sands will not buffer the pH of the AMD and could be lost as a source of water.

Jackson (1993) investigated the potential impacts of rising groundwater on the landfill sites of County Durham. Three sites in the south-west of the coalfield which were likely to be affected soon after pumping ceases were identified. Whilst in the longer term five sites in the Team valley and two in the Lumley area are vulnerable.

The Impact on Surface Waters

The water pumped from the nine inland pumping stations in the Durham Coalfield to maintain the water table at a low level is of a reasonable quality and is discharged into the Rivers Wear and Team (Younger, 1993). The Kibblesworth discharge (25.7 Ml/d) acts to dilute sewage effluent in the River Team.

The obvious areas in which there are likely to be surface discharges of AMD are the Rivers Wear and Team. North East Water's treatment plant at Lumley presently takes water from the River Wear. Water quality deterioration due to AMD could result in the works having to be substantially upgraded or completely abandoned. Harbourne (1994) values the works at £15 - 30 million. Replacement costs have been estimated at £24 million (Hansard, 1994).

County Durham, in particular Durham City and its cathedral, has a significant tourist industry. Should AMD reduce the aesthetic value of the River Wear there is likely to be a loss of revenue (Harbourne, 1994).

The potential impact of AMD on the flora and fauna of the River Wear is a cause for concern. In 1990 the stretch of river that is most likely to be affected by pollution was classified as a 1B by the NRA (Hansard, 1993). Younger and Bradley (1994) examined five streams in County Durham that are presently polluted by AMD, the hydrochemistry of these streams is shown in Table 2.1. Work done by Jarvis (1994) on the Stoney Heap and Crook discharges (see Figure 2.1) showed that the biota diversity and abundance were significantly affected by the acidity and deposition of ferric hydroxide associated with AMD.

Geotechnical Impacts

Richardson (1983) identified two main subsidence hazards in the Newcastle area. The first of these is the High Main seam which has had coal extraction of 75 - 90 %. Second, in the Scotswood and Whickham areas both the Low Main and the Brass Thill seams have had the coal almost completely extracted. These high extraction rates are due to strong sandstone roofs (although in the case of the High Main it is extensively cracked) which have to date, prevented subsidence. However, the impact that AMD will have on their stability is questionable. Younger (1993) argues that areas of bord and pillar workings will be at greater risk of subsidence after they are intersected by the rising water table.

Turner (1993) indicates that there will be an increased probability of methane explosions in Redheugh and central Gateshead, where there is already a history of explosions caused by methane in residential areas.

Possible Solutions

Younger and Harbourne (1995) used cost benefit analysis to investigate various abandonment scenarios. Costs were summed for: compensating for reduced flows in the River Wear, abandonment of the Lumley treatment works, the loss of boreholes due to groundwater pollution and geotechnical impacts. Over a hundred year period the cheapest option was to continue to pump. A range of discount rates were used. The discount rate is a way of measuring the value of money over time. Two methodologies were used, the present value approach and the equivalent annual cost approach. In one case only, when the discount rate was set at a value of 15 % (the highest value in the range), was the lowest cost estimate for abandoning pumping marginally cheaper. It was noted that this method does not consider any ecological or amenity value, with these additional qualitative elements, continuing to pump seems to be a valid option.

2.2.7 The Persistence of AMD

Many cases of AMD are characterised by a first flush of highly polluting water that decreases in potency with time. Kames Colliery (NS685262) near Muirkirk was closed in 1969; until that time the mine had been dewatered at an average rate of 0.008 m^3/s (0.69 Ml/d). AMD was soon noted in a tributary of the River Ayr called Garvel Water at rates from 0.021 - 0.047 m^3/s (1.8 - 4 Ml/d) in 1974. By 1980 the flow had reduced to between 0.003 - 0.026 m^3/s (0.26 - 2.2 Ml/d). The initial iron concentration was 70 mg/l, but had fallen to 25 mg/l by 1980 (Robins, 1990).

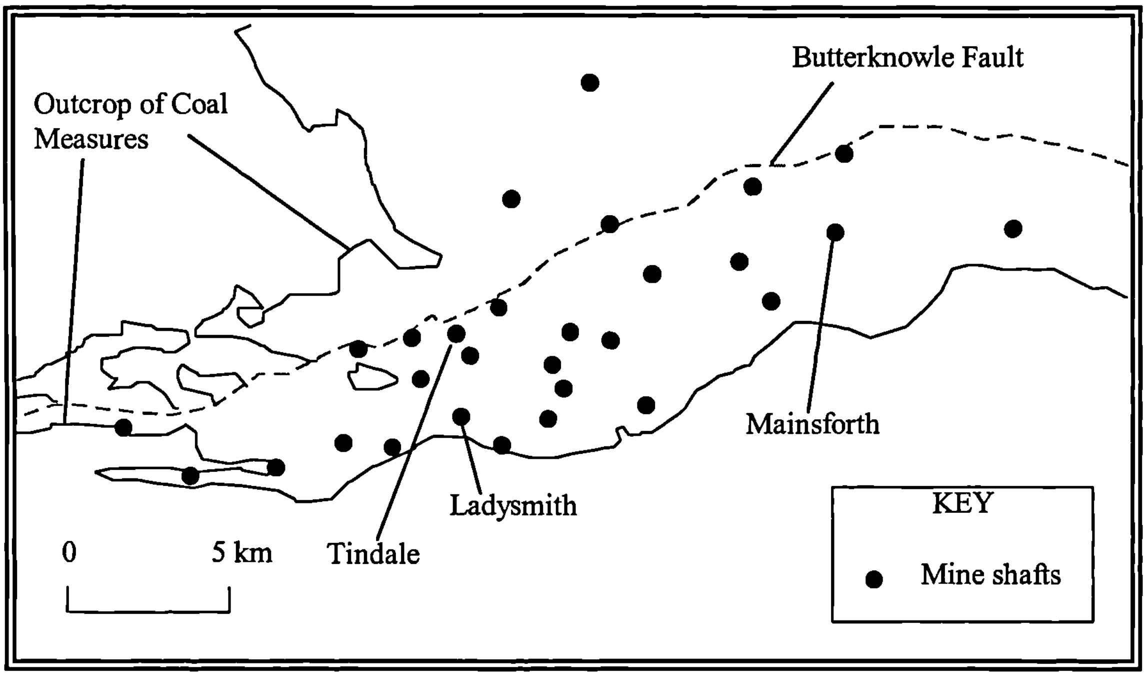
Warner (1973) states that pollution from deep mines can continue for a virtually unlimited length of time. This is illustrated by the River Don in the Pennines which is being polluted by AMD from the Bullhouse Colliery at Millhouse Green. Although it was abandoned in the early 1960's, the river continues to run orange and there are no flora or fauna (Hansard, 1994). Acomb Colliery in Northumberland was closed in 1952 and still continues to pollute an adjacent stream with AMD.

The initial decline in the polluting nature of AMD is exponential (Frost, 1979). However, it eventually settles into a persistent level of pollution. This can be explained by two processes; seasonal fluctuations in water level or sub-aqueous oxidation of pyrite (Younger, 1997). Sub-aqueous oxidation of pyrite occurs at a slower rate than atmospheric oxidation and yields only a few moles of Fe and SO_4. This explains the reduction of pollution as the sulphates and iron oxides left by the atmospheric oxidation are exhausted after inundation, leaving only the products of sub-aqueous oxidation. Seasonal fluctuations in water level allow a volume of strata to alternate between atmospheric oxidation and hydrolysis. Hence a small section of strata continues to produce AMD even when the groundwater level is in equilibrium. Younger (1997) describes the pollution caused by seasonal fluctuations as 'juvenile acidity' as opposed to 'vestigial acidity' which is caused by groundwater rebound immediately after dewatering is ceased.

Mainsforth Colliery Case Study

A study by Cairney and Frost (1975) of the water quality deterioration of the minewater at Mainsforth Colliery illustrates the persistence of pollution caused by varying the groundwater level. The colliery is part of the Durham Coalfield. However, it is hydrogeologically separated from the central coalfield by the Butterknowle Fault (see Figure 2.4). It was an extremely wet pit producing 13.6 - 16.5 Ml/d. The seven coal seams from the Five Quarter to the Brockwell were extensively worked. They are interconnected to the extent that the mine can be regarded as a single hydrological unit.

Figure 2.4: The Durham Coalfield, south of the Butterknowle Fault



After: Cairney and Frost (1975)

The colliery was closed in 1970 and over the period August 1970 to June 1974 the groundwater level was allowed to rise in a stepped fashion. Three floodings occurred in this time, the pumping regime between inundations was such as to keep the water level stationary. When the water level was held at a constant level the water quality gradually improved. However, this process was not continuous, suggesting that the rate of flooding is not the only factor involved.

The first two main fluctuations in pumping and therefore, in water levels, caused immediate deteriorations in water quality. Typical values were: iron concentrations of 100 mg/l, sulphate concentrations in excess of 1300 mg/l and total dissolved solids of up to 3500 mg/l. Yet the third flooding did not result in a marked water quality deterioration. This is due to mixing with water from the adjacent Magnesian Limestone. The average pumped water quality from the upper part of the Magnesian Limestone in 1970 was: pH 7.8, alkalinity (as $CaCO_3$) of 190 mg/l, sulphate concentrations of 136 mg/l and total dissolved solids of 532 mg/l. The acidity of the minewater from the third inundation was buffered by the alkaline waters from the limestone.

Frost (1979) analysed the water quality at Mainsforth colliery for the period February to October 1971. An exponential decline in iron concentrations with time was found, with a half life of 350 days. Equation 2.11 represents the regression which was fitted to the data set.

$$\log C_c = 1.684 + 0.102 \log Q' - 0.000858t \qquad \textbf{Eqn: 2.11}$$

Where:

C_c is the concentration of iron in water pumped from the flooded shaft (mg/l),

Q' is the pumping rate (m^3/sec) and

t is the time in days.

Controlling the groundwater rebound by intermittent pumping ultimately did little to mitigate river pollution by AMD. The water quality has still not returned to pre-rebound values (Younger, 1993).

2.3 Solutions to the Problem of AMD

2.3.1 Engineering Structures to Control AMD

Foreman (1974) describes methods of controlling AMD which do not include treatment. Some examples are: deep mine hydraulic sealing, deep mine surface sealing and underground dams. However, it was a deep mine surface seal that failed in the case of the Wheal Jane incident and underground dams proved ineffective in stopping AMD pollution at Broken Banks, County Durham (Younger and Bradley, 1994).

2.3.2 Treatment of AMD

The treatment of AMD requires two basic elements: the neutralisation of acidity and the precipitation of metal contaminants (Hedin *et al*, 1994). All methods of treatment have problems of cost, space, maintenance of the plant and sludge disposal.

Conventional Treatments

Barton (1978) describes various methods of treatment including neutralisation, reverse osmosis, ion exchange, flash distillation, freezing, electrodialysis and solvent extraction.

Physical methods of treatment include facilities for sludge settlement and engineering cascades that promote oxidation (NRA, 1994). Chemical treatments are generally expensive, due to the cost of chemicals and sludge disposal.

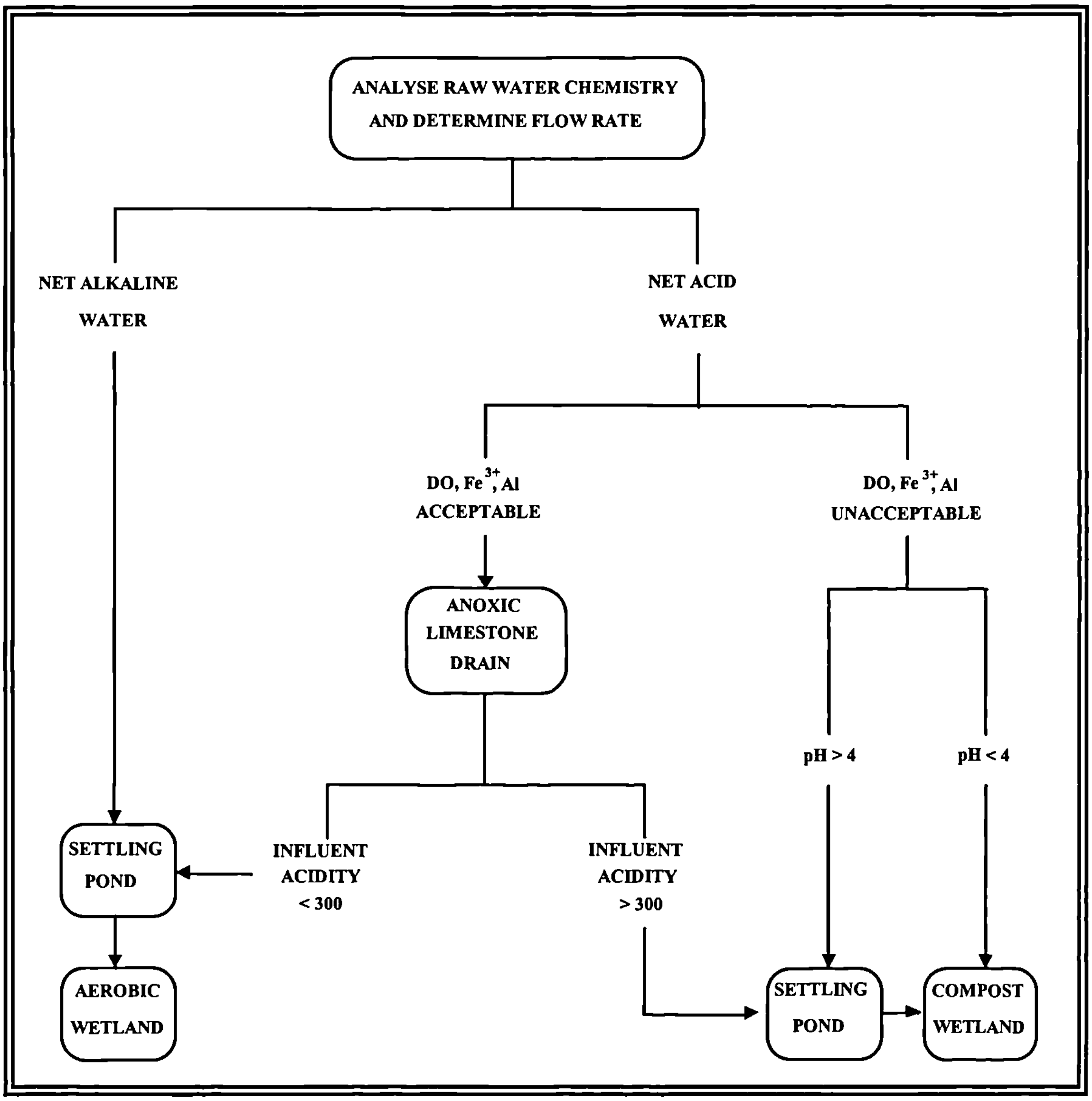
A biological method of reducing the polluting effect of AMD from open cast mines and spoil heaps is described by Kleinmann (1980). The oxidation of pyrite can be slowed by killing *Thiobacillus ferrooxidans*, which plays a major part in accelerating the rate of pyrite oxidation in the formation of AMD. However, it is too late for this in the deep mines of Britain, since most of the mines that are causing concern have had pyrite oxidation occurring for centuries.

Passive Treatment

Passive treatment encompasses both wetlands and passive chemical treatment. They make use of natural chemical and biological processes. They are comparatively low in cost, since they require no chemical input and have minimal operational and maintenance costs. However, they do require a large amount of land and are slower than conventional treatment (Hedin *et al*, 1994).

Two types of wetland exist, aerobic and anaerobic. By using these in conjunction with anoxic limestone drains (ALDs) and settling ponds, Hedin *et al* (1994) propose a methodology by which AMD of any nature can be treated, (see Figure 2.5).

Figure 2.5: Flowchart Showing Chemical Determinations Necessary for the Design of Passive Treatment Systems.



From: Hedin *et al* (1994)

ALDs are used as a pre-treatment for AMD which is acidic. They provide an environment that is low in oxygen and high in CO_2. AMD is put in contact with limestone (preferably with a high $CaCO_3$ content) and alkalinity is produced (Hedin *et al*, 1994). However, AMD which contains dissolved oxygen with ferric iron or aluminium is not suitable for treatment with an ALD. Both ferric iron and aluminium form metal hydroxide particulates which precipitate causing clogging. In addition ferric hydroxide armours the limestone (Hedin *et al*, 1994).

Aerobic wetlands are most effective when AMD is net alkaline. The system promotes aeration and metal oxidation processes. A typical treatment may involve a series of aeration structures linking wetland cells, which are generally less than a hectare in size. Typically iron is removed at a rate of 10 - 20 $g/m^2/d$ and manganese at a rate of 0.5 - 1.0 $g/m^2/d$ (Hedin *et al*, 1994).

Anaerobic wetlands (compost wetlands) are used if the AMD is net acidic and unacceptable for treatment by ALD or if after treatment with an ALD the AMD still contains acidity concentrations exceeding 300 mg/l. Alkalinity is generated at rates of 2 - 12 $g/m^2/d$ by the combined use of bacterial activity and limestone dissolution. The bacterial activity also results in the precipitation of metal sulphates (Hedin *et al*, 1994).

2.3.3 Continuing to Pump

Continuing to pump a coalfield, superficially appears to be an uneconomic course of action. However, Harbourne (1994) economically evaluated the different 'solutions' available to the impending AMD problem in the Durham Coalfield (see Section 2.2.6). Over a time scale of a century the overall best economic option was to continue pumping. Younger and Harbourne (1995) suggest that pumping should be continued until a more permanent solution (perhaps involving new technology) can be developed. This is likely to be the best solution when dealing with AMD on a coalfield scale. Wetlands are ideal for dealing with pollution caused by the closure of individual mines or areas where rebound has reached the surface and AMD is already a problem. However, large areas of land would be needed to treat AMD on a coalfield scale. Younger and Harbourne (1995) estimate a maximum total area of 62.5 hectares would be needed to treat the predicted volumes of discharge from the Durham Coalfield.

2.4 The UK Coal Industry

2.4.1 The History of the British Coal Industry

Coal Mining Prior to Nationalisation

Coal was first mined in Northumberland by the Romans. However, after they left Britain there is no record of the use of coal for nearly a thousand years (Hall, 1981). During the reigns of Queen Elizabeth I and King James I (James VI of Scotland) timber became less plentiful and coal began to take on more importance as a fuel (Hall, 1981). However, it wasn't until the invention of the Newcomen steam engine in the early eighteenth century that dewatering allowed significantly deep mining.

Demand for coal production and exports rose through the Victorian era, growing continuously until the First World War; when demand was vast. However, equipment and miners were scarce, leading to the exhaustion of the richer, most accessible seams. During the Second World War production of coal was so important that the Government temporarily took control of the mining and allocation of coal. On 1 January 1947 the coal industry was finally nationalised.

The Oil Crisis

Electricity generation has long been a major market for coal. In 1979 nearly 70 % of all coal sales in Britain were to electricity generating boards (Manners, 1981). During the 1960's coal and oil competed for the electricity generation market. Prices were similar but oil had advantages, being cleaner and easier to handle.

In 1960 the Organisation of Petroleum Exporting Countries (OPEC) was formed. By the late 1960's OPEC began to demand greater control over oil production and a larger share of the revenues. In 1973 the price of oil rose to an unprecedented level making coal a highly competitive fuel. However, the UK electricity generating boards had already committed investment to oil and nuclear power stations.

The Coal Industry since 1979

By the end of 1979 the Conservative Government had made a positive statement on the future of the nuclear power industry. They publicly endorsed the idea of further investment in the Coal Industry; however, minutes leaked from a cabinet meeting (23 October 1979) stated that: 'a nuclear programme would have the advantage of removing a substantial portion of electricity production from the dangers of disruption by industrial action by coal and transport workers' (Winterton and Winterton, 1984). The Government committed themselves to start construction of one new nuclear power station a year from 1982. Britain did not require the proposed investment in both coal and nuclear power (Manners, 1981).

At the same time, the market for coal was shrinking. The contraction of the steel industry meant a huge drop in demand for coking coal. Imported coal was cheaper due to government subsidies of deep mines and the low extraction costs associated with opencast workings. The Government's commitment to free market economics meant that through the 1980 Coal Industry Act they withdrew much of their financial support. The National Coal Board (NCB) was expected to break even by 1984.

However, Barratt-Brown stressed the inadequacy of free market economics with regard to energy policy: '...the possibility of oil or natural gas running out in 30 years time does not at all enter into its current price. Scarcity is only a measured by price as a result of a gap between supply and demand today, or in the near future, not in the distant future.' (Winterton and Winterton, 1984).

This all led to the 1984/5 strike which was the longest national strike to ever occur in Britain. A total of 12,000 miners left the industry thereafter.

In 1979 there were 223 NCB collieries producing deep mined coal; by 1992 there were only 50. With a view to privatisation, on 13 October 1992 Michael Heseltine announced that British Coal would close 31 pits, 27 permanently and 4 on a 'care and maintenance' regime. However, after vigorous public outcry, by the end of the month the number of collieries earmarked for closure was reduced to 21. Further closures are anticipated after new coal supply contracts are negotiated by power generation companies in the Spring of 1998.

2.4.2 The Legal Situation

Although working mines have regulations to prevent them from polluting the environment the situation with abandoned mines is not so clearly defined. Pollution from mines is placed on a different footing to other kinds of water pollution. It is therefore not always an offence to permit water from abandoned mines to enter ground or surface water (Howarth, 1988).

1991 Water Resources Act

The Water Resources Act 1991 deals with pollution of surface water courses. Section 85(1) states a pollution offence is when one: "....causes or knowingly permits any poisonous, noxious or polluting matter or any solid waste matter to enter any controlled waters".

Under section 161 the NRA has a responsibility to take action to prevent contaminated water from entering controlled waters, or to deal with the subsequent pollution. It is entitled to recover expenses reasonably incurred in such work from those who caused or knowingly permitted the pollution. However, this is not the case for permitting pollution in abandoned mines (NRA, 1994). Section 89(3) states that: "A person shall not be guilty under Section 85 by reason only of his permitting water from an abandoned mine to enter into controlled waters."

Therefore past operators of mines are not held legally responsible for permitting pollution once abandonment occurs. However, it could be argued that the act of abandonment causes pollution, but the success of a prosecution on this basis requires the proof that the chain of events resulting in the pollution was caused by the abandonment of the mine.

Allowing the water to rebound may be seen as simply permitting the water to return to its previous level and thus its natural state. The unnatural state may therefore be seen as having been caused not by switching off the pumps, but by the lowering of the water level to allow mining in the first place. Therefore the pollution is not a result of mine abandonment but of the creation of the mine (NRA, 1994).

The Royal Commission on Environmental Pollution of 1992 recommended that legislative action should be taken to cover responsibility for pollution from abandoned mines (Hansard, 1994). The government stated in October 1992 that it was "....considering the framework of legal responsibility for pollution in abandoned mines" (Department of the Environment, 1992).

Dalquharran Case Study

The Dalquharran mine in the Dailly coalfield in Ayrshire was closed in August 1977 and pumping was stopped. On the 21 October 1979 a discharge of 0.026 m^3/s (2.25 Ml/d) to the Quarrelhill Burn occurred. This discharge had an iron content of 1200 mg/l, a pH of 4.5, a dissolved sulphate content of 6000 mg/l and an aluminium content of 100 mg/l. There was a complete fish kill and an inert orange ochre coated the beds and banks of the River Girvan (Robb, 1992).

In 1981 the Clyde River Purification Board took legal proceedings against the NCB for the AMD caused by the closure of the Dalquharran Mine. The NCB were found to be responsible and fined £750. This was the first time that the NCB has been found responsible for pollution from abandoned mines. Remedial action was taken by the NCB to limit the pollution caused and was partially successful. However, it must be stressed that the intention was merely to limit pollution not prevent it. Pollution of the River Girvan still occurs, however, it has reduced; for example, the iron content in 1992 was 300 mg/l (Robb, 1992; Whitelaw, 1993).

Anglers Association Case Study

In March 1993 the Anglers Co-operative Association brought a private prosecution against British Coal after AMD polluted the River Rhymney near Caerphilly, Mid Glamorgan. The pollution was believed to be from the Britannia Colliery which was closed in 1990 (Bennett, 1993; Environmental Law and Management, 1993). The chain of events linking the pollution event with the closure of the colliery was not proven and the case was dismissed (Tickell, 1993).

Coal Industry Bill

In March 1994 the Coal Industry Bill went through the House of Commons. A new Clause 3 concerning minewater was debated. Its intention was to prevent discharges of AMD from occurring by requiring the licensee to continue pumping from mines after closure. However, the new clause 3 was rejected at the vote (Hansard, 1994). The minister (Tim Eggar) stated that the Coal Authority would be responsible for pollution from abandoned mines except where it is passed to the private sector through leases (Hansard, 1994). However, this is not a part of the Coal Industry Bill legislation. Therefore the situation continued to be such that no one would be legally responsible for pollution resulting from mine abandonment.

The Coal Industry Bill went through the House of Lords in April 1994. On the 26th April 1994 Lord Strathclyde stated that the Government would expect the Coal Authority to go beyond the minimum standards of environmental responsibility which are set by its legal duties, and to seek the best environmental result which can be secured from the use of the resources available to it (Barry T., Department of the Environment, Personal Communication, 1994).

The NRA - British Coal Memorandum of Understanding

In 1994 the only agreement between the NRA and British Coal was based on a memorandum of understanding, which was drawn up on 18 November 1993. It promised regular meetings between technical representatives of both groups. The NRA and it's consultants have access to particulars of recent mining activity and past abandonment plans. There will be 14 days notice in writing of British Coal's intention to stop pumping at any colliery, unless an emergency arises. Where colliery closure is implemented, British Coal and the NRA will give due regard to future activities and the need for a consented discharge to controlled waters and where there is fundamental disagreement between the two groups either can call a meeting at national level to be held within 10 days (NRA, 1994).

Subsequently similar agreements have been developed between the Environment Agency (created by the 1996 Environment Act) and both the Coal Authority and RJB.

The Present Situation

The 1996 Environment Act changed the law so that a mine operator will be responsible for uncontrolled drainage of water from any mine abandoned after 1999.

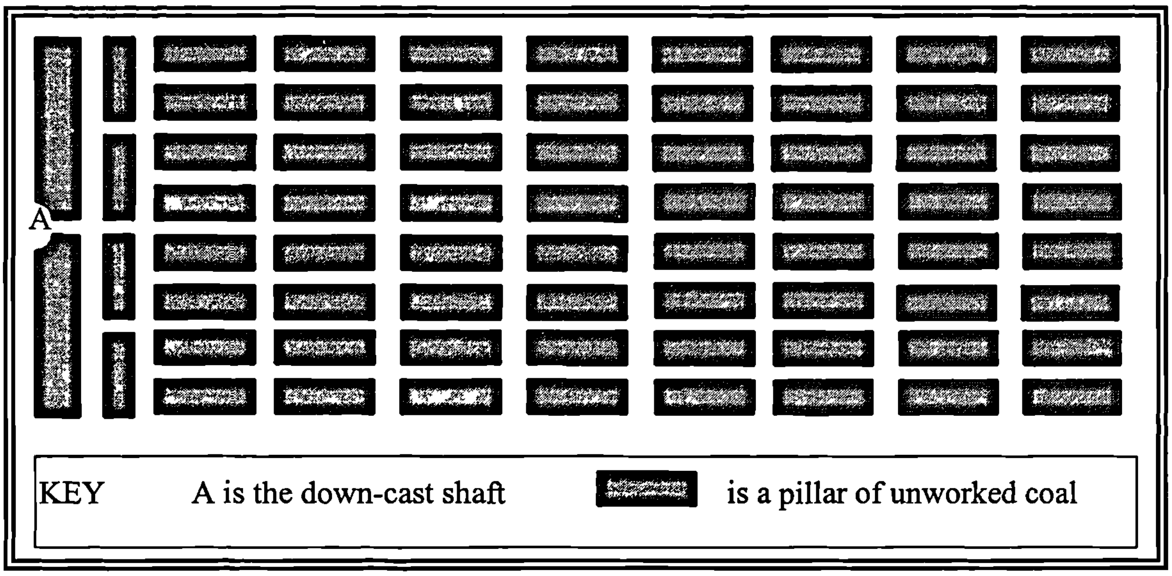
2.5 Hydrogeology of Mined Coal Measures

2.5.1 Mining Techniques and their History

The oldest mines, which are closest to the surface, were worked either at outcrops or using bell-pits where the coal seam was close to the surface. Bell-pits are mines where a shaft has been sunk a few meters to the coal seam and coal has been extracted in a circle a few meters in radius (Atkinson, 1966). Most bell-pits have now collapsed and in areas which have been mined using this method a pattern of circular indentations can be seen in the surface topography.

The 'bord and pillar' method (also known as 'pillar and stall' and 'stoop and room') involved leaving large areas of coal to support the roof of the mine. Bord and pillar working entails abstracting some 25 % of the seam, the remainder being left as pillars to support the roof of the mine (Harrison and Scott, 1987). The pillars were rectangular and in a regular pattern. See Figure 2.6. Robbing of pillars, in north-east England, began in the 1730s (Atkinson, 1966; Hill, 1991). This was dangerous due to the risk of roof collapse. The collapsed material is termed 'goaf'. Mines were separated by areas of unworked coal, termed barriers.

Figure 2.6: Schematic Diagram of Bord and Pillar Workings.



In 1795 a safer method of doing this called 'panel working' was invented. A colliery was divided into sections of 10 to 20 acres around which thick stone walls were built and then alternate pillars would be removed (Atkinson, 1966). This led to an extraction rate of up to 80 %.

By 1900 longwall mining was more common than the bord and pillar method. This resulted in a far higher proportion of the coal being extracted, mainly from lower levels (Atkinson, 1966; Hill, 1991; Richardson, 1983). This pattern of mining has led to great heterogeneity in the hydrogeology of worked coal measures.

2.5.2 The Nature of Flow in Worked Coal Measures

The difficulties associated with predicting hydrogeological behaviour are compounded if there has been a long history of mining. Early workings are often unknown and unmapped (Henton, 1974). Random collapse and the likelihood of unrecorded pillar and barrier 'robbing' add to this effect. (See Section 2.5.1.) Aljoe and Hawkins (1994) have applied aquifer testing to underground mines that have experienced widespread roof collapse and conclude that both Darcian and pseudokarst type flow conditions can exist in different places. This is characterised as preferred flow pathways within a general diffuse flow system.

This study of mines in western Pennsylvania found velocities of 3.4 - 20 m/d through mine voids, though higher velocities occurred where extensive workings were close to the surface discharge point (Aljoe and Hawkins, 1994). These values are an order of magnitude slower than reported by Aldous and Smart (1988) for flooded British workings in the Forest of Dean where velocities were found to be 460 m/d. In underground streams of 0.5 km in length velocities of 1840 m/d and 16000 m/d were found. The slowness of the flow recorded in the work by Aljoe and Hawkins (1994) is attributed to unmeasurably low hydraulic gradients in the areas of extensive workings.

Borehole tests on the saturated solid material surrounding the mine voids showed that the hydraulic conductivity in the strata adjacent to the voids (2.05×10^{-3} m/min; 2.95 m/d) was an order of magnitude greater than in the pillars (7.44×10^{-5} m/min; 0.11 m/d) (Aljoe and Hawkins, 1994). This flow was largely independent of the observed conduit flow through the nearby voids, although there was some evidence of hydrologic communication. These values of hydraulic conductivity compare with values of 10^{-6} - 10^{-8} m/s (0.09 m/d - 9×10^{-4} m/d) found for unworked strata in the Durham Coalfield (Minett, 1987).

The nature of the hydrologic communication between worked and unworked coal measures will vary according to local conditions. Singh *et al* (1986) note that inflows of water to longwall mine faces have been reported (by various authors) at rates of 2×10^{-3} to 8×10^{-2} m^3/s.

2.5.3 Groundwater Rebound

In working mines, water which seeps into the workings is removed by pumping. However, when a mine is abandoned and pumping has ceased the water level rises within the mine in a process called groundwater rebound. Groundwater rebound through worked coal measures is a complex process. The heterogeneity of the strata means that the term 'water table' is not strictly valid (Henton, 1979).

The physical consequences of mining on the local geology can have a marked influence on the hydrogeology. Mining alters the hydrological regime of the rock mass by changing the direction of flow, creating additional pathways through which water may flow and generally allowing greater movement of water through the strata. The alterations to the hydrological regime may be direct or indirect. Direct results are the structure of the mine itself (e.g. shafts and adits), whilst indirect results include bed separation and fissuring (Henton, 1979; Ngah *et al*, 1984; Aldous *et al*, 1986; Singh *et al*, 1986; Puente and Atkins, 1989).

Harrison and Scott (1987) describe the difficulties of predicting conditions in areas of extensive collapse commonly associated with mining. One factor which is an indicator of the likely hydrogeological conditions is the nature of the roof of the mine. In seams with a competent roof rock, collapse will have broken the rock, leaving voids and channels through which water may flow freely. Whereas in seams with a *plastic roof* rock, it is possible that it may settle and seal against seatearth clays giving low hydraulic conductivities. For example, sandstone forms a much higher permeability 'goaf' than shale, (see Section 2.5.1). Smith and Colls (1996) describe the variation in the pattern of voids (and hence permeabilities) within the Leicestershire coalfield. Roadways where the roof remains largely intact contrast with areas which have undergone subsidence and the space is filled the goaf and interconnected voids.

The fracturing and collapse of the coal measures means that as the groundwater rises it is in contact with a large surface area of rock. There is also greater movement of water through the rock and a larger surface area of oxidised pyrite to be dissolved (Henton, 1979). Although the quantity of water which is likely to discharge is ultimately controlled by recharge, it's estimation is often complicated by inadequate knowledge of the local strata stability, porosity and permeability (Ngah *et al*, 1984).

As groundwater levels rise, ponding can occur. Where water is ponded it stagnates and the iron and acidity tend to stratify, the lower levels of these waters having considerably poorer quality water than the upper levels. Consequently if a discharge occurs from the upper part of a mine system the water quality is potentially less harmful than a discharge from the lower levels (Cairney and Frost, 1975; Ladwig, 1985; Miller and Thompson, 1974).

The factors on which the timing and quality of discharges depend are unique to the hydrology and geology of each area. They are therefore very difficult to predict. It can take anytime between a few months to many years for the groundwater level to reach a point where discharges arise at the surface. Henton (1979) describes a small hydrogeologically isolated section of the Fife Coalfield from which an AMD discharge occurred within a year of cessation of pumping but concludes that larger areas generally take at least 10 years for this to occur.

2.6 Modelling Water in Mines

2.6.1 Introduction

The literature on modelling water flow in mines is limited, therefore, a description of conceptual models used to represent fracture flow systems has been included. The mining environment is essentially a man made fracture flow system.

Models of minewater can broadly be divided into flow and chemical transport models. Flow models can be further categorised as those applied to active and those applied to inactive workings. Models of inflow to active deep mines are used as a tool for planning dewatering. It is only recently, with the threat of AMD that modelling flow in inactive mines has been of interest.

2.6.2 Conceptual Models of Flow in Fractured Systems

Anderson and Woessner (1992) describe three types of conceptual model which have been applied to fracture flow systems. The Equivalent Porous Medium (EPM), Discrete Fracture and Dual Porosity models. However, the National Research Council (1996) divides models into three slightly different groups: EPM's (also known as Equivalent Continuum Models), Discrete Fracture (also known as Discrete Networks) and hybrid techniques, which combine the two. In this division, the Dual Porosity models are regarded as a subset of EPM's. These models represent flow through both the fracture and the surrounding matrix.

The EPM is the most commonly used approach. It represents fractured material as a continuum. A representative elementary volume (REV) of material with effective parameters is defined. The effective parameters produce a flow pattern similar to that in the fractured material (Anderson and Woessner, 1992). This method is dependent on representative effective values being identified. It gives a poor representation of local conditions, but can reproduce regional flow systems adequately. It is best used on models of a large scale, where the fractures are highly interconnected (National, Research Council, 1996).

The REV has a minimum size, under which the assumption of a continuum is no longer valid. The minimum REV for the same site may be different for flow and transport models. The size of the minimum REV varies according to the strata involved and may be infinite if the strata contains relatively large fractures (Guérin and Billaux, 1994).

The Discrete Fracture models, assume flow only occurs in the fractures, whilst neglecting the surrounding rock matrix. Flow through a fracture is commonly idealised as occurring between two smooth parallel plates.

A stochastic approach can be applied to both EPM and Discrete Fracture models. Stochastic models represent variables in terms of probability models. In the case of EPM's the variables that are taken from probability models are hydraulic properties, whereas, in Discrete Fracture models the location, extent, orientation and conductivity of the fractures can be represented stochastically. Probability models can be used with Monte Carlo simulation, producing output in the form of probability distributions (National Research Council, 1996).

2.6.3 Models for Inflow to Active Deep Mines

Analytical Models

Fawcett *et al* (1984) appraised both analytical and numerical models of water inflow to deep mines. The analytical models mainly comprised well models. These are limited because they assume homogeneous and isotropic media and can only be used with simple boundary shapes.

Perry (1993) assessed the models used by the US Bureau of Mines to plan the control of inflow to mines. The Bureau has developed models which can represent bord and pillar workings but as yet, not longwall mining. MINEFLO is a customised version of Geraghty and Miller Inc.'s QUICKFLOW. It has been used to model dewatering in both surface and deep mines. It can incorporate permeability zoning, fissures and uniform flow. Sources and sinks can be represented as points, lines or areas.

Ricca and Hemmerich (1978) developed a suite of models to simulate recharge to, and discharges from, deep mines, surface mines and refuse piles. The Deep Mine Model is coupled to a modified version of the Stanford Watershed Model. This part of the model requires data on:

- precipitation,
- evaporation,
- drainage areas,
- surface water bodies,
- overland flow,
- stream flow characteristics,
- vegetation cover,
- soil moisture,
- groundwater percolation,
- water table fluctuations and gradient,
- interbasin characteristics and
- mine operation.

The authors note that a minimum of three years of continuous daily stream flow data are essential. The deep mine part of the model requires data on:

- the areal extent and age of the workings,
- the surface watershed area,
- the location of adits,
- seam thickness and length,
- stratigraphy above the mine,
- acid production characteristics of the strata,
- mine conditions under which pyrite oxidation can occur,
- chemical reaction rates,
- diffusivity and concentration of oxygen through the stratum,
- temperature and pressure at the coal seam faces,
- daily water infiltrating and percolating to the mine aquifer,
- factors controlling the hydraulics governing the transfer of water from storage in the surrounding aquifers into the mine workings and
- mine discharge quantity and quality records.

The model calculates flow into the mine from surrounding aquifers, then water is routed through the mine. The area is divided into 'micro volumes' to calculate oxidation and the acid loads removed by leaching, inundation and gravity diffusion. The model simulates discharge from a single opening. The model outputs data on:

- daily infiltration to the mine aquifer,
- daily minewater discharge,
- acid loads associated with each of the three removal mechanisms,
- total daily minewater discharge and
- acid load removal from the mine.

The large volume of data required has limited the application of this model. However, a study was done on the Roaring Creek catchment in West Virginia, an area of 75.6 km^2, of which a third of the mined area was modelled.

The results of the hydrological part of the model were successful in most respects. The model was able to reproduce trends in minewater flow but there were problems generating peak and low discharge points. Total yearly flow volume was underestimated. The acid loads component of the model simulated the recorded data reasonably well, although the yearly total was an overestimate. Leaching was found to be the primary removal mechanism of acid products. The shortcomings of the model results were thought to be associated with the quality of the data.

Numerical Models

Numerical models are generally more appropriate for this type of modelling. However, such models tend to require substantial quantities of data. For example, Fawcett *et al* (1984) describe the Pennsylvania model by Owili-Eger and Manula (1976) which requires a large amount of field data that needs to be complemented with estimates from published data. The model is a two-dimensional transient model which can represent the movement of air and water in both the saturated and unsaturated zones above a deep mine and predict water flow rates into it.

Radial flow models have been successfully used to model water inflow into sections of deep mines. Lloyd *et al* (1983) used an electrical analogue radial flow equations to model water inflow to a proposed shaft and drift in the Warwickshire Coalfield. It was found to be reliable for steady state flow, and later work encompassed non-steady flows.

Lloyd *et al* (1991) describe work by Edwards (1988) using radial flow codes to model seepage into a shaft. A model was also developed to represent inflow into a drift. However, the drift model's complexity and the limited data available meant that a radial flow approximation was used as an alternative. Lloyd *et al* (1991) also describe work applying saturated flow equations to longwall mines.

Singh *et al* (1985) used a boundary element method to calculate groundwater inflow to longwall coal faces through heterogeneous anisotropic rock strata. The conclusion of the paper was that mining induced heterogeneity has a major influence on minewater inflow, whilst anisotropy though less important, is significant. Later work by Singh *et al* (1986) produced models of hydraulic conductivities induced by longwall mining. The resultant horizontal hydraulic conductivities were in the range 1 - 60 times that of the undisturbed values.

2.6.4 Models for Flow in Inactive Workings

Rogoz (1994) developed a model which simulated the flooding of abandoned mine workings within a working coalfield. The work was done on the Upper Silesian Coal Basin where there are many interconnected mines which form a complicated hydraulic system. The model attempts to predict the progress of flooding, caused by the abandonment of one mine within a group of connected working mines.

The prediction of water level rise in the abandoned mine is based on the water inflow rate and the water capacity of the rock mass and goaf. The carboniferous aquifer is assumed to be the source of all water inflows. Each inflow is calculated using either Equation 2.13 or 2.14.

$$Q_{Hi} = \frac{H_S - H}{H_S - H_{oi}} Q_{oi} \qquad \text{for } H > H_{oi} \qquad \textbf{Eqn: 2.13}$$

$$Q_{Hi} = Q_{oi} \qquad \text{for } H <= H_{oi} \qquad \textbf{Eqn: 2.14}$$

Where:

H is the water level in the mine workings,

H_{oi} is the original head at the point of inflow,

H_S is the head of the static water table in the carboniferous water bearing strata,

Q_H is the flow rate when the water table in the mine workings is the water level H and

Q_{oi} is the flow rate of the inflow before the start of flooding.

All the connections between the abandoned coal mines and adjacent mines are deduced and the lowest one identified. Once the water level in the abandoned mine reaches this level, the recharge into the abandoned mine is assumed to flow to the adjacent mine and be pumped away. However, if the adjacent mine is also abandoned the water continues to rise in both workings until it reaches the level of the lowest connection from either mine to a working mine.

Rogoz (1978) argues that the quantity of water that can be held by old workings can be calculated by multiplying the volume of mined coal by the water capacity coefficient. The water capacity coefficient is a function of the mining method, the depth (or rock pressure) and the quality of the material used to shore up the old workings. In areas that haven't been filled it is in the range 0 - 0.45. It is calculated using Equation 2.15.

$$c = \frac{V_Z}{V_P} \qquad \textbf{Eqn: 2.15}$$

Where:

c is the capacity coefficient,

V_Z is the water capacity of the old workings and

V_P is the volume of extracted coal, calculated using Equation 2.16.

$$V_P = \frac{AM}{\cos\alpha} \qquad \textbf{Eqn: 2.16}$$

Where:

A is the area of flooded workings,

M is the thickness of extracted coal seam and

α is the inclination of the coal bed.

Standard groundwater modelling software has been used to predict groundwater rebound over entire coalfields. Wardell Armstrong (1993) used Aqua (a two-dimensional model) to predict groundwater rebound in the Durham Coalfield. It predicted that if pumping throughout the coalfield ceased there would be discharges of AMD in the south-west of the region within six months. The groundwater in the north-west of the region would rebound to the surface in 10 - 20 years, whilst in the eastern, coastal area discharges would occur in 25 - 50 years.

Toran and Bradbury (1988) applied the finite difference model MODFLOW to an abandoned lead-zinc mine in south-western Wisconsin. A two-dimensional model was developed, it was able to represent past groundwater drawdown and recovery and to make predictions about continued recovery. An extensive archive of data was used, which was collected before, during and after mining. One layer was used to represent the Sinnipee aquifer, which consists of three contiguous formations the Galena Dolomite, the Decorah Formation and the Platteville Dolomite. The Maquoketa Shale, lies above the aquifer and where it occurs, limits vertical recharge. The Glenwood Shale and the St. Peter Sandstone beneath the aquifer were represented by a leakage boundary in the model.

Modelling was divided into three stages: a pre-mining steady-state model and transient models of mining and associated dewatering and subsequent recovery. A simple porous media seems an appropriate assumption since the scale of the model is regional and the fracture patterns of the dolomites are intense. The model was calibrated using hydraulic conductivity, recharge, anisotropy and specific storage. The results were fitted qualitatively against maps. A cone of depression with a similar slope to the observed one was produced. However, Toran & Bradbury (1988) conclude that the difficulties in matching both drawdown and recovery periods were only surmountable due to the extensive data set.

2.6.5 Chemical Transport Models

Some complex models such as the work done on Roaring Creek by Ricca and Hemmerich (1978) have a chemical component. Morth *et al* (1972) describe a model which was developed to describe flow and quality of AMD from a drift mine in the McDaniels Test Mine at the Ohio State University. The data input needed is temperature, rainfall and the parameters to calculate the oxidation rate. The latter is a function of the oxygen concentration at the coalface, the pyrite surface area available for oxidation and the reaction rate constant. The pyrite available and the reaction rate must be estimated using data from laboratory research into pyrite oxidation. The model output consists of drainage flow and daily acid load. The daily acid load was calculated by summing the loads produced by leaching, flushing and diffusion.

Chemical transport models have not been used to any great extent because the geochemical processes are not well represented. However, MOC and MOCDENSE are two-dimensional contaminant transport models which deal with advection, dispersion and mixing (and in the case of MOCDENSE; density). They do not, however, deal with retardation, temperature and viscosity (Perry, 1993).

More appropriate models for the chemistry of sulphide oxidation are codes with redox capabilities, which can be used in conjunction with groundwater flow models. WATEQ4F has been used successfully in minewater management projects to interpret ground and surface water samples. The output of WATEQ4F can be used as input to a chemical mass balance code such as BALANCE, or to NETPATH which models water quality changes along a flow path (Perry, 1993).

2.6.6 Limitations of Previous Models

The aim of the modelling in this thesis is to predict groundwater rebound as a means of identifying the location and timing of potential discharges of AMD after coalfield closure. Therefore, a model which can encompass an entire coalfield is necessary. Analytical models tend to be limited by their assumption of a simple environment. The Ricca and Hemmerich (1978) Deep Mine Model works on the kind of scale that is necessary. However, the data requirements are unrealistically large and the surface water component (the Stanford Watershed Model) is now outdated.

Existing numerical models of water flow into active mines were designed to predict water flow through working faces. The detailed scale and large data requirements of these models would make them inappropriate for use, even in combination with some kind of storage modelling.

There are major problems connected with using standard groundwater software to model groundwater rebound in abandoned coalfields. All such software uses Darcy's law which assumes a simple porous media in which laminar flow occurs. A coalfield consists of interconnected workings, areas in which the roof has collapsed and tracts of unworked coal which act as barriers. Flow in the unworked coal measures will be Darcian, but in the workings the flow is likely to be turbulent; comparable to stream flow rather than groundwater flow. Perry (1993) argues that models that are based on idealised flow are inappropriate for the fractured and highly disturbed strata which is the result of mining.

Rogoz (1994) has a good approach. The storage coefficient (or capacity coefficient) has been identified as the key factor governing the rate of rise of water in a mine. However, it is assumed that part of the coalfield is working and so that the water will be pumped away rather than rise to the point where it discharges at the surface.

3 Development of a Flow Modelling Approach

3.1 Data Problems in the UK

A major problem involved in modelling groundwater flow in coal measures is that they have commonly been pumped to prevent them from containing water. Therefore, no appropriate hydrogeological information is available. In addition the type of records that have been kept by the mining operator, have not been collected with hydrogeological modelling in mind and are therefore often inappropriate.

The format of the available structural data is generally too detailed (or paradoxically too sparse) to be of use. Aggregating the information on the numerous mine plans for a large region would be a monumental task. The most crucial plans are those closest to the surface and therefore the oldest. However, it is only since the coal industry was nationalised in 1947 that reliable, comprehensive plans have been kept (Richardson, 1983). In 1870 it became a requirement to record the abandonment of mines under the Mines Inspection and Regulation Act (NRA, 1994). In 1872 it became mandatory to keep accurate plans, which had to be lodged with the mining records office. However, these often showed only the extent of the workings and not the depth or any geological information.

This problem of lack of appropriate data, means that a modelling approach needs to be developed that does not require large quantities of data, and recognises the limitations of whatever data are available.

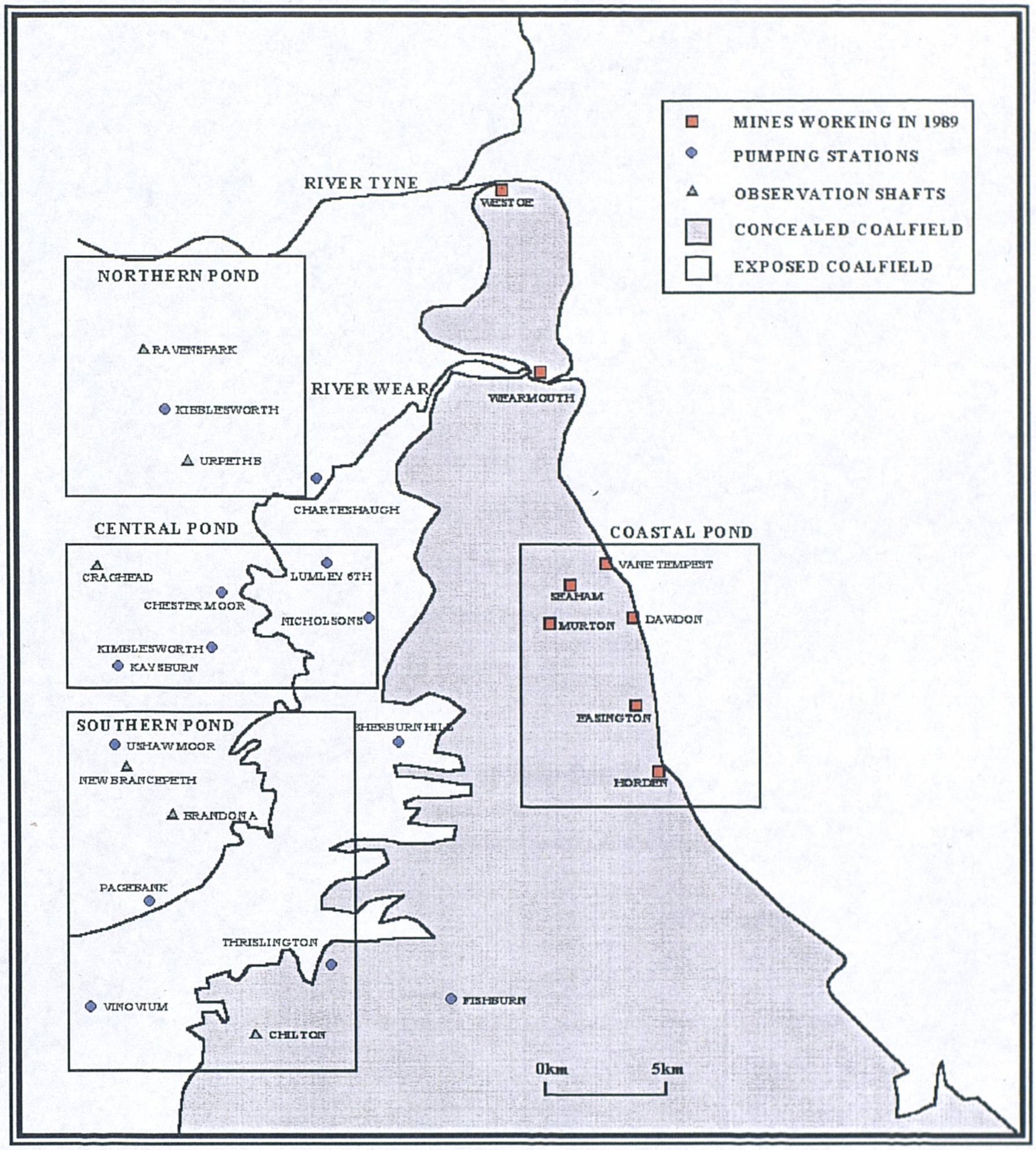
3.2 The Ponds Concept

The considerable difference between the hydrogeological properties of worked coal measures and the surrounding unworked strata has long been recognised. Minett (1987) described the NCB's policy of conceptualising the worked areas as 'ponds' separated by barriers of unworked coal or major faults. The ponds concept is also used elsewhere in the literature. For instance, Peters (1978) describes 'catchment areas' and 'pumping basins'. The term for ponds varies regionally, for example, in Fife they are known as basins in Durham 'ponds', in Staffordshire as 'pounds' and in the USA as 'pools'.

Minett (1987) divided the part of the Durham Coalfield which lies south of the Butterknowle fault into a series of ponds. Dumpleton (1995) has used ponds to conceptualise the South Yorkshire / Derbyshire / Nottingham coalfields system. This conceptualisation is not limited to the UK. Aljoe and Hawkins (1994) (working for the US Bureau of Mines) describe mine 'pools' which comprise the mine workings (intact or collapsed) and the strata immediately above and adjacent to them.

Work on the central part of the Durham Coalfield by Sherwood and Younger (1994) used the concept of ponds to develop a lumped parameter model. The coalfield was divided into four rectangular ponds, divided by barriers of unworked coal. See Figure 3.1. The dimensions of the ponds and associated barriers were deduced by analysis of historic abstraction rates and water level data. The model predicted that the first discharges of AMD in the southern ponds would be in 15 years, in the central pond in 30 years, in the northern pond in 40 years and in the coastal pond in 58 years.

Figure 3.1: Location of Ponds in the Durham Coalfield



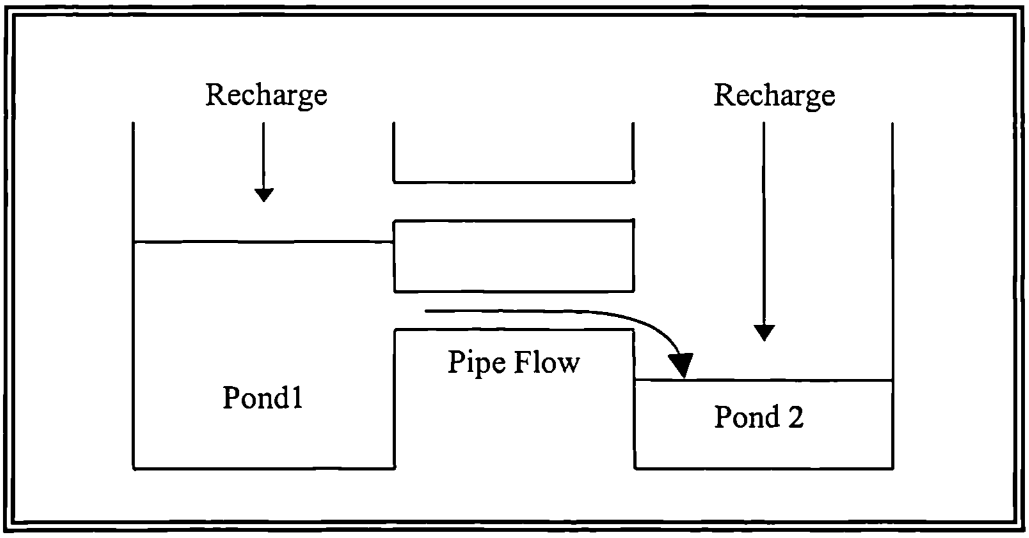
3.3 GRAM: The Conceptual Model

GRAM (Groundwater Rebound in Abandoned Mineworkings) is a lumped parameter model which conceptualises a coalfield as a series of ponds connected by pipes. The ponds are discrete areas which are bounded by vertical sides of intact coal through which there is no flow. Thus it shares assumptions with the discrete fracture conceptual model described in Section 2.6.2.

The plan geometry of the ponds can be of any shape. The hydraulic gradient is assumed to be flat within each pond and the hydraulic conductivity is assumed to be large enough to allow the water table to conform to this flat hydraulic gradient.

Flow between ponds and discharge to the surface is modelled using equations for pipeflow (see Section 3.3.2). In reality connection between worked areas are often in the form of roadways, hence the use of pipeflow equations gives a realistic method of representing the nature of the flow in this environment. A schematic diagram of how two ponds would interact is shown in Figure 3.2.

Figure 3.2: Schematic Diagram of Two Ponds and their Connections.



The data requirements of GRAM are small, realistically aimed at the limited data sets that are available. The assumption of flat hydraulic gradient means that flow is only directly modelled using pipeflow equations. Hence values of hydraulic conductivity are not needed, as they would be for traditional groundwater modelling. However, parameter values for the pipeflow equations are needed and can be calibrated against observed water level data.

3.3.1 Calculation of Recharge

Precipitation is applied over the surface catchment area of each pond. Effective rainfall is calculated by subtracting the evaporation rate for the timestep (generally days) by the precipitation for the same timestep. Should evaporation exceed precipitation, effective rainfall is set to zero. In lieu of suitable data the daily evaporation rate can be estimated as the annual rate divided by the number of days in the year. As a consequence of this simplification, the summer daily evaporation rate will be an underestimate and during the winter there will be an overestimate. Since both calibration and predictive simulation are likely to be run for a minimum of a decade, this will only have a negligible effect on the overall water balance.

The percentage of the effective rainfall which is run-off is then subtracted from the total volume of effective rainfall to give a value of recharge. The run-off percentage can be established using a water balance or by estimation of river flow if there is an appropriate river in the catchment. Ward and Robinson (1990) estimate that globally 34% of total precipitation runs-off. Marsh and Littlewood (1978) found that for nine basins in England and Wales over the period 1960 - 1976 the mean run-off was 428 mm (the corresponding rainfall was 897 mm).

The recharge can be attenuated over a number of timesteps, using a method similar to the simple unsaturated zone transfer function applied to the Chalk and Permo-Triassic sandstones by Calver (1997). The user can thereby specify a set of values which define how long it takes recharge (or its pulse) to reach the water table.

Recharge is then applied over the whole area of each pond. The removal of water by pumping (and addition of it by inflow from adjacent mines or aquifers, or from the sea) is also applied over the area of the entire pond. This is necessary because of the assumptions of a flat hydraulic gradient and a relatively fast rate of flow within each pond.

3.3.2 Pipeflow Equations

The transfer of water between ponds and discharge to the surface is modelled using the Bernoulli equation for head loss between two reservoirs connected by a pipe, flowing full. Hence in the model, flow along pipes can only occur when the pipe is completely submerged in at least one pond. The Bernoulli equation has been applied to the head loss between two ponds (Equation 3.1). The total head loss is the sum of the friction head loss and the minor losses (Featherstone and Nalluri, 1982). The minor losses consist of entry and exit losses. The friction head loss is calculated using the Darcy-Weisbach equation (Chadwick and Morfett, 1993).

$$\underbrace{H}_{\text{Gross Head}} = \underbrace{\frac{0.5V^2}{2g}}_{\text{Entry Loss}} + \underbrace{\frac{V^2}{2g}}_{\text{Exit Loss}} + \underbrace{\frac{\lambda L V^2}{2gD}}_{\text{Friction Head Loss}} \qquad \textbf{Eqn: 3.1}$$

Rearranging Equation 3.1 to make velocity the subject gives Equation 3.2.

$$V = \sqrt{\frac{2g\Delta H}{\left(1.5 + \frac{\lambda L}{D}\right)}} \qquad \textbf{Eqn: 3.2}$$

Where:

V is the velocity of flow in the pipe (m/s),

ΔH is the head difference between the ponds (m),

g is acceleration due to gravity (m/s^2),

D is the pipe diameter (m),

L is the pipe length (m) and

λ is a non-dimensional coefficient which is a function of the roughness and diameter of the pipe.

In GRAM the value of λ can be defined using either the Prandtl-Nikuradse or the Colebrook-White equation.

Prandtl and Nikuradse Equation

Prandtl and Nikuradse divided turbulent flow into three zones (Colebrook, 1939). In the rough turbulent zone λ is only a function of the relative roughness k/D. Equation 3.3 represents the relationship for λ in the rough turbulent zone.

$$\frac{1}{\sqrt{\lambda}} = 2\log\frac{3.7D}{k} \qquad \textbf{Eqn: 3.3}$$

Where:

k is the surface roughness (m).

This equation is limited by the assumption that flow is in the rough-turbulent zone. However, it has the major advantage that it does not need iteration to solve. As a consequence the code is simple and keeps calculation time to a minimum. This is important because the Bernoulli equation is a steady state equation, so the time step must be kept as small as is practical.

Colebrook-White Equation

The most commonly used equation for turbulent pipeflow is the Colebrook-White. Colebrook and White combined the von Kármán-Prandtl rough and smooth pipe flow equations (Colebrook, 1939). This results in Equation 3.4.

$$\frac{1}{\sqrt{\lambda}} = -2\log\left[\frac{k}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right] \qquad \textbf{Eqn: 3.4}$$

Where:

Re is the Reynolds number, which is given by Equation 3.5.

$$VD/\nu \qquad \textbf{Eqn: 3.5}$$

Where:

ν is the kinematic viscosity (m^2/s).

Kinematic viscosity is the ratio of dynamic viscosity (μ) to mass density (ρ). The variation in kinematic viscosity is small for the range of pressures and temperatures that occur in most groundwaters, it is therefore common to consider it constant. At 15.5 °C, ρ is 1000 kg/m^3 and μ is 1.124 cP, therefore ν is 1.124 x 10^{-6}m^2/s (Freeze and Cherry, 1979).

In the Bernoulli equation (see Equation 3.1) entry and exit losses can be termed the minor head losses. Equation 3.6 (the Darcy-Weisbach equation for friction head loss) can be obtained by neglecting the minor losses and assuming that the total head can be given by the friction head loss.

$$H = h_f = \frac{\lambda L V^2}{2gD} \qquad \textbf{Eqn: 3.6}$$

Where:

h_f is the friction head loss (m).

By rearranging and substituting for λ in the Colebrook-White (Equation 3.4), the Equation 3.7 is produced.

$$V = -2\sqrt{2gD\, {h_f}/{L}}\, \log\left[\frac{k}{3.7D} + \frac{2.51\nu}{D\sqrt{2gD\, {h_f}/{L}}}\right] \qquad \textbf{Eqn: 3.7}$$

This can be used to get a value for velocity which can in turn be used to estimate the minor losses. As in Equation 3.8.

$$h_m = \frac{0.5V^2}{2g} + \frac{V^2}{2g} \qquad \textbf{Eqn: 3.8}$$

Where:

h_m is the minor head loss (m).

Minor losses can then be taken from the total head to obtain a better estimate of friction head loss. Solution is achieved by iteration.

A study was done comparing the volume of flow calculated by the Colebrook-White and the Prandtl and Nikuradse equations. Table 3.1 shows that the difference in volume of the flow is 0 - 1x10^{-3} % of the total volume, where flow is in the rough-turbulent zone. Therefore, where the assumption of a rough-turbulent zone is valid, the simplicity and speed of operation of the Prandtl and Nikuradse equation makes it preferable to the Colebrook-White.

Table 3.1 Comparison of Volumes of Flow Calculated using the Prandtl and Nikuradse and the Colebrook-White Equations.

Water level in upper pond (m)	Water level in lower pond (m)	Roughness Coefficient (mm)	Length of Pipe (m)	Discharge calculated by the Prandtl and Nikuradse equation (m^3/day)	Discharge calculated by the Colebrook-White equation (m^3/day)	Difference (m^3/day)
-204.06	-297.79	20	1000	99.39	99.31	0.08
36.45	35.89	20	1000	7.68	7.61	0.08
-204.06	-297.79	31	850	1150.50	1150.21	0.29
36.45	35.89	31	850	88.93	88.64	0.28
-204.06	-297.79	4	22.86	11.75	11.73	0.02
36.45	35.89	4	22.86	0.91	0.89	0.02
-204.06	-297.79	31	182.88	2475.25	2474.96	0.28
36.45	35.89	31	182.88	191.33	191.04	0.28
-204.06	-297.79	31	30.18	6014.50	6014.23	0.28
36.45	35.89	31	30.18	464.89	464.62	0.28
36.45	33.72	11.63	2000	175.16	174.40	0.76
-37.07	-297.79	2×10^{-4}	1000	2586.90	1624.20	962.71
40.15	36.45	2×10^{-4}	1000	1141.18	652.90	488.28
-32.94	-297.79	3×10^{-5}	1000	1726.22	908.67	817.55
42.03	36.45	3×10^{-5}	1000	1577.23	821.61	755.62
40.15	33.72	6×10^{-9}	1000	2507.12	888.52	1618.60
-32.94	-37.07	0.03	1000	798.68	673.97	124.70
42.03	40.15	0.03	1000	538.86	436.94	101.92
-32.94	-37.07	0.03	1000	798.68	673.97	124.70
42.03	40.15	0.03	1000	538.86	436.94	101.92

3.3.3 Storage Coefficient Variability

The ponds have thus far been assumed to be vertically homogeneous. This is obviously not true. Despite the mining induced fissures in the roofs and floors of workings; the mined seams themselves are likely to have a higher storage coefficient than the strata between the seams. For instance, Lancaster (1995) studied the Ladysmith and Tindale shafts, south of the Butterknowle fault in the Durham Coalfield (see Figure 2.4). Water level data which start three to four years after pumping was ceased, show a stepped rebound. This is indicative of a vertically varying storage coefficient. Therefore a vertically varying storage coefficient was added to GRAM.

This method assumes that the seams are horizontal. A series of zones for each pond are input to GRAM. Each zone has a storage coefficient and a base height. As a pond's water level rises into a new zone the storage coefficient is changed accordingly.

3.3.4 Monte Carlo Simulations

The simplicity and relatively short run-times associated with GRAM make it ideal for Monte Carlo simulation. A range of parameters can be represented by probability distributions; however, two factors influence the choice of which parameters should be treated probabilistically:

- the perceived reliability of the data, and
- how sensitive GRAM is to errors in their estimation.

GRAM has the capacity to allow values for the storage coefficient, the percentage run-off (and therefore indirectly the recharge rate) and the roughness of any pipe to be taken from a probability distribution data set.

The use of a stochastic storage coefficient is only possible when not using the vertically varying storage coefficient. The use of a data distribution for the roughness of a pipe is necessary if a pipe is not activated during the calibration period because the water levels have not exceeded it. The characteristics of the data distribution can be taken from pipes that have been calibrated.

The FORTRAN code incorporates a random number generator, which creates a number between 0 and 1, the probability of which is evenly distributed (Pegram, G., University of Natal, Personal Communication, 1995). This number is multiplied by 1000, truncated to an integer and used to identify which element from the data distribution is to be read into GRAM. The data distribution is a random data set produced by Minitab forming a normal distribution from a given mean and standard deviation.

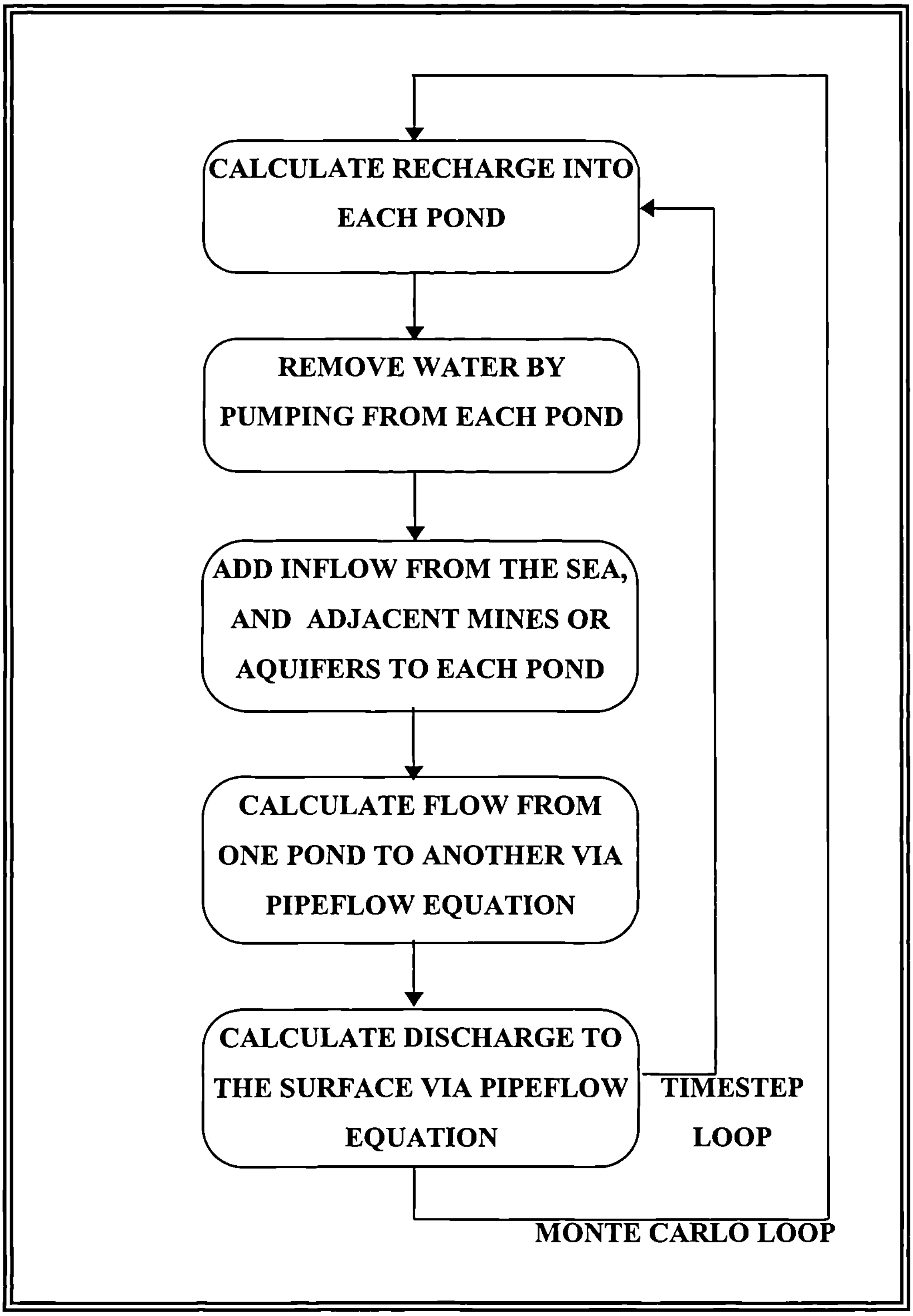
3.1 GRAM: The FORTRAN Code

A copy of the FORTRAN code is in Appendix 1. The input data required for GRAM are as follows:

- precipitation (mm),
- evaporation (mm/year),
- attenuation of recharge over time, (see Section 3.3.1),
- area of each pond (m^2),
- area of surface catchment of each pond (m^3),
- storage coefficient,
- original water level (mAOD),
- percentage run-off,
- abstractions (m^3/timestep),
- marine inflow (m^3/timestep),
- inflow from adjacent mines or aquifers (m^3/timestep),
- the number of pond connections, and for each their:
    - height (m),
    - roughness coefficient (mm),
    - diameter (m),
    - length (m),
    - kinematic viscosity (m^2/s),
- the number of surface discharge points and for each their:
    - height (m),
    - roughness coefficient (mm),
    - diameter (m),
    - length (m)
    - kinematic viscosity (m^2/s),
- which parameters will have Monte Carlo simulation applied to them and for each a probability distribution

The code takes the form of the flowchart shown in Figure 3.3.

Figure 3.3: Flowchart of GRAM Code



GRAM outputs the following data:

- A water balance consisting of a comparison of the change in storage volume and the difference between the volume of water entering and leaving the system,
- water level data for each pond,
- time of first flow from each surface discharge point,

- the volume of each surface discharge over time and
- the average volume of flow from each surface discharge point.

3.5 WinGRAM

The data are input to GRAM via a series of ASCII files. Although the volume of data is not large, finding the location of a calibration variable can be time consuming, particularly to the uninitiated user. Therefore a Visual Basic 3.0 preprocessor (WinGRAM) was developed. This displays the data from the input files in a format which allows the user to easily pinpoint pieces of data. It also has the facility to universally enter data for any parameter for all the ponds or pipes

WinGRAM is complimented by an Excel 5.0 Macro postprocessor (also written in Visual Basic 3.0), which is used whilst fitting the model. The macro automatically imports the output file containing the water level data and displays it with the recorded data on a graph. It also calculates the residual mean and the absolute residual mean of the differences between the two data sets. This allows the user to concentrate on the conceptualisation of what is happening in the system rather than the mechanics of moving data around.

The pre- and postprocessors have been used in practical class situations, which have tested their robustness and proven their user-friendliness.

3.6 Limitations of GRAM

The hydrogeological data used in this model are likely to be sparse because of the nature of the coal mining environment. In particular, the model is sensitive to estimates of the storage coefficient. The estimation of this is particularly difficult and is perhaps the greatest single source of error.

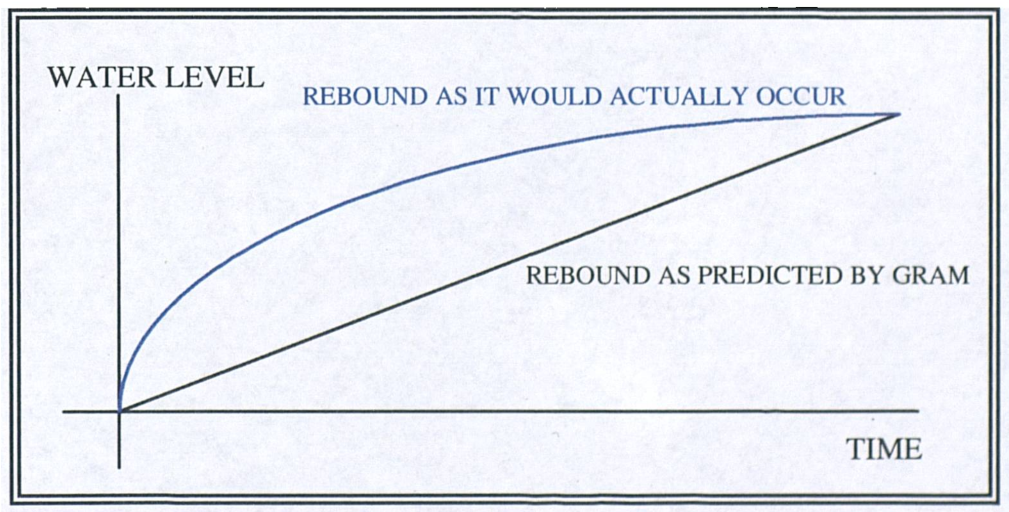
GRAM does not incorporate any modelling of the unsaturated zone or of soil moisture. This shortcoming can be mitigated by using recharge as one of the values in the Monte Carlo simulation.

GRAM does not consider rivers that may flow across the model area. Baseflow can only be represented as discharge to the surface through a discrete point, like all other surface discharges. Therefore, outflow through stream beds is unquantified. Recharge induced by a river is completely neglected. This recharge is likely to be a negligible proportion of the water balance of a modelled coalfield area, because of the mining precautions taken to prevent this.

The fact that the pipes only flow full is a limiting assumption. It adds to the simplicity and speed of the code. However, it means that a flow which is a few centimetres deep in the bottom of an intact roadway during the calibration period is represented by a small diameter pipe. In other circumstances, this roadway may be able to transmit far greater volumes of water.

The flat hydraulic gradient assumed over the ponds means that graphs of rebound have a uniform gradient; (see Figure 3.4). In actuality, these are more likely to be curved as the hydraulic gradient around the point of abstraction flattens and voids fill. The curve will be at its steepest initially as the voids in the 'cone of depression' caused by the abstraction fill. Hence the initial predictions of water level will be inaccurate. However, the estimate of the time taken for the pond to fill remains valid as the most significant factors controlling the system are recharge and storage volume.

Figure 3.4: Notional Comparison of the Likely Actual Progress of Groundwater Rebound and Groundwater Rebound as Predicted by GRAM



4 Flow Models for the Dysart-Leven Coalfield

4.1 The Dysart Leven Coalfield

4.1.1 Location

The Dysart-Leven Coalfield is one of several Fife coalfields. It lies in eastern Fife to the east of Glenrothes; see Figure 4.1. Along the coast it stretches from Kirkcaldy in the south-west to Leven in the north-east. To the west it reaches Thornton and Markinch. The River Ore flows from west to east across the coalfield, as does its tributary the Lochty Burn. The River Ore is a tributary to the River Leven which flows across the northern limit of the coalfield.

Figure 4.1: Location of the Fife Coalfields.

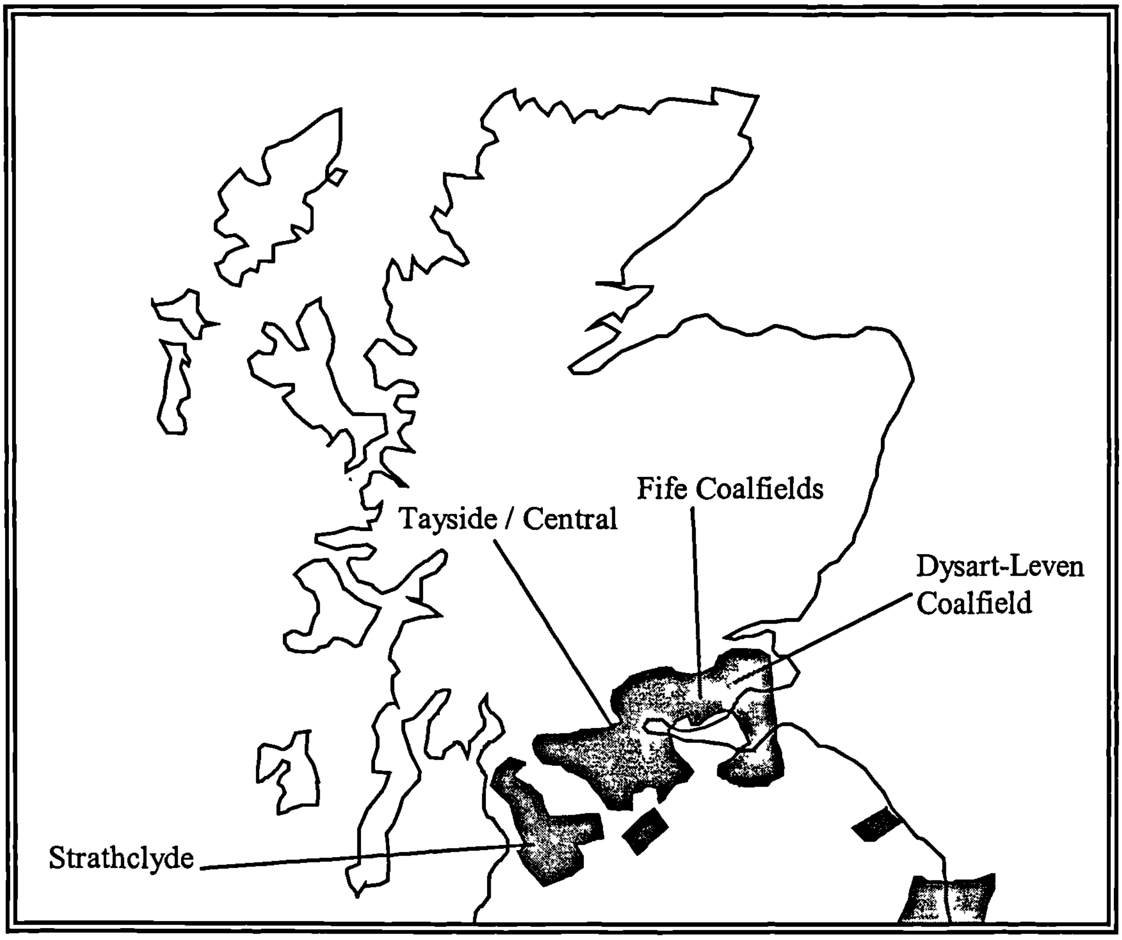
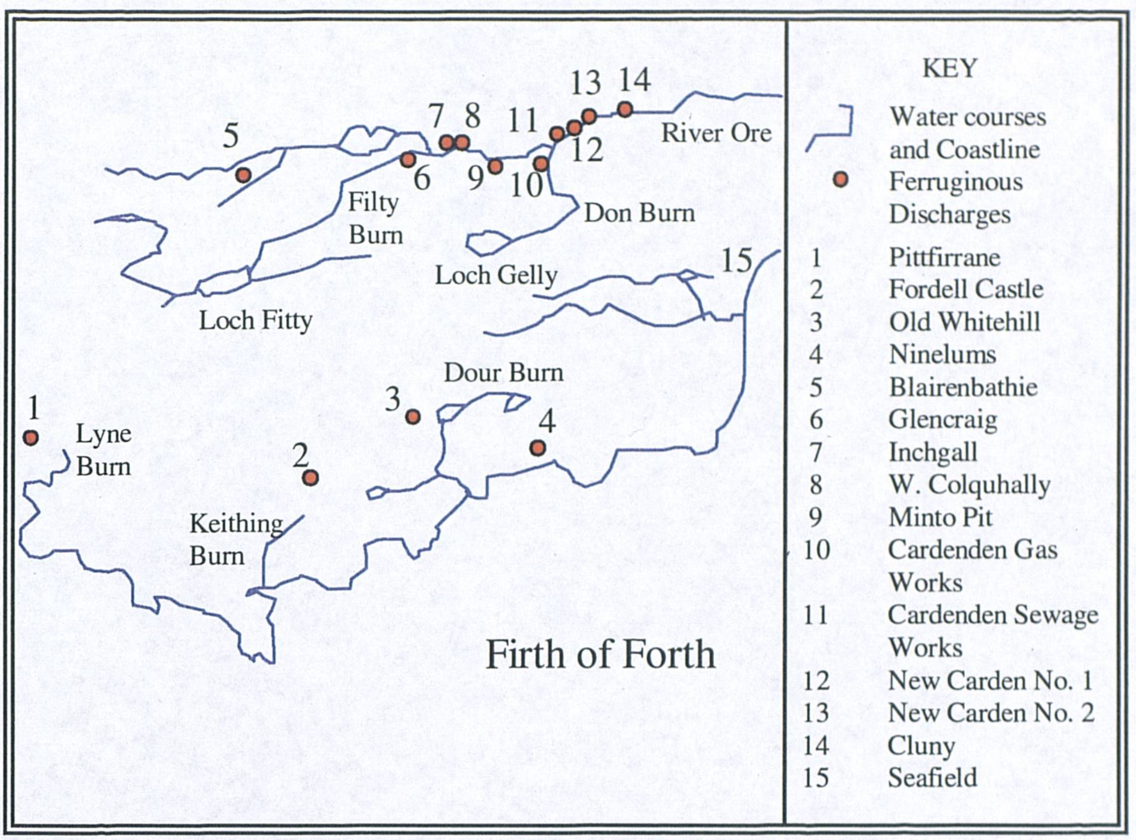


Figure 4.2: Existing Discharges of AMD in the Fife Coalfields.



After: Robins (1990)

4.1.2 AMD in the Fife Coalfield

Other Fife coalfields (see Figure 4.2) to the west of the Dysart-Leven Coalfield already exhibit AMD. However, they worked the Limestone Coal Group (Dinantian), whilst the Dysart-Leven Coalfield worked the Lower and Middle Coal Measures (Westphalian). The Limestone Coal Group is separated from the Lower and Middle Coal Measures by 600 m of unworked strata in the Upper Limestone Group and the Passage Group. However, the depositional environment of the Limestone Coal Group was very similar to that of the Coal Measures. Therefore the AMD discharging from the other Fife coalfields should be a good, but imperfect indicator of the nature of discharges from the Dysart-Leven Coalfield.

The Fife Coalfield was abandoned in the late 1960's. As a result the surrounding water courses, particularly the River Ore and the Keithing Burn have been polluted by AMD. The area most affected by AMD is roughly triangular in shape and covers 70 km^2. See

Figure 4.2. It stretches from Dunfermline in the west, to Methil in the east and Cardenden in the north (Henton, 1979; 1981; Robins, 1990).

In February 1977 AMD emerged from an old adit at Fordell Castle (NT147852) near Inverkeithing, causing problems downstream for a local papermill (Henton, 1979). The adit drains approximately 9 km^2 of coalfield. The flow began at a rate of 0.38 m^3/s (32.8 Ml/d), but fell to 0.26 m^3/s (22.5 Ml/d) in 1978 and by 1980 averaged a steady 0.24 m^3 s (20.7 Ml/d). Over the same period the iron content fell from 28 mg/l to 19 mg/l (Robins, 1990).

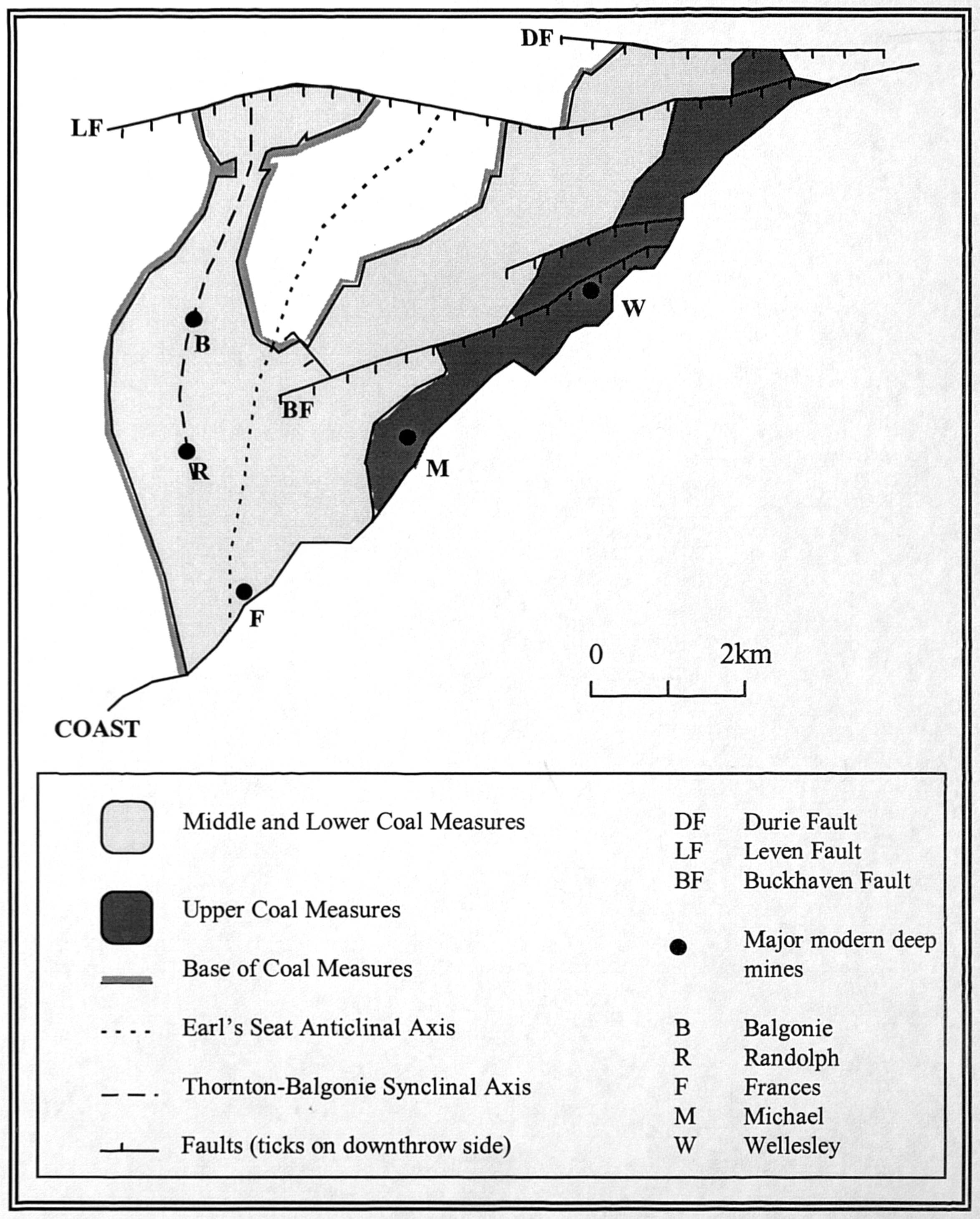
More recently the discharge has been affected by the dewatering of the nearby Keirskeath opencast mine. Dewatering was in operation from mid 1986 to mid 1989 during this time the discharge decreased (Younger, 1995). By the end of May 1989 it had dropped to approximately 0.028 m^3/s (2.4 Ml/d). After dewatering ceased in 1989 the discharge gradually increased in volume and then remained stable until the summer of 1994. In June and July 1994 the volume of flow almost doubled (Younger, 1995). As yet the reason for this behaviour can only be surmised.

4.1.3 The Geology of the Dysart-Leven Coalfield

The geology of the Dysart-Leven Coalfield consists of the uppermost Namurian Passage Group conformably overlain by Carboniferous Westphalian Coal Measures (see Figure 4.3). They occupy an area of 50 km^2 on land and extend at least 25 km^2 beneath the sea.

The Coal Measures Strata fall into three divisions the Lower, Middle and Upper (which are known elsewhere as the Westphalian A, B and C). The Lower and Middle Coal Measures comprise the Productive Coal Measures and the Upper Coal Measures are known as the Barren Red Coal Measures. The dividing line between them is the Skipsey's Marine Band (Knox, 1954). The base of the Coal Measures is marked by the pavement of the Lower Dysart Coal (Knox, 1954). The underlying Passage Group in this area is a sequence of mudstones, sandstones, grits and thin largely unworked coals

Figure 4.3: The Geology of the Dysart-Leven Coalfield.



The workable coal seams extend from the Lethemwell seam (in the top of the Passage Group) to the base of the Barren Red Coal Measures (Knox, 1954). Table 4.1 shows the worked seams, their thickness at Frances Colliery and their stratigraphic position.

Table 4.1: The Productive Coal Seams in the Dysart-Leven Coalfield.

Seam	Thickness at Frances Colliery (m)	Distance between seam and the seam above at Frances Colliery (m)	Total Sulphur (wt %; mean of available data)
Pilkembare	1.20 - 1.50	-	1.15
Wall	Extraction hydraulically isolated	32	1.60
Barncraig	1.45	15	1.01
Coxtool	1.15 - 1.20	32	0.80
Den	Not mined in study area	16	0.88
Chemiss	1.50 - 1.75	38	0.87
Bush	1.10 - 1.40	18	1.40
Wemyss Parrot	0.75	48	1.20
Wood (Four Foot)	0.9 - 1.2	17	0.70
Earl David's Parrot	1.2	26	0.55
Bowhouse	1.2 - 1.8	15	1.05
Branxton	0.9 - 1.2	21	0.75
More	0.9	18	0.70
Boreland	0.6 - 0.9	24	0.75
Sandwell	0.9	22	1.30
Victory	Not mined in area		
Dysart Main	2.1 - 2.75	60	0.57
Lower Dysart	1.1 - 1.4	25	1.91
Lethemwell	1.4	73	0.63

Coal Measure rocks have a variable cyclicity (Anderton *et al*, 1979). The succession of rocks between one coal seam and the next is termed a cyclothem. The elements of a cyclothem are usually coal, structureless siltstones known as seatearths (which are often but not always underlying the coal seams), marine bands (which are often fine grained dark, carbon rich mudstones), sandstone and shale (Anderton *et al*, 1979). A typical Westphalian cyclothem in the Durham Coalfield is 12m thick and from top to bottom consists of: coal, seatearth, mudstone, siltstone, sandstone and shale (Minett, 1987; Richardson, 1983). Given the generally similar depositional facies of the Dysart-Leven Coal Measures, similar cyclothems are anticipated here (though no sediment layer studies of this area have been published).

High sulphur coals are commonly associated with marine bands, (see Section 2.1.2). Younger *et al* (1995) describe the relative sulphur contents of the seams in the Dysart-Leven Coalfield; see Table 4.1. The coalfield has three marine bands, which are *Lingula*-bearing shales. The Lower Dysart Coal is a high sulphur coal and overlies the *Lenisulcata* marine band. There are several medium-sulphur coals; the Pilkembare, Wall, Bush, Wemyss Parrot, Bowhouse and Sandwell. Of these, the Skipsey's Marine Band lies above the Pilkembare; and the Queenslie Marine Band lies between the Bush and the Wemyss Parrot. All the seams have spatially variable sulphur content, the inland area around Randolph and Balgonie having the highest concentrations.

It is probable that the Coal Measures of the Dysart-Leven Coalfield correspond to those of the Midlothian Basin on the other side of the Firth of Forth (Dron, 1902). The outcrop of the Coal Measures form a horse-shoe shape (see Figure 4.3). The western arm of the horse-shoe terminates at the Leven Fault which has a displacement of 370 - 460 m. The eastern ends with the Durie Fault which has a displacement of 275 - 370 m. The western arm consists only of the Lower and Middle Coal Measures, but the eastern arm comprises all three divisions of the Coal Measures.

There is a fold axis running north to south with two main anticlines (to the west the Earl's Seat Anticline and to the east the Lundin Anticline) and the Leven Syncline which lies between them. To the east of the Lundin Anticline the coal measures dip to the Temple Fault which forms the eastern-most limit of the coalfield (Knox, 1954). West of the Earl's Seat Anticline lies the Balgonie Syncline. At the north end of this syncline is the small Barnslee-Treaton Basin, and at the south the main part of the syncline forms the Thornton Basin. The Barnslee-Treaton Basin extends as far up as the Chemiss Seam, whilst the Thornton Basin only consists of the lower half of the Productive Coal Measures up to the top of the Earl David's Parrot Coal (Knox, 1954).

The landward part of the Coal Measures is largely free from igneous intrusions. However, in the part of the coalfield under the sea there is a thick intrusion of dolerite, which cuts upward through the entirety of the Productive Coal Measures. It is at some distance from the shore, running parallel to it for a distance of at least 8.85 kilometres. (Knox, 1954). Anderton *et al* (1979) note that during the formation of the Coal Measures in Midland Scotland there were volcanic episodes which produced the dolerite intrusion and volcanic tuffs off the coast of Fife in the Firth of Forth.

The Passage Group is more than 200 m thick (Geikie, 1902). The mudstones, sandstones, grits and coals of the Passage Group form a continuous belt along the western edge of the coalfield. They also form the core of the Earl's Seat Anticline and occupy the western half of the area between the Leven and Durie faults (Knox, 1954). While the Passage Group contains numerous worked seams in the Westfield inlier to the north-west, it has only worked seam (Lethemwell) in this area.

4.1.4 The Mining History and Extent of the Workings

Knox (1954) identified over 100 shafts in the Dysart-Leven Coalfield. However, the coalfield can easily be divided into the areas worked by the seven largest collieries: Wellsgreen, Seafield, Balgonie, Randolph, Frances, Michael and Wellesley.

Coal was extracted from Bell Pits in the Balgonie area as early as the 13th Century. By the 1730's deep mining was taking place at Balgonie. The pit was finally closed in 1960 (Pearson, 1993). Photograph 4.1 shows the spoil heap at Balgonie and the polluted stream draining it.

Michael Colliery was opened in 1898 and worked until 1967 when it had to be closed. An underground fire which killed nine men meant that the pit shafts had to be sealed. In 1977 Michael was linked to Frances allowing coal to be extracted from Michael once more (Pearson, 1993). As the coal was depleted inland, extraction was concentrated in the undersea portions of the coalfield, accessed from Wellesley, Michael, and Frances (Younger *et al*, 1995). Frances was the last of these three to be worked and it still has vast reserves of coal under the sea (Beveridge *et al*, 1991). Photograph 4.2 shows the winding gear at Frances.

However, there was no mining at Frances after the end of the national miners' strike in 1985. Frances was one of the pits which were 'mothballed'. This has meant that the coalfield has continued to be dewatered to protect the workings from water inflow in case extraction was reinitiated in the future (Younger *et al*, 1995). In 1985 abstraction at Randolph was ceased, allowing the groundwater in the inland collieries to rebound to the level where it flows into the adjacent coastal collieries, Frances and Michael, which continued to be pumped. In 1994 British Coal decided that Frances would never reopen. The Forth River Purification Board (FRPB) employed Bullen Consultants to predict the consequences of British Coal ceasing abstraction at Frances and Michael. They were then able to negotiate a solution with British Coal (involving rebound to -56 mAOD followed by pump and treat) to prevent AMD discharging into surface waters.

Photograph 4.1: Spoil Heap at Balgonie Shaft.

Photograph 4.2: Winding Gear at Frances Colliery

4.1.5 The Hydrogeology of the Dysart Leven Coalfield

General Framework

The coalfield is hydraulically isolated; faults separate it from the Leven Coalfields in the north. Of the seven collieries of the coalfield, five (Balgonie, Randolph, Frances, Michael and Wellesley) have interconnected workings. There is no apparent connection between these collieries and Seafield Colliery in the south or Wellsgreen Colliery in the north. There was once a single roadway connection in the workings between Frances and Seafield but this was sealed in 1987. Prior to this point a volume of approximately 0.92 Ml/d flowed from Seafield to Frances via the Whin Dooks.

The hydrogeology of the Dysart-Leven Coalfield is typical of mined coalfields. The unmined areas having very low permeability and storage coefficients compared to the mineworkings. Bullen Consultants (1994) estimate hydraulic conductivities of 0.09 m/d in unworked strata, 5 m/d in areas of collapsed strata and in excess of 100 m/d in the mined voids. However, these voids are likely to be separated by areas with lower hydraulic conductivities, therefore a more realistic estimate of effective hydraulic conductivity for the voids may be in the region of 10 - 100 m/d.

Pumping History

Data on the pumping history of the coalfield was obtained from British Coal archive memos.

Balgonie

Until November 1968 Balgonie was pumped at a rate of 6.15 Ml/d to keep the water level at -86.87 mAOD. Since then no abstraction has taken place. However, the level of water in the shaft has varied in response to the pumping in the Randolph shaft.

Randolph

The Randolph pit initially stopped pumping in May 1968. However, on 9 August 1971, pumps were restarted at 9.16 Ml/d. The average abstraction rate thereafter was 7.86 Ml/d. Over a period of six weeks the water level in Randolph changed from -55.93 mAOD to -60.05 mAOD. In Balgonie the change in water level was -55.56 mAOD to -54.86 mAOD. From then until June 1981 the pit was pumped from October to May each year at a rate of 17.68 Ml/d. After a partial shaft collapse in June 1981 the abstraction rate dropped to 9.49 Ml/d. When the pumps were turned off on 8 March 1985 the abstraction rate was 7.86 Ml/d. The water level in Randolph was -54.25 mAOD and in Balgonie was -46.63 mAOD. The water levels subsequently settled at -37.19 mAOD in Randolph and -32.31 mAOD in Balgonie

Frances

There is a scarcity of pumping rate data for Frances Colliery. However, before 1985 the average abstraction rate was apparently 7.86 Ml/d. This rate was enough to maintain the water level at approximately -223 mAOD, to prevent water flowing into Michael along a roadway at 213.36 mAOD. After 1985, when Randolph stopped pumping, the abstraction rate was increased to 9.03 Ml/d, to maintain the same water level.

Michael

Prior to the closure of Randolph in 1985 the pumps at Michael operated at around 13.09 Ml/d keeping the water level at -293.83 mAOD. After that time abstraction rates gradually increased in order to maintain the same level. Table 4.2 shows the average pumping rate each year.

Table 4.2: Average Abstraction Rate in Michael Shaft 1985 - 1992

Year	Ml/d
1985	14.85
1986	18.17
1987	24.08
1988	24.77
1989	24.33
1990	25.04
1991	21.96
1992	22.03

The overall gain in pumping after cessation abstraction from Randolph was around 10 Ml/d (1991 - 92 were rather dry years). This is more than the sum of the former abstraction rates of Randolph and Balgonie; therefore there must be inflow from Wellesley.

Wellesley

Prior to the cessation of dewatering in March 1972 the pumping rate was 7.20 Ml/d maintaining a water level of -525.78 mAOD. Over the next 22 years a slow rise in water level was observed. In December 1976 the water level was -303.28 mAOD and by July 1994 the water level was -203.00 mAOD and still slowly rising when the shaft was backfilled and measurements were discontinued.

4.1.6 The Chemistry of Pumped Minewaters

The water abstracted from the Dysart-Leven Coalfield has not always been of good quality. The pumped discharge from Randolph Colliery was a particular problem, being corrosive to clothing and leather (Muir, c 1953). In the shallow workings of Randolph, acidic water was particularly associated with the Lower Dysart Seam. In the deep workings of the Frances Pit the water was alkaline, except where the Lower Dysart seam was worked when it was strongly acidic (Muir, c 1953).

Due to the poor water quality, Randolph was only pumped from October to May each year for the period 9 August 1971 to 8 March 1985. This meant that the discharge could be diluted by the larger winter river flows. Despite this, there are limited archive data for the chemistry of the water pumped from the inland collieries (see Table 4.3). Both the pH and the iron content of the waters from Randolph and Balgonie are highly variable but generally polluting.

The pumped minewaters from the coastal ponds Michael and Frances are moderately ferruginous and of neutral pH (see Table 4.3). Younger (1995, Personal Communication) concluded that the waters from the coastal ponds have a considerable seawater component, with Frances (according to the conductivity) almost twice as saline as Michael.

The salinity of the water from the inland ponds Randolph and Balgonie is considerably lower (total dissolved solids of 860 - 1080). Total dissolved solids of 1000 mg/l or less would indicate fresh water, whilst values of 10 000 mg/l - 100 000 mg/l indicates saline water (Freeze and Cherry, 1979).

The sodium and chloride contents and conductivities of Michael and Frances are far greater than those in Table 2.1, indicating that they are likely to have a seawater component. They are also warmer than most shallow Scottish groundwaters (cf. Robins, 1990).

Table 4.3: The Chemistry of the Pumped Waters

Pond	Michael	Frances	Randolph	Balgonie
	Sampled 6 October 1994		Archive Data	
Calcium (mg/l)	311.6	159.6	-	-
Magnesium (mg/l)	317.9	318.9	-	-
Sodium (mg/l)	1304	1721	-	-
Potassium (mg/l)	78.15	58.75	-	-
Iron (total) (mg/l)	34.42	12.15	2 - 700	2 - 700
Manganese (mg/l)	1.497	1.104	-	-
Aluminium (mg/l)	0.7223	1.088	-	-
Zinc (mg/l)	0.0119	0.0153	-	-
Nickel	0.0277	0.1926	-	-
Alkalinity (mg/l as $CaCO_3$)	409	162	significant	significant
Sulphate (SO_4) (mg/l)	1713.3	1239	-	-
Chloride (mg/l)	2662.5	5880	-	-
pH	6.89	6.87	3.2 - 6.6	6.1 <
Temperature (^oC)	17.0	15.7	-	-
Eh (mV)	-37	-3	-	-
Conductivity	10500	19350	-	-

The levels of magnesium in the Michael and Frances waters are much higher than those indicated in Table 2.1. However, there is no obvious source of magnesium in the minerals of the coalfield. Therefore it is likely to have come from seawater which typically has a magnesium content of 1290 mg/l (Younger, University of Newcastle upon Tyne, Personal Communication, 1996). This gives a figure of around 25 % of the water in both Michael and Frances being of marine origin.

The iron concentrations of the Frances and Michael waters is relatively high suggesting that the recharge from rainwater is becoming polluted with AMD as it flows down through the workings. However, the sulphate levels cannot be explained by the chemistry of pyrite oxidation alone, which would produce 2 moles of sulphate per mole of iron.

The iron concentration of Michael represents 0.616 moles of iron (34.42 / 55.847; 55.847 being the atomic weight of iron) which is the equivalent of 1.23 moles of sulphate which can be explained by pyrite oxidation. Doing the same calculation with the figures for Frances gives 0.435 moles of sulphate which can be explained by pyrite oxidation. The actual molality of sulphate in the Michael water is 17.84 (1713.3 / (32.06 + 15.9994 x 4); 32.06 being the atomic weight of sulphur and 15.9994 being the atomic weight of oxygen). The same calculation produces a molality of 12.90 for Frances. This leaves 16.61 and 12.47 moles of sulphur unexplained in Michael and Frances respectively. The sulphur molality of sea water is 28.2. This gives percentages of the Michael and Frances water which are of seawater origin of approximately 59 % and 44 % respectively.

Saline Intrusion

These high levels of water inflow from the sea indicate that the abstractions at Michael and Frances have resulted in a disturbance of the natural hydrodynamic balance. As a consequence, saline intrusion into the Coal Measures aquifer has occurred. The different densities of fresh and saline waters mean that when saline intrusion occurs distinct zones of fresh and saline waters are produced. The denser saline waters displace fresh water at the bottom of the aquifer.

The Ghyben-Herzberg relationship between fresh and saline waters, in a homogeneous, unconfined coastal aquifer gives satisfactory results where flow is predominantly horizontal (Todd, 1980). It indicates that interface between fresh and saline water can be found at a depth below sea level which is equal to approximately forty times the height of the fresh water above sea level.

In the field this interface does not exist, there is in actuality a 'mixing zone' or 'zone of diffusion'. The size of the mixing zone is dependant on the geology and can vary in thickness from 1 m to greater than 100 m. In general, this zone is thickest in highly permeable strata which are subject to heavy pumping (Todd, 1980).

Using this model the Dysart-Leven Coal Measures aquifer is likely to have a thick zone of mixing between fresh and saline waters. However, the coalfield is not homogenous; seawater will be able to enter workings and mining induced fissures. As a consequence of this heterogeneity the true pattern of seawater ingress into the workings will not follow a simply predictable pattern.

4.1.7 The Blair Den Shafts

A visit to the coalfield in May 1996 indicated that there are unrecorded discharges from the Blair Den shafts. These shafts access shallow workings which predate nationalisation. These shallow workings lie directly above those of Frances colliery. It seems that they have filled up and discharged to the surface without allowing flow to the remaining workings from Frances. The ferruginous discharges are from shafts located at the high water line and are estimated to yield only a few m^3 a day. Photographs 4.3 and 4.4 show the discharges.

These discharges illustrate the compartmentalisation of the hydraulic units in the coalfield. The workings from Blair Den can thus be considered as entirely separate from the remainder of the workings in the coalfield, where the water levels have been maintained at a low level.

Photograph 4.3: Discharge from Blair Den Shaft

Photograph 4.4: Discharge from Blair Den Shaft Flowing Towards the Sea.

4.2 Applying GRAM to the Dysart-Leven Coalfield

4.2.1 Introduction

The five interconnected collieries of the Dysart-Leven Coalfield lend themselves to being represented by ponds and pipes. Therefore, the coalfield can be modelled using GRAM.

4.2.2 Data used by GRAM

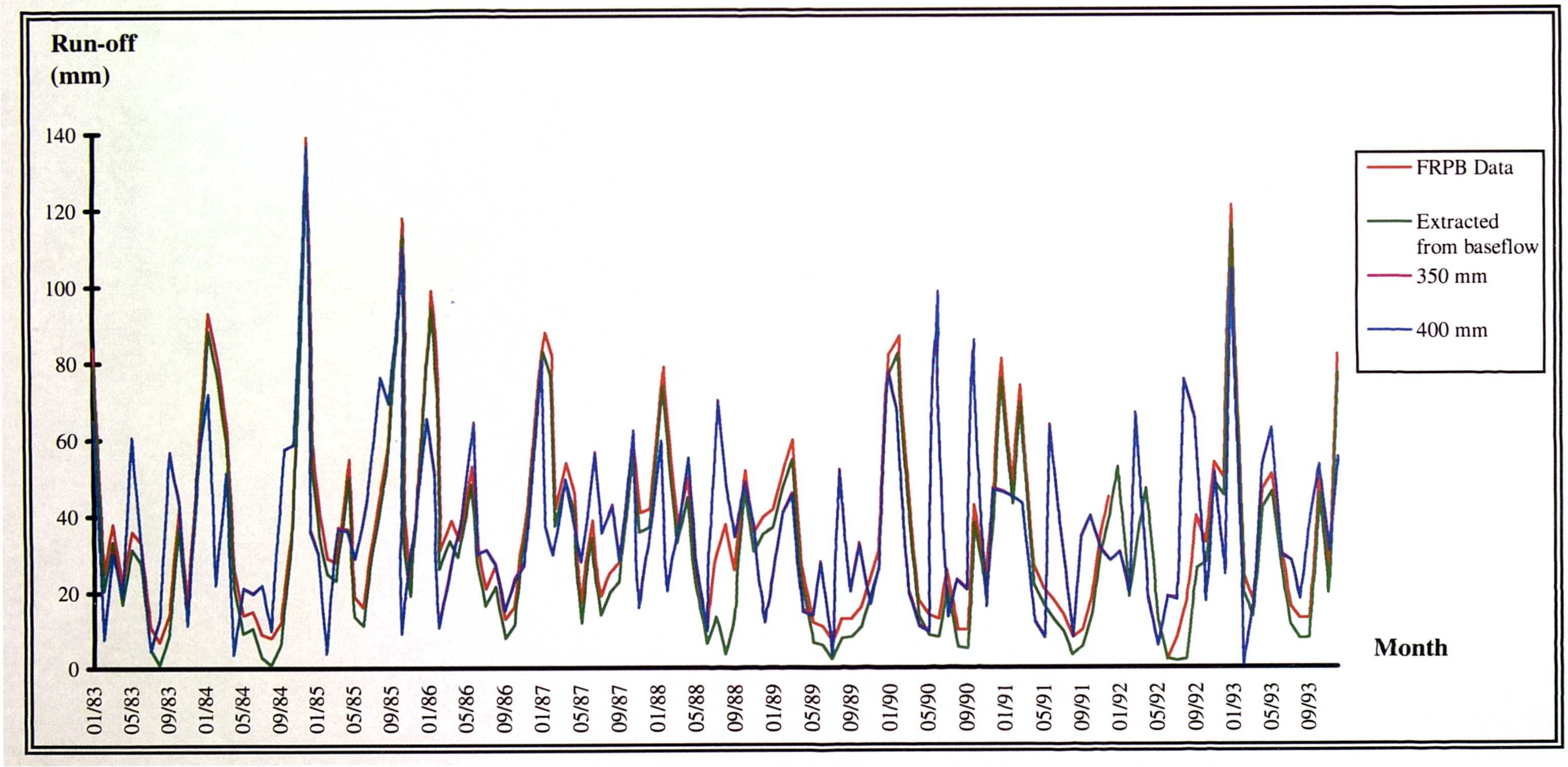
Hydrological Data Collection and Estimation

The values for rainfall, evapotranspiration, attenuation of recharge over time and percentage run-off were established by analysis of the hydrology of the River Ore catchment. The coalfield covers an area which is mainly within the bottom of the Ore catchment. Rainfall data for Tiel Path (NO289010) and Silburn (NO393019) and flow data for the River Ore (at NT330997) for the period 1983 - 1993 were provided by the Forth River Purification Board (FRPB).

Comparison of the Tiel Path and Silburn data sets showed that they were broadly very similar. Therefore, it was assumed that the rainfall recorded at Tiel Path was representative of rainfall over the entire catchment area (162 km^2) upstream of the gauging station.

FRPB provided total monthly run-off data for the period 1983 - 93. To verify these data run-off was roughly calculated by dividing the hydrograph of the River Ore into baseflow and run-off. A visual analysis of the hydrograph indicated a daily baseflow of approximately 0.3 m^3/s. Subtracting this from the daily river flow produced monthly run-off data which were approximately equal to the data provided by the FRPB (the data sets having a correlation coefficient of 0.993). Figure 4.4 shows how similar the data sets are, the FRPB data having slightly higher peak values than the data produced by dividing the River Ore hydrograph

Figure 4.4: Run-Off Data



The run-off was also calculated using the rainfall data, and estimates of evaporation and percentage run-off. For each year (1983-1993), the evaporation and percentage run-off were varied until the best fit to the monthly run-off data provided by the FRPB was found. Robins (1990) suggests a range of values for total annual actual evapotranspiration of 350 mm to 400 mm, for this area. Therefore, evaporation was set at 350 mm and at 400 mm and the percentage direct run-off was calibrated. For every year there was minimal difference between the values produced by the different evaporation rates. The rate of 350 mm, being marginally better, was the value chosen. The calibrated percentage run-off for each year is shown in Table 4.4. The mean value is 64.67 %, which is the value which will be used in the simulations. The data produced using the mean value broadly correlates to the run-off data provided by the FRPB (350 mm having a correlation of 0.651 and 400 mm having a correlation of 0.649). The run-off data produced are shown in Figure 4.4. The data produced by the two different evaporation rates are so similar that they appear as one line. The run-off data created using the mean value of percentage run-off broadly correlates with the data provided by the FRPB, reproducing most of the peaks in the data.

Table 4.4: Percentage Run-Off

Year	Percentage Run-Off Which Produced the Best Fit.
1983	62.1
1984	70.0
1985	67.0
1986	72.0
1987	69.7
1988	67.4
1989	63.5
1990	55.7
1991	65.2
1992	54.5
1993	64.3

GRAM has the facility to attenuate recharge, the user can define the percentage of recharge that reaches the groundwater surface, for each timestep after precipitation has occurred. This was calibrated by smoothing the effective rainfall over various numbers of days and comparing the hydrograph produced with the recorded hydrograph. The best fit to the real hydrograph was found to be produced by the values shown in Table 4.5.

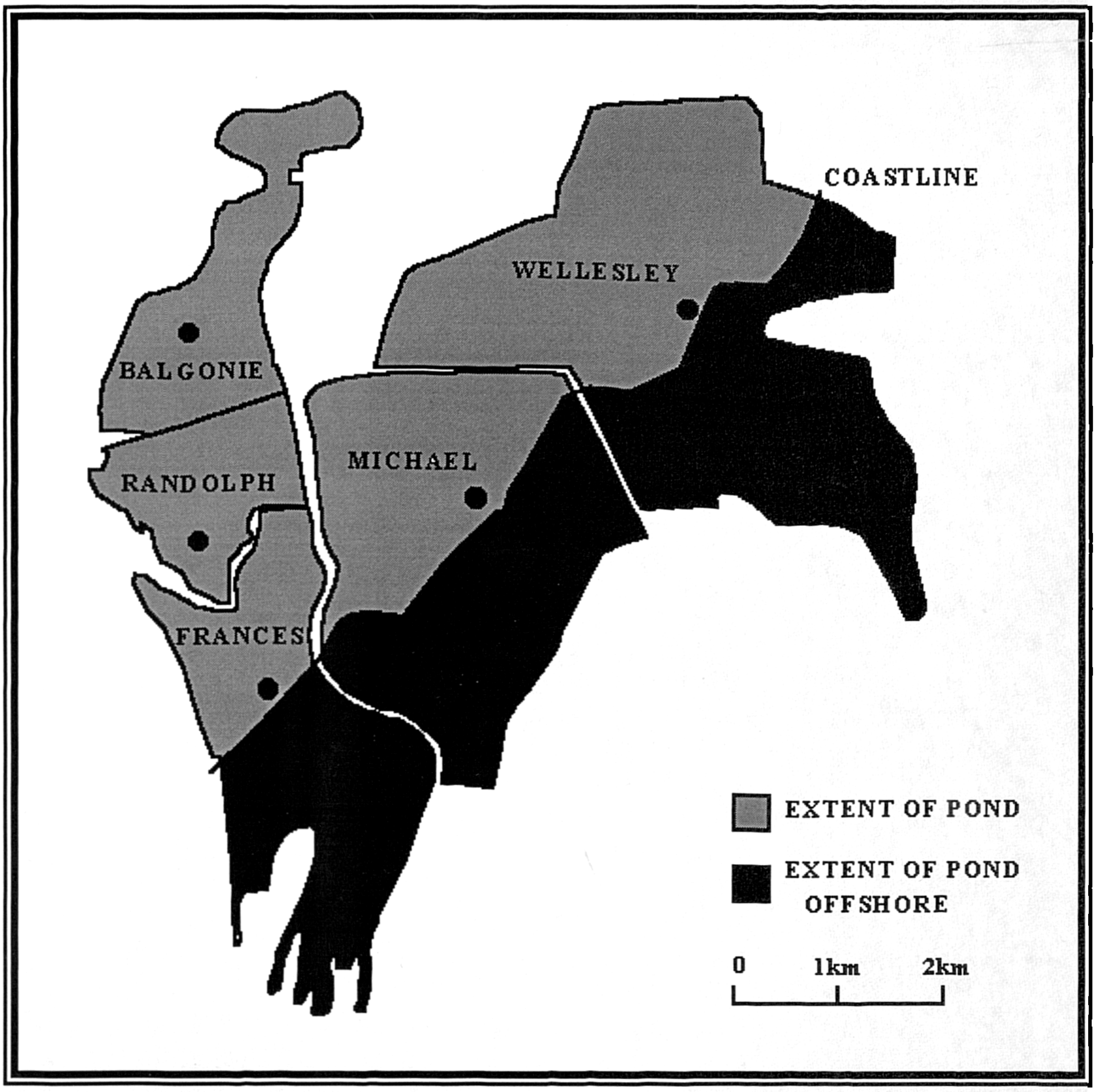
Table 4.5: Recharge Attenuation Figures

Days After Rainfall	Fraction Reaching Groundwater
1	0.1
2	0.25
3	0.3
4	0.25
5	0.1

Information from the British Coal Archive

The extent of each pond was calculated using 6 inch to 1 mile mine plans, provided by British Coal. These contained data in two formats, the 0 datum being either 5000 ft (1524 m) or 10000 ft (3048 m) below sea level. By overlaying the extent of workings in each seam an outline of the furthest workings from the main shaft of each colliery was produced. This was taken to be the edge of the pond.

Figure 4.5: The Extent of the Ponds in the Dysart-Leven Coalfield

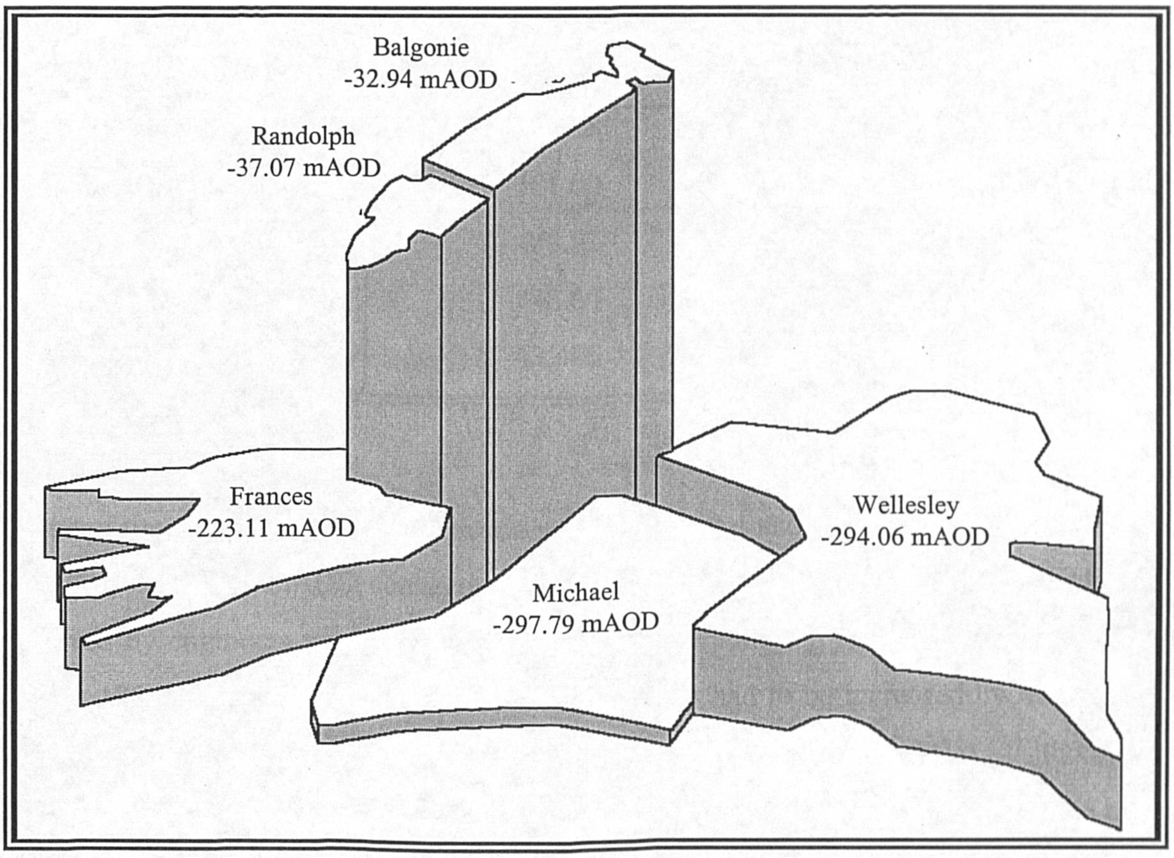


Workings from different shafts did overlap. This was a particular problem with Michael and Frances. Since 1977 coal has been extracted from Michael via Frances. The small areas of overlap were assigned to the ponds from which they were worked most extensively. The larger areas were divided as evenly as possible between the ponds involved. Figure 4.5 shows the extent of each pond.

Barbour (Bullens Consultants, Personal Communication, 1994) calculated the void space in the worked coal measures from the mine plans. With a 30 % margin of error it was estimated that the bulk specific yield was 0.021. This is the same order of magnitude as estimates of 0.058 for the Durham Coalfield (Minett *et al*, 1986; Younger and Sherwood, 1993).

Historic water level and abstraction data were provided by British Coal (see Section 4.1.5). Figure 4.6 shows the water levels in the ponds in 1994, prior to the cessation of pumping.

Figure 4.6: Depths of Water Within the Ponds in the Dysart-Leven Coalfield



Younger (University of Newcastle upon Tyne, Personal Communication, 1994) compiled data on the connections between the ponds. These data are summarised in Tables 4.6.

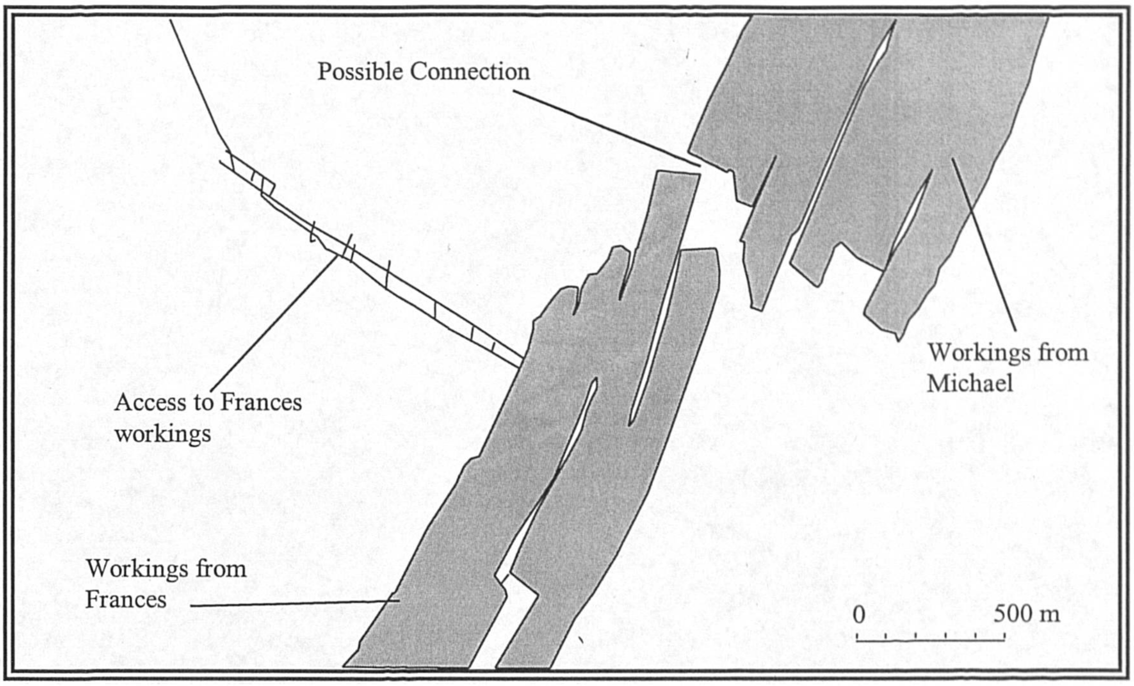
Table 4.6: Connections Between the Ponds in the Dysart-Leven Coalfield

Ponds connected	Height (m AOD)	Seam
Randolph - Balgonie	-85.34	Dysart Main
	-118.87	Lower Dysart
Balgonie - Michael	-39.62	Dysart Main
Randolph - Michael	-56.08	
Randolph - Frances	-39.62	Dysart Main
Frances - Michael	-213.36	Dysart Main
	-518.16	Barncraig
Michael - Wellesley	-335.28	Barncraig
	-381.00	Chemiss
	-438.91	Chemiss
	-548.64	Barncraig
	-435.86	Barncraig

Some of the connections between ponds were conjectural and not proven to exist. For instance, the -56.08 mAOD connection between Randolph and Michael was not widely believed by engineers working for British Coal until pumping at Randolph ceased in March 1985. Subsequently the abstraction at Frances had to be increased by less than 1.20 Ml/d whilst at Michael it increased from 13.09 Ml/d to 23.50 Ml/d. Although some of the additional flow to Michael must have been caused by the continuing rise in water levels in Wellesley, this provides compelling evidence that the connection between Randolph and Michael does exist.

On the other hand, the -518.16 mAOD connection between Frances and Michael through a barrier in the Barncraig seam remains unproven; whether it is active or not can be addressed during model calibration. Figure 4.7 shows the area of the Barncraig seam where the seepage may occur between the workings from Frances and Michael.

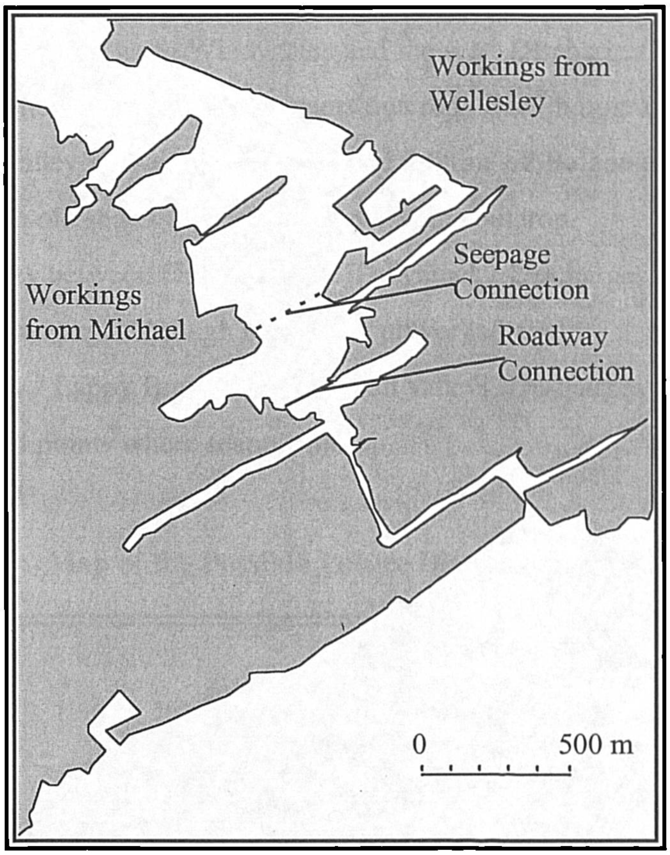
Figure 4.7: Workings in the Barncraig Seam Extracted From the 6 inch to 1 mile Mine Plans



The lengths of the roadways is in some cases recorded and in the remaining cases estimated. The diameter of only one of the roadways in the workings was recorded as approximately 2.3 m. This value was assumed to represent the maximum diameter of all the connections.

Figure 4.8 shows the Chemiss seam where there are connections between the workings from Michael and Wellesley. The southerly connection being a roadway (182.88 m long at -438.91 mAOD) and the northerly connection is through the Chemiss waste (259.06 m long at -381 mAOD).

Figure 4.8: Workings in the Chemiss Seam Extracted From the 6 inch to 1 mile Mine Plans



When the length of a connection has not been recorded the estimation of the length is dependent on the quality of the mine plans. Some seams have been worked so extensively that the mine plans become very complex and confusing. This was the case for the mine plans of the Dysart Main seam, where the connection lengths could only be roughly estimated.

The probable future discharge points were ascertained using the locations of shafts and workings, seam outcrop patterns, topography and surface drainage features (Younger, University of Newcastle upon Tyne, Personal Communication, 1994). The location of the most likely discharge points are given in Table 4.7. These can broadly be divided into six zones, which are shown in Figure 4.9. These zones are:

1. The coast between Dysart and the southern foreshore at West Wemyss. The Productive Coal Measures outcrop along this section of the coast.

2. The three coastal shafts along the coast between West Wemyss and the River Leven. The Barren Red Coal Measures overlie the Productive Coal Measures on this section of coast.
3. The Leven valley between Windygates and the sea. Discharges may occur through old shafts, adits and points where seams outcrop. See Photograph 4.5.
4. The Leven valley between West Mill and Milton of Balgonie. Discharges may occur through old shafts and points where seams outcrop.
5. The Ore valley between Hurl Burn and Tullybreck. Discharges may occur through old shafts or seepages through barriers of unworked coal.
6. The Kingslaw / Lappy Burn / Wemyss Den valleys. Discharges may occur through old shafts and points where seams outcrop.

Figure 4.9: Map of the Possible Future Discharge Zones and Points

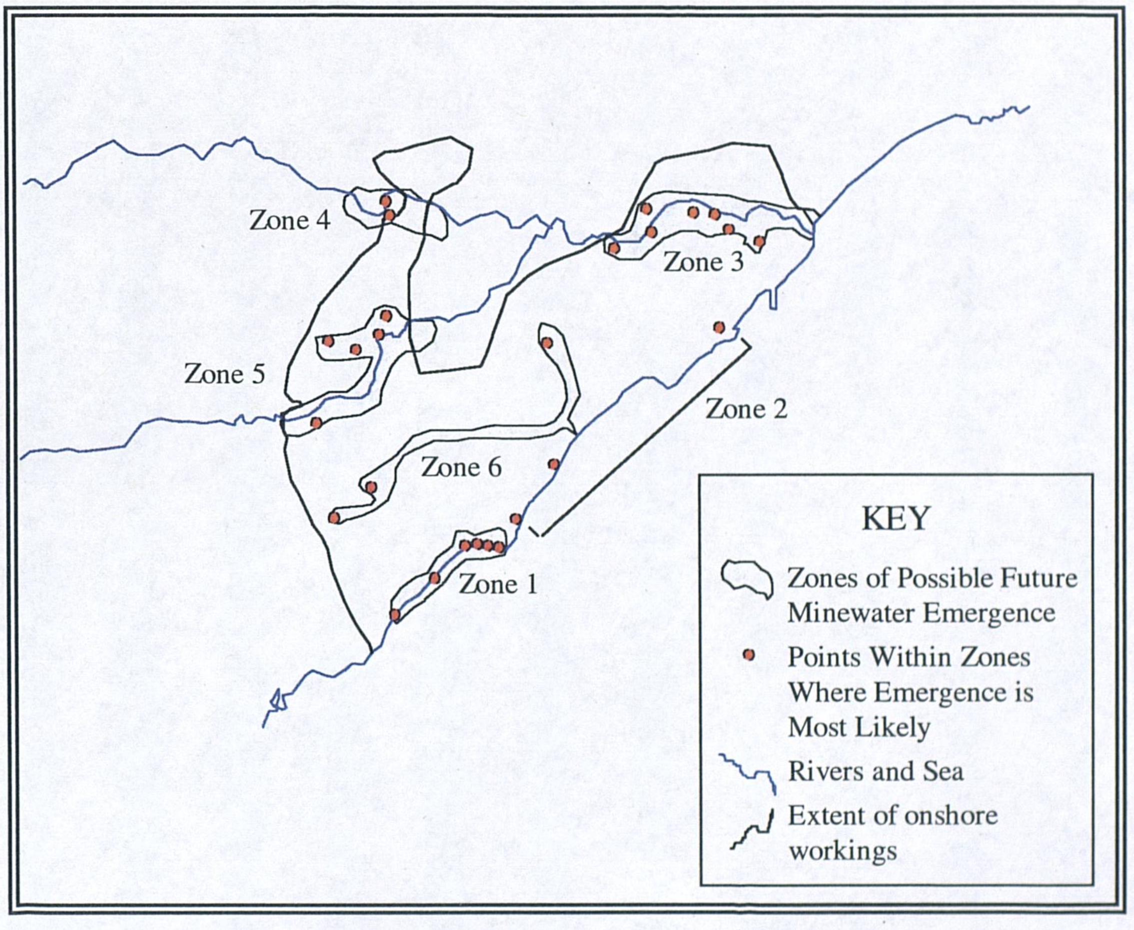
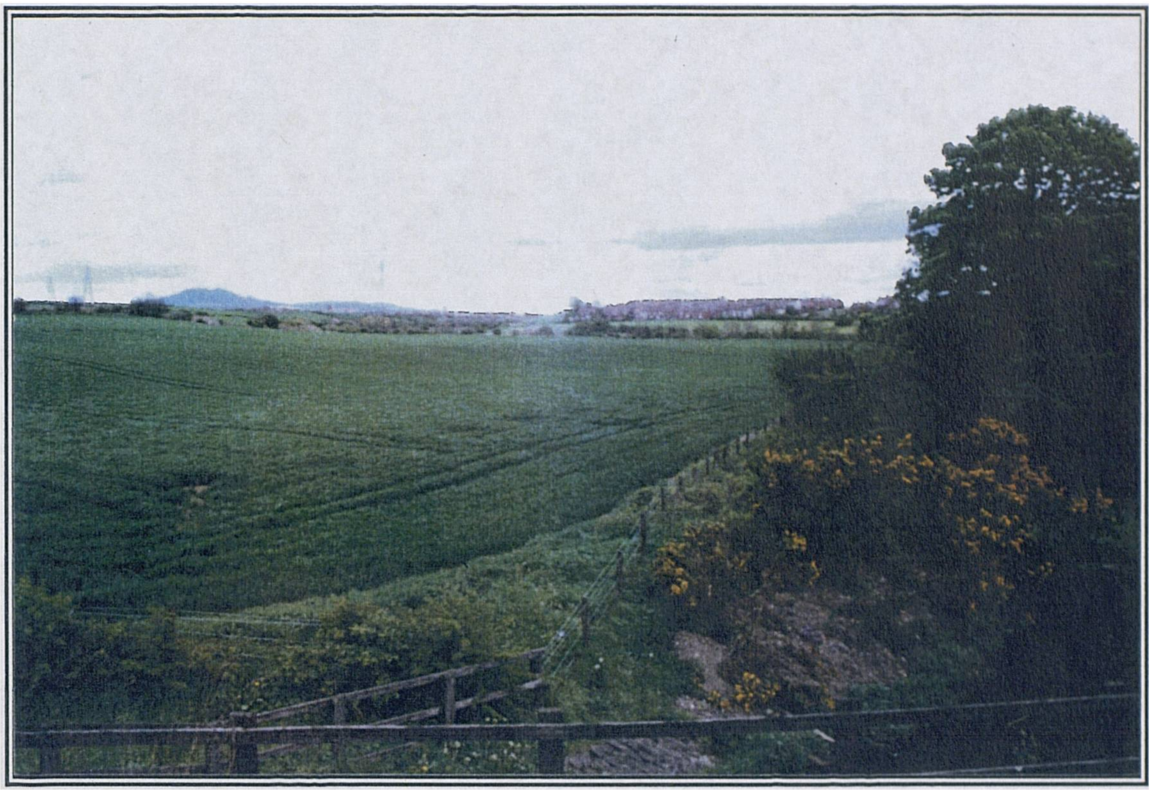


Table 4.7: Location of Probable Future Surface Discharge Points

Pond	Discharge Point	Height (m AOD)	Grid Reference
Wellesley	Wellesley Shafts	6.7	NT366986
	Old Shaft	20	NT348999
	Old Shaft	25	NO354002
	Duniface Adit to Kennoway Burn	20	NO352005
	Bowhouse Outcrops	20	NO360008
	Chemiss Outcrops	20	NO364006
	Kirkland Shafts	20	NO367004
	Leven Shafts	25	NO374002
	Drainage Level in Leven Harbour	5	NO383003
Michael	Victoria Shaft	7.3	NT322947
	Lady Shaft	15	NT324947
	Reservoir Shaft	15	NT326947
	Coxtool Shaft	15	NT326947
	Windmill Shaft	20	NT329951
	Michael Shafts	11.6	NT336962
	Wemyss Den Burn	45	NT338977
Frances	North Foreshore at Dysart	10	NT307933
	Foreshore below Frances Colliery	10	NT310937
	Frances Shaft	45	NT309938
	Blair Den shafts	5	NT314943
	Blair Den shafts	15	NT314943
	Blair Den shafts	25	NT314943
	Blair Den shafts	35	NT314943
Randolph	Discharge between Ore Bridge and Railway viaduct	48	NT294973
	River Ore, north-east of Balbeggie Cottage	50	NT286966
	Kingslaw Burn	85	NT294952
Balgonie	Balgonie Engine Shaft	40	NO308004
	Old Shaft	40	NO307009
	Discharge to Lochty Burn	45	NT301982
	River Ore between Lochty Burn confluence and New Bridge	43	NT307984
	Furnace Shaft at Lochty Farm	45	NT296983
	River Ore near Tullybreck	45	NT313986
	Julian Shaft	48	NT306987
	Lochty Side Shaft	50	NT298986
	Discharge between Ore Bridge and Railway Viaduct	48	NT294973

Photograph 4.5: The Leven Valley: Possible Location of Future Discharges of AMD



Preliminary Water Balance

A simple water balance (an average per day over the period January 1985 - March 1994) gives average values of 22.64 Ml/d recharge and 31.23 Ml/d abstraction from Michael and Frances. Over this period there has been a gain in storage, therefore there must be another source of water to the system. The difference between recharge and abstraction amounts to 8.59 Ml/d and the estimated gain in storage (assuming a storage coefficient of 0.021) is 2.88 Ml/d. Resulting in a total of 11.47 Ml/d error in the water balance. This can be accounted for by marine inflow to the three coastal ponds.

Chemical analyses (see Section 4.1.6) suggested a range of values of marine inflow of between 25 % and 60 % of the total inflow to the Michael and Frances ponds. At this stage this does not help divide the total marine inflow between the Wellesley, Michael and Frances ponds. There are no chemical data for Wellesley; and the data for Michael and Frances are equivocal regarding relative concentrations. Frances is twice as saline as Michael, but analysis of the sulphate levels gives values of Michael being 59 % seawater in origin whilst Frances is 44 %. This is complicated by the fact that the recharge is not solely divided between marine inflow and recharge from rainfall, recharge will also indirectly come from other ponds. Hence it is necessary to calibrate the values of marine inflow for each pond.

4.2.1 Calibrating GRAM

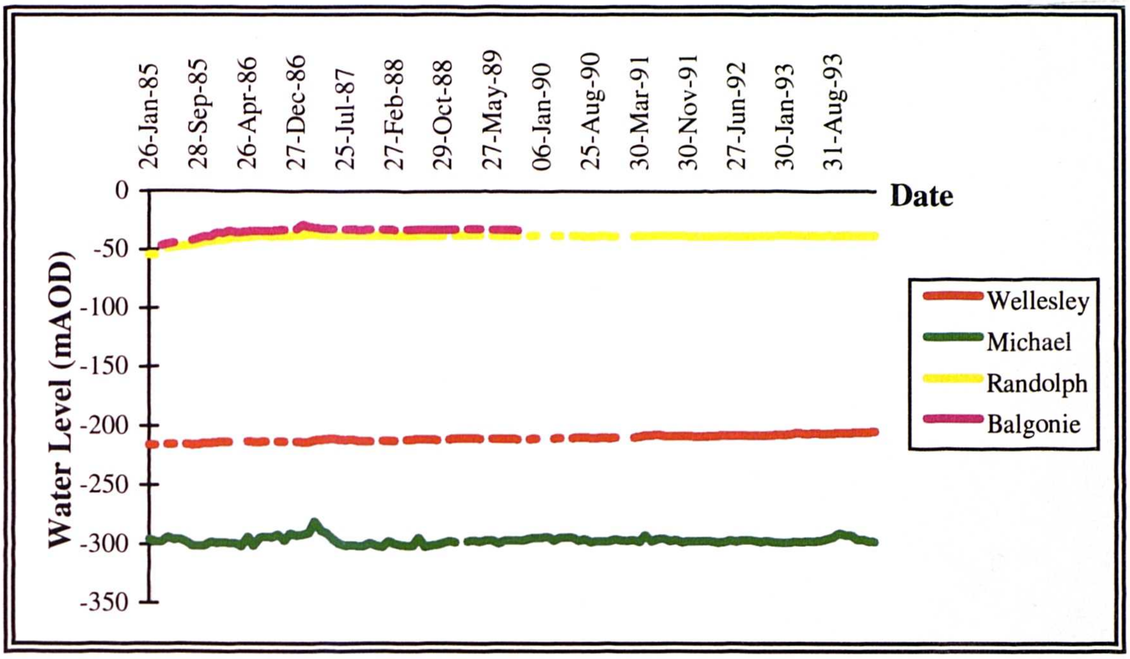
Selection of Time Period for Calibration

British Coal provided water level data sets for Wellesley, Michael and Randolph for the period January 1985 to March 1994 and for Balgonie from January 1985 to November 1989. (Monitoring of water levels ceased after these times.) These data are shown in Figure 4.10. There is no data set available for Frances, apart from a single figure of -223 mAOD, corresponding to a sump elevation. It can be assumed that the water level was kept at approximately this level (see Section 4.1.5).

There is a complete set of rainfall data for the Tiel Path rainfall gauge for the period January 1985 to March 1994, therefore this period was chosen for calibration. Data on the pumping rate at Michael is available. A continuous set is not available for Frances, which was pumped at an approximate rate of 7.86 Ml/d. The pumping rate at Randolph fell from 9.49 Ml/d in June 1981 to 7.86 Ml/d in March 1985 when abstraction ceased. To maintain water levels the abstraction rate at Frances was increased to 9.03 Ml/d, whilst the abstraction rate at Michael had to be increased by approximately 10 Ml/d to an average of 23.50 Ml/d.

During the calibration period the water levels in the coalfield adjust to the cessation of pumping in Randolph.

Figure 4.10: Water level data for the Main Calibration Period



Preliminary Calibration

The main aim of the calibration was to find values for the diameter and roughness coefficient of the pipes and to quantify the marine inflow to Wellesley, Michael and Frances. Calibration of GRAM is an iterative process, since it is impossible to adjust one relationship between ponds without impacting on the relationships with other ponds.

The maximum pipe diameter of 2.3 m resulted in massive flows of water between ponds. This is because pipes are assumed to flow full. Therefore, the diameter of all the pipes had to be reduced by a factor of 10 to get sensible flow volumes.

One of the pipes does not become active during the calibration period. The water level in Frances does not reach the point at which the upper pipe connection to Michael is used. (This is the purpose of the abstraction at Frances.) Therefore for the deterministic runs the parameters of this pipe must be estimated.

From January 1985 to the end of 1987 the connection from Seafield to Frances through the Whin Dooks was open with a flow volume of 0.92 Ml/d. In GRAM this was included as an inflow from another mine / aquifer.

The model was initially run with the marine inflow evenly divided between Michael, Wellesley and Frances. The water level in Frances fell continuously, indicating that a higher proportion of the marine inflow should be allocated to that pond.

Prior to changing the marine inflow values other methods of maintaining the water level in Frances were attempted. Frances gains water from Randolph and loses it to Michael. The pipe from Randolph is at -39.62 mAOD and the pipe to Michael is at -518.16 mAOD. The existence of the latter pipe is questionable and therefore the diameter of this pipe was set to zero to prevent Michael draining Frances. However, the water level in Frances continued to fall.

The water level in Randolph settles at about -37 m, the pipe to Frances is at -39.62 mAOD and will only be activated if is it submerged. Hence the pipe is only used for part of the calibration period. Enlarging the diameter of the pipe is counterproductive, since although it increases the volume of flow it also reduces the amount of time the pipe is activated. Making the pipe very smooth did not sufficiently increase the volume of flow going into Frances. Therefore the volume of marine inflow to Frances was increased to 5.45 Ml/d, leaving approximately 6 Ml/d divided between Michael (3.95 Ml/d) and Wellesley (2.1 Ml/d).

Checking the Marine Inflow Values

To improve confidence in the increased value of marine inflow to Frances the calibration was checked. The model was run for the period January 1983 to January 1985. Rainfall data were available for this period as were approximations of the abstraction rates and water levels. This was not intended to be a recalibration, but rather a re-examination of the water balance.

From January 1983 Randolph was pumped for eight months each year at a rate of 9.49 Ml/d. Since the pumping was only for eight months a year, the average rate of abstraction from Randolph was set at 5.26 Ml/d. The aim of this pumping was to maintain the water levels in Randolph and Balgonie at approximately -54 mAOD and -46 mAOD respectively. Frances was pumped at 7.86 Ml/d to maintain a water level of -

223 mAOD and Michael's pumping rate was 13.1 Ml/d maintaining a water level of -295 mAOD.

The water level data for Wellesley are more limited. In March 1972 the water level at Wellesley was -525.78 mAOD, in December 1976 it was -303.28 mAOD, in January 1985 it was -216.09 mAOD and in July 1994 it was -204.06 mAOD. This rebound curve makes it difficult to estimate the water level in January 1983. It was decided to extrapolate back, using the rate of rebound from January 1985 to July 1994. The estimate obtained is -218.62 mAOD which is probably an overestimate, because the extrapolation was based on a straight line rather than a curve.

During this calibration period a reduced number of the pipes were active. The pipes from Frances to Michael, Balgonie to Michael and Randolph to Frances were not submerged at either end by the water levels in the ponds. Therefore, Frances was isolated from the other ponds (although flow from the Whin Dooks was active) and the marine inflow value could be tested.

The values of marine inflow that had been established during the main calibration, were verified by checking them against the January 1983 - January 1985 data. The water level at Frances rose by less than 4 m over the time period, whilst the water levels at Michael and Wellesley rose by less than half a meter. This indicates that the marine inflow volume to Frances may be slightly too large. However, the marine inflow volumes to Michael and Wellesley seem to give water levels which we would expect. Since the data for both the calibration period and the checking period are so limited for Frances, the value of 5.45 Ml/d marine inflow was considered to be good enough.

Pipe Properties and Marine Inflow which Achieve Final Calibration

The pipe roughness coefficients and diameters were calibrated to give the best fit possible to the observed data. All the pipes between each pair of ponds were assumed to have the same level of roughness, unless the connection is a seepage face. Initially, the calibration had pipes of variable diameters. However, this would complicate assigning a value to the uncalibrated pipe between Michael and Frances. Therefore the diameters of all pipes were changed to 0.12 m (the smallest value in the range) and their roughness changed accordingly. Therefore, the uncalibrated pipe can be given a diameter of 0.12 m and a roughness coefficient which is the mean value of all the pipes. Table 4.8 shows the calibrated values.

Table 4.8: Calibrated Roughness Coefficient Values

Connections	Roughness Coefficient (mm)
Wellesley - Michael	31 (also 20 and 4 for seepage faces)
Randolph - Michael	0.0002
Balgonie - Michael	$3x10^{-5}$
Randolph - Frances	$6x10^{-9}$
Balgonie - Randolph	0.03

The marine inflow values that were produced by the calibration are shown in Table 4.9. The marine inflow per m^2 of seabed is comparable to rates from published data quoted by Bullen Consultants (1994).

Table 4.9: Rates of Marine Inflow to the Coastal Ponds

Pond	Marine inflow rate (m^3/d)	Marine inflow per m^2 seabed per day
Wellesley	2100	2 mm
Michael	3950	5 mm
Frances	5450	8 mm

The marine inflow values seem variable, however, this can be expected. Aston and Whittaker (1985) studied water inflow to undersea longwall mining faces in the north-east coalfield. Variable inflow rates were found in the range of 860 m^3/d to 5180 m^3/d at wet faces At a point where a face intersected a 2 m fault a feeder of 13820 m^3/d was recorded. Factors such as major faults, or the existence of water bearing sandstones in the Coal Measures Strata, increase the local rate of marine inflow.

The offshore workings from Frances are not overlain by the Barren Red Coal Measures, as they are in Michael and Frances, therefore the workings are closer to the sea bed and more susceptible to marine inflow.

Water Balance for the Calibration Period

A daily water balance was produced for GRAM for the period January 1985 to March 1994; the average values were:

Marine inflow and flow from Seafield via the Whin Dooks	=	11.8 Ml/d
Recharge	=	22.6 Ml/d
Abstraction from Michael and Frances	=	31.2 Ml/d
Input - Output	=	3.2 Ml/d
Gain in Storage over whole area	=	2.9 Ml/d

The difference between the change in storage and input - output is 0.3 Ml/d. This is lost from the system by numerical round-off errors. It amounts to 1 % of the input.

The inflows to Frances, Michael and Wellesley were calculated for the different sources during the main calibration period. Of the total flow to Frances: 55.8 % came from marine inflow, 27.4 % came from recharge, 13.7 % came from Randolph and 3.1 % came from Seafield via the Whin Dooks. Of the total inflow to Wellesley: 19.8 % came from marine inflow and 80.2 % came from recharge. Of the total inflow to Michael: 17.9 % came from marine inflow, 22.7 % came from recharge and 59.4 % came from Randolph, Balgonie and Wellesley. Of this 69.8 % is from Wellesley of which 19.8 % is seawater in origin and therefore a total of 30.9 % of Michael's water is seawater in origin.

‘Goodness of Fit’ of Final Calibration

GRAM can fit the pond water levels to the general trends in the recorded data, but does not recreate the peaks shown in Balgonie and Michael. There is a peak in the water level in Balgonie on 3 January 1987 which is mirrored by a smaller peak in Randolph. It was hypothised that the pipe between Balgonie and Michael had been blocked, and the blockage failed at this time. This was introduced to the FORTRAN code; however, a better fit was not produced. Another possibility is that the peaks occur as the water levels rise into low storage coefficient areas of unworked coal measures, where the water level reacts faster to changes in recharge.

The water levels in Frances show a slight increase through the calibration period (as they did in the checking period). However, the water levels in Michael and Wellesley are consistent. Since more complete data sets are available for these ponds than for Frances, the calibration has focused on getting the water levels in Michael and Wellesley to a good calibration, whilst Frances is approximately correct.

The absolute residual mean and the residual mean of the difference between the recorded water levels and modelled water levels are shown in Table 4.10. The high values for Michael and Balgonie indicate the problems GRAM has fitting to the peaks that the water level hydrographs exhibit. The calibration is shown in Figure 4.11. The scale means that some detail is missed, therefore Figures 4.12 and 4.13 show the inland and coastal ponds respectively.

Table 4.10: Calibration Statistics

Pond	Residual Mean	Absolute Residual Mean
Wellesley	-0.200	0.709
Michael	-4.202	4.779
Frances	-	-
Randolph	-0.243	1.007
Balgonie	1.325	1.497

Figure 4.11: Fit of Synthetic Data to the Real Hydrograph for January 1985 to March 1994

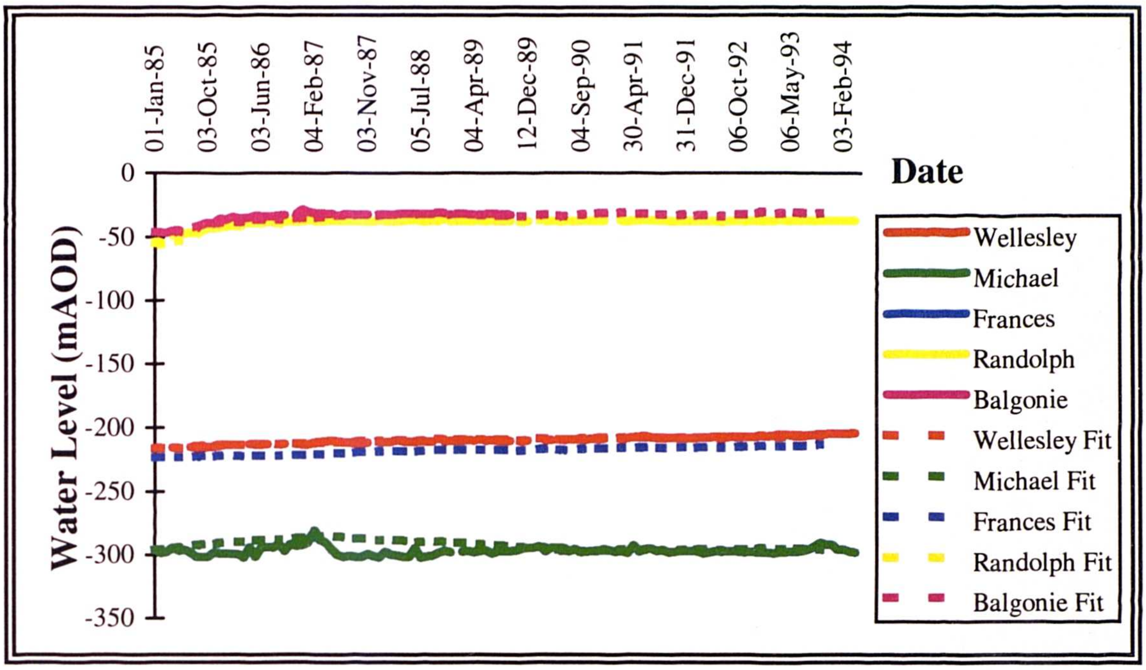


Figure 4.12: Fit of Synthetic Data to the Real Hydrograph for Randolph and Balgonie

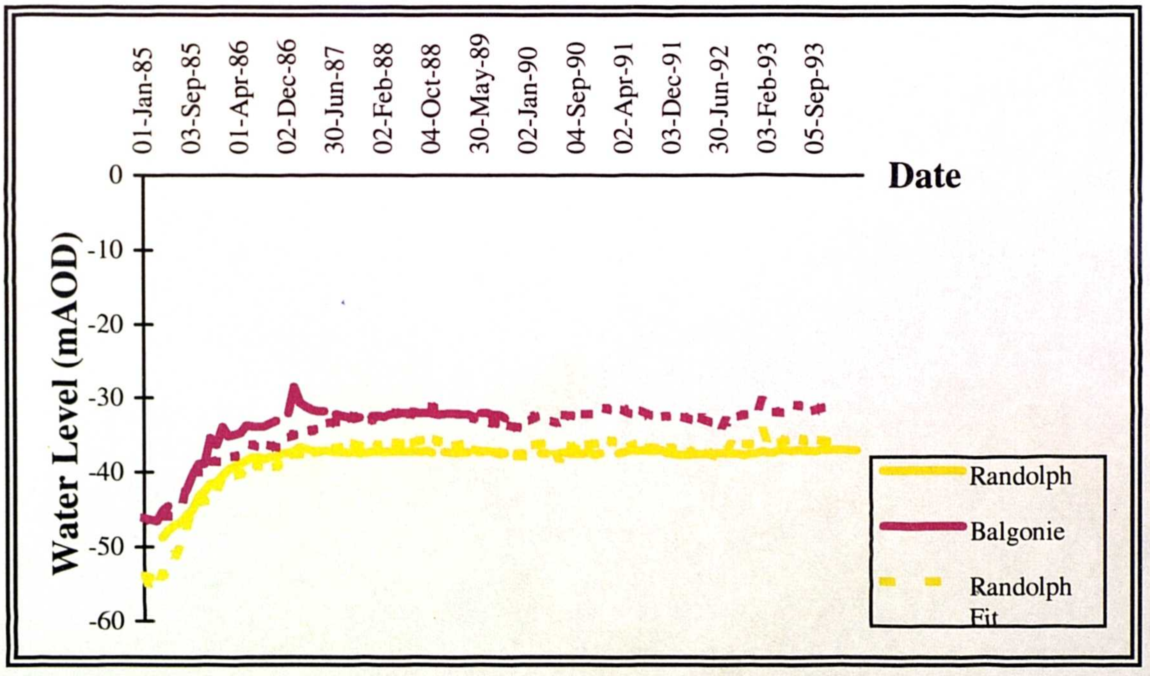
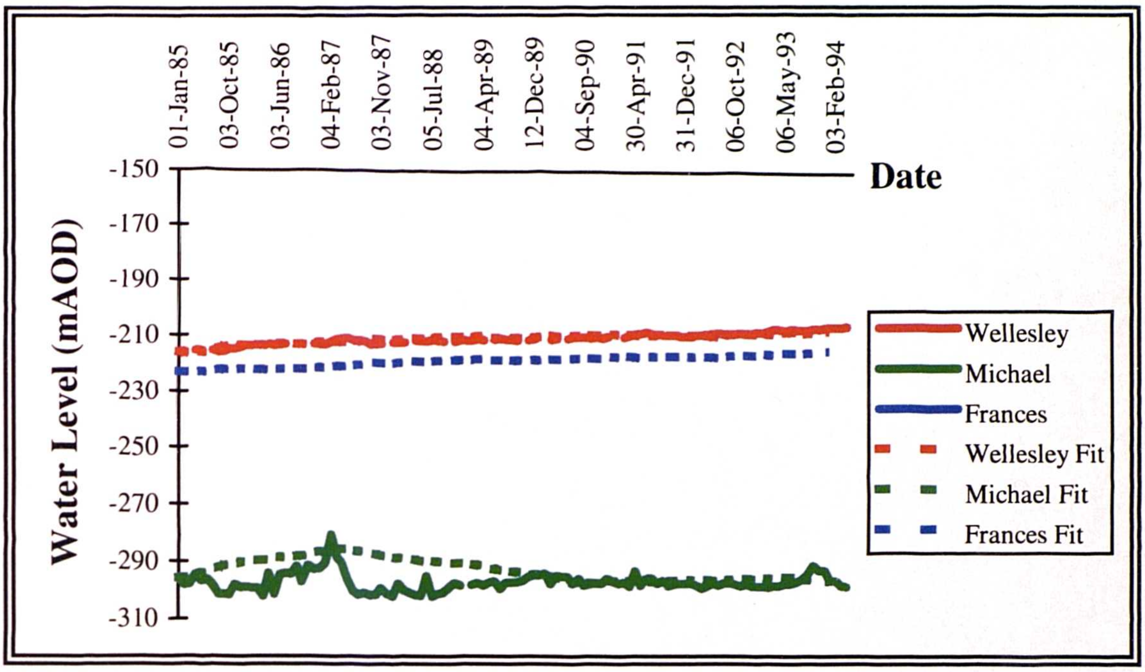


Figure 4.13: Fit of Synthetic Data to the Real Hydrograph for Wellesley, Michael and Frances



4.2.1 Deterministic Predictions

To run a deterministic simulation the roughness coefficient for the pipe at -213.36 mAOD between Frances and Michael must have a value. There is no calibrated value for this pipe, therefore the best option is to set it as the mean (11.633 mm) of the roughness coefficients assigned to the other pipes. Three scenarios were used for modelling:

1. The coastal outflow points are not operational. (Thereby maximising discharge to inland waters.)
2. The coastal outflow points are maximised. (Thereby minimising discharge to inland waters.)
3. An intermediate case. (The coastal outflows are operational, but not maximised.) This scenario is thought to be the most likely.

Some degree of calibration of the discharge pipes was necessary to achieve these scenarios. All the pipes are assumed to be 20 m long and have a roughness coefficient of 30 mm. The diameters of the pipes were calibrated for the different scenarios, so that the water levels in the ponds do not exceed the ground surface. The values applied are shown in Table 4.11.

Table 4.11: Pipe Diameters used in Discharges to the Surface

Pond	Type of discharge	Intermediate Scenario (m)	Maximum Flow to the Sea Scenario (m)	No Flow to the Sea Scenario (m)
Wellesley	Discharge to land	0.08	0.08	0.08
	Discharge to the sea		0.20	0
Michael	Discharge to land	0.08	0.08	0.08
	Discharge to the sea		0.14	0
Frances	Discharge to land	0.08	0.08	0.08
	Discharge to the sea		0.12	0
Randolph	Discharge to land	0.08	0.08	0.08
Balgonie	Discharge to land	0.08	0.08	0.08

Detailed data of the comparative likelihood of different discharges occurring within the same pond is not available. This is in part addressed by the three different scenarios. The identical pipe properties mean that discharges at the same height from the same pond automatically produce equal discharge volumes. In reality the discharge pipes will have different properties, resulting in different volumes of discharge. Therefore the total discharge from each pond is a more useful discharge volume than data for individual discharges.

Figure 4.14 shows the rebound curves for the intermediate scenario. The results of all three scenarios are shown in Tables 4.12 and 4.13. A more detailed list of discharges is available in Appendix 2.

Figure 4.14: Rebound Curves for the Intermediate Scenario

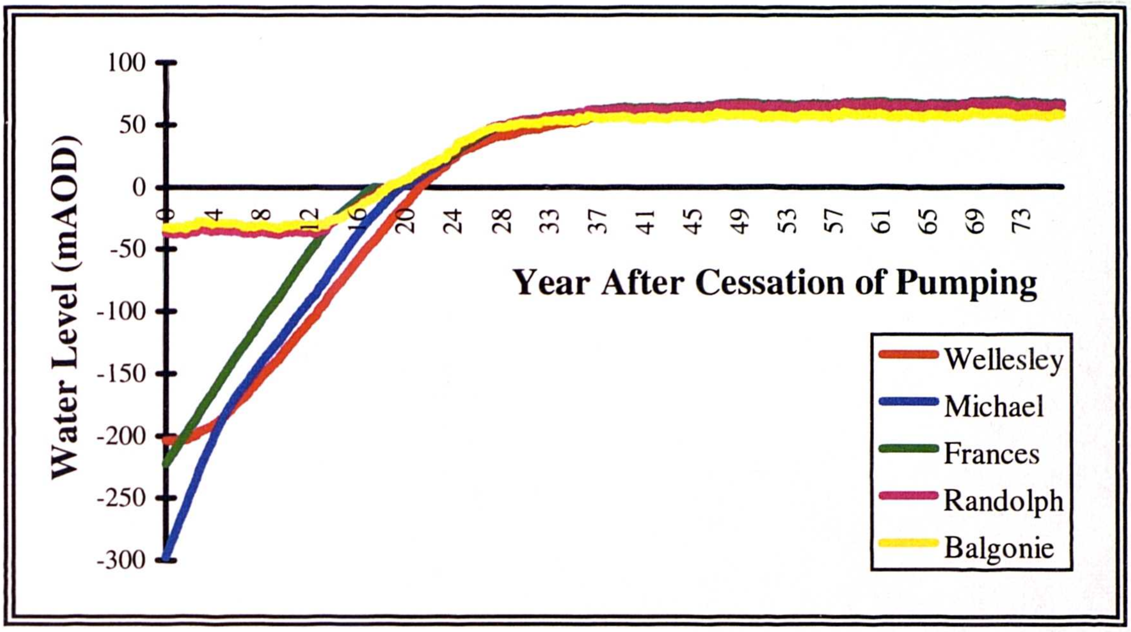


Table 4.12: Deterministic Analysis of Volume of Flow

Pond	Volume of Flow (Ml/d)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	8.932	9.755	10.032
Michael	6.677	7.334	1.033
Frances	5.321	5.217	1.081
Randolph	0	0	1.085
Balgonie	0.939	0	7.350
Total	21.869	22.306	21.347

Table 4.13: Deterministic Analysis of Time of First Surface Discharge

Pond	Time of First Discharge (years)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	22.32	22.33	24.10
Michael	21.55	21.55	27.59
Frances	20.26	20.26	27.30
Randolph	-	-	27.78
Balgonie	30.02	-	26.04

4.2.5 Monte Carlo Simulations

Three major elements of doubt are included in the deterministic model. These are the storage coefficient, the percentage run-off (and therefore indirectly the recharge rate) and the dimensions of the pipe connecting Michael to Frances in the Dysart Main Seam. These three elements were varied using Monte Carlo simulation.

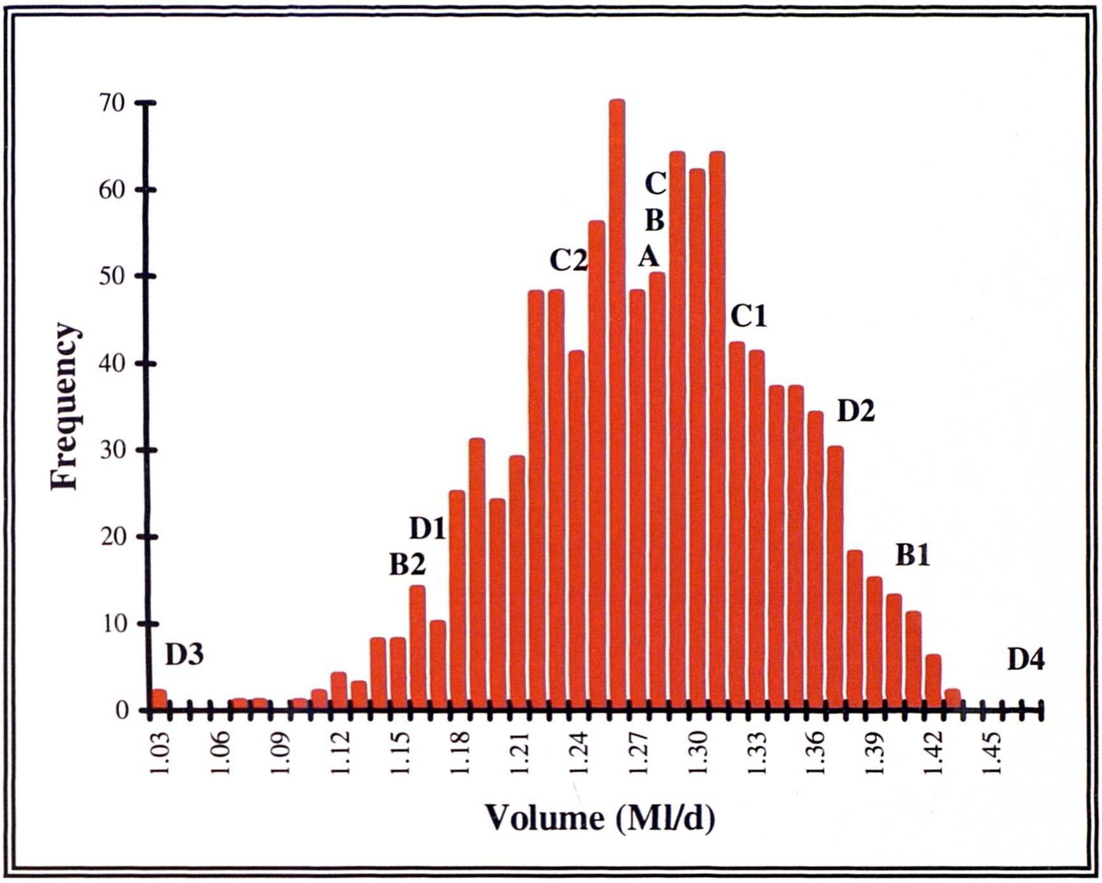
The storage coefficient was estimated as a figure of 0.021, with an error in void estimation of 30 %. This 30 % margin of error was assumed to constitute two standard deviations away from the mean. Therefore one standard deviation is 3.15×10^{-3}. The percentage run-off data set has a mean of 64.67 % and a standard deviation of 5.59 %. These values were obtained by taking the distribution of the 11 values of percentage run-off calculated for the period 1983 - 1993, which are shown in Table 4.4. The pipe roughness data set has a mean of 11.633 mm (as used in the deterministic predictions) and a standard deviation of 16.038 mm (based on the distribution of the roughness of the calibrated pipes).

These means and standard deviations were used to generate data sets which are essentially probability distributions. Each data set was produced by Minitab from the mean and standard deviation. However, some of the distributions (in particular the values for pipe roughness) had elements that strayed into negative numbers. These data had to be weeded out. This increased the mean of the distribution as a whole, but maintained its shape above the cut-off point. The actual mean and standard deviation of the truncated data set produced for the pipe roughness had a mean of 17.5 and a standard deviation of 12.0.

Each scenario was run a thousand times with values taken from the probability distributions. A sample of the resultant probability distributions for the intermediate scenario are shown in Figures 4.15 and 4.16. The statistics describing the results of the stochastic modelling are shown in Tables 4.14 - 4.17 and in more detail in Appendix 2. Not surprisingly the means and median values are largely similar to the deterministic results.

When a discharge occurs less than 1000 / 1000 times the statistics are given in two forms. Firstly for the total 1000 runs assuming flow of zero when no discharge occurs, (this data shows a close correlation with the deterministic results). Secondly, for only those discharges that did occur. Full details are shown in Appendix 2.

Figure 4.15: Probability Distribution of Volume of Discharge from Wellesley Shafts



Key to Figure 4.13 and 4.14

A	Deterministic Value
B	Mean Value
B1	Mean Plus Two Standard Deviations
B2	Mean Minus Two Standard Deviations
C	Median Value
C1	Upper Quartile
C2	Lower Quartile
D1	Scenario 1
D2	Scenario 2
D3	Scenario 3
D4	Scenario 4

Figure 4.16: Probability Distribution of Time of Discharge from Wellesley Shafts

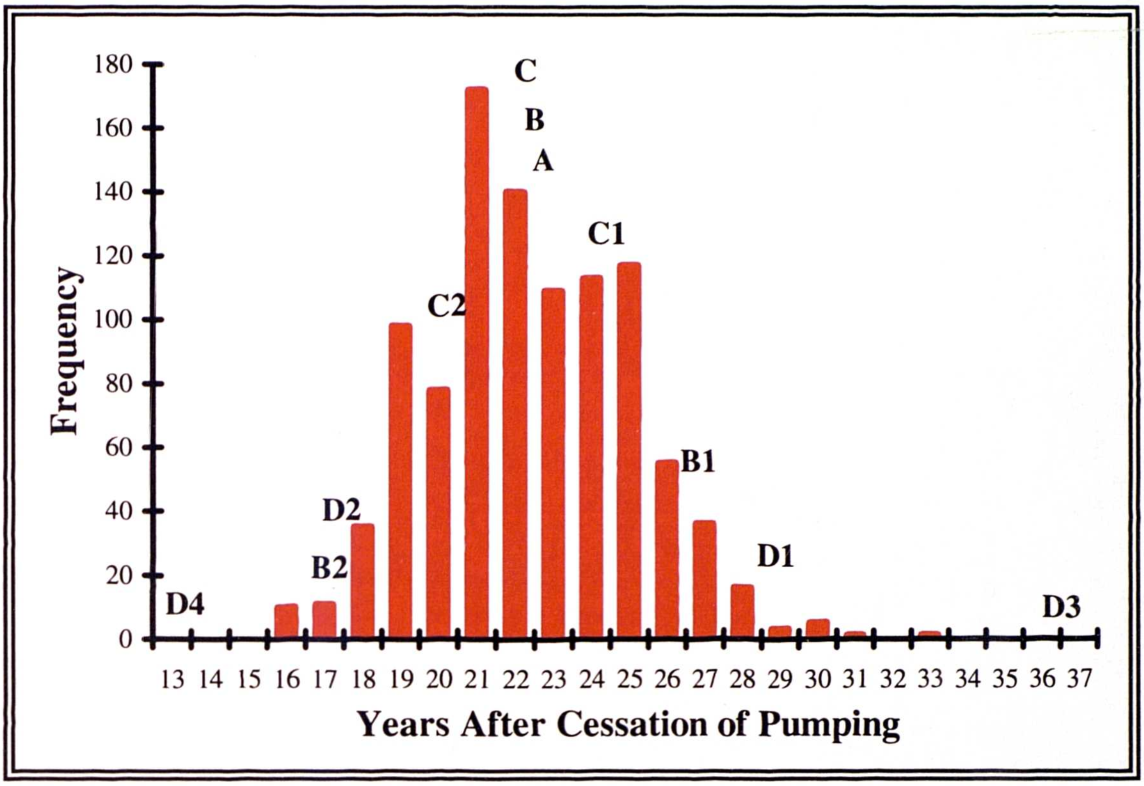


Table 4.14: Stochastic Analysis of Volume of Flow

Pond	Mean Volume of Flow (Ml/d)					
	Intermediate Scenario		Maximum Flow to the Sea Scenario		No Flow to the Sea Scenario	
	Of No.	Of 1000 Runs	Of No.	Of 1000 Runs	Of No.	Of 1000 Runs
Wellesley	8.946		9.890	9.800	10.090	
Michael	6.800	6.736	7.509	7.484	1.054	
Frances	5.387	5.337	5.274		1.104	
Randolph	0.003	0.0002	-	-	1.889	
Balgonie	1.336	1.125	0.027	0.001	7.465	
Total	22.472	22.144	22.700	22.560	21.602	

Table 4.15: Stochastic Analysis of Time of First Surface Discharge

Pond	Mean Time of First Discharge (years)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	22.16	22.17	23.97
Michael	21.26	21.28	27.44
Frances	19.67	19.67	26.99
Randolph	39.87	-	27.51
Balgonie	29.57	34.47	25.70

Table 4.16: Stochastic Analysis of Volume of Flow

<table>
<tr><th rowspan="3">Pond</th><th colspan="6">Median Volume Of Flow (Ml/d)</th></tr>
<tr><th colspan="2">Intermediate Scenario</th><th colspan="2">Maximum Flow to the Sea Scenario</th><th colspan="2">No Flow to the Sea Scenario</th></tr>
<tr><th>Of No.</th><th>Of 1000 Runs</th><th>Of No.</th><th>Of 1000 Runs</th><th>Of No.</th><th>Of 1000 Runs</th></tr>
<tr><td>Wellesley</td><td colspan="2">8.978</td><td>9.942</td><td>9.847</td><td colspan="2">10.127</td></tr>
<tr><td>Michael</td><td>6.054</td><td>6.732</td><td>7.485</td><td>7.466</td><td colspan="2">1.053</td></tr>
<tr><td>Frances</td><td>5.386</td><td>5.350</td><td colspan="2">5.271</td><td colspan="2">1.101</td></tr>
<tr><td>Randolph</td><td>0.001</td><td>0</td><td>-</td><td>-</td><td colspan="2">1.880</td></tr>
<tr><td>Balgonie</td><td>1.335</td><td>1.132</td><td>0.020</td><td>-</td><td colspan="2">7.466</td></tr>
<tr><td>Total</td><td>22.505</td><td>22.192</td><td>22.718</td><td>22.584</td><td colspan="2">21.627</td></tr>
</table>

Table 4.17: Stochastic Analysis of Time of First Surface Discharge

Pond	Median Time of First Discharge (years)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	21.97	21.98	23.86
Michael	21.07	21.08	27.09
Frances	19.55	19.55	26.68
Randolph	35.74	-	27.18
Balgonie	29.16	35.73	25.31

4.2.6 Analysis of Simulation Results

The stochastic modelling produced values which are very similar to the results of the deterministic modelling. The standard deviation and quartile range for each discharge gives a measure of the spread of the stochastic results and hence the level of uncertainty associated with each estimate.

Figures 4.15 and 4.16 show distributions representing the time and volume of flow from the Wellesley shafts. The statistics that have been calculated for this discharge are also shown. The measure of two standard deviations either side of the mean, clearly encompasses nearly all the discharges, (the standard deviation of the volume of discharge being approximately 5 % of the mean, and the standard deviation of time of discharge being just over 10 % of the mean).

The intermediate scenario (which is the scenario considered most likely to occur) predicts discharges from the coastal ponds in approximately 20 years, whilst Balgonie would discharge in less than 30 years and Randolph does not discharge at all, when GRAM is run in deterministic mode. However, when it is run in stochastic mode at the lowest decant point in the pond (at the Ore Bridge and Railway Viaduct) discharge occurred on 103 of the 1000 runs after an average of just over 40 years. There were also eight runs when a second discharge occurred to the River Ore, north-east of Balbeggie

Cottage after an average of just under 40 years. (This apparent paradox, is because the eight times when both flows occurred are the quickest eight of the 103 discharges at the Ore Bridge and Railway Viaduct.)

The deterministic predictions of flow volumes are 8.93 Ml/d from Wellesley, 6.68 Ml/d from Michael, 5.32 Ml/d from Frances, 0.94 Ml/d from Balgonie and no flow from Randolph. The quality of the pumped discharges from Randolph has been very poor, hence the fact that discharges are unlikely from that pond is good news. The discharges from Randolph are small because the water is flowing to Michael (and to a lesser extent Frances) from where it discharges to the surface. However, most of the discharges from Michael and Frances are at the coast and flow into the sea.

4.2.7 Sensitivity Analysis Scenarios

As a form of sensitivity analysis, the extreme cases scenarios were examined. When a large value for recharge (and therefore a low value for percentage direct run-off) is combined with a low storage coefficient the rise in water levels will be most rapid. Conversely when a low value for recharge (and therefore a large value for percentage direct run-off) is combined with a high storage coefficient then it will be slowest. Therefore, several intermediate deterministic scenarios were run with the following combinations:

1. Percentage run-off and storage coefficient 1 standard deviation above the mean.
2. Percentage run-off and storage coefficient 1 standard deviation below the mean.
3. Percentage run-off and storage coefficient 2 standard deviations above the mean.
4. Percentage run-off and storage coefficient 2 standard deviations below the mean.

The probability of both factors exceeding 1 standard deviation away from the mean in opposite directions is 2.52 %. The probability of both factors exceeding 2 standard deviations away from the mean in opposite directions is 0.052 %. Therefore the figures in Tables 4.18 and 4.19 and Appendix 3 can be used as a measure of confidence in the means, medians and probability distributions.

Table 4.18: Deterministic Analysis using Scenarios 1 and 2

Pond	Volume of Flow (Ml/d)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Wellesley	7.582	10.076	5.909	11.046
Michael	5.901	7.315	4.959	8.113
Frances	4.607	5.944	3.755	6.504
Randolph	-	0.005	-	0.153
Balgonie	0.066	2.254	-	3.511
Total	18.156	25.593	14.623	29.328

Table 4.19: Deterministic Analysis using Scenarios 3 and 4

Pond	Time of First Discharge (years)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Wellesley	28.46	17.08	36.30	12.96
Michael	27.64	16.23	36.04	12.41
Frances	26.08	14.45	34.90	10.95
Randolph	-	35.73	-	21.05
Balgonie	46.74	21.38	-	14.94

The sensitivity analysis values are marked onto Figures 4.15 and 4.16. The data for both the volume and timing of discharges shows that combining the extremes of storage coefficient and recharge gives a range of values which goes beyond the extreme values of the distribution. Scenario 3 is so extreme that there are no discharges from the inland ponds or the high discharge points of the coastal ponds.

4.2.8 Application of the Colebrook-White Equation

GRAM was run with the Colebrook-White equation using the values of parameters from the previous model calibrations. However this resulted in a loss of calibration. The results of the two equations are only similar in the rough-turbulent zone, see Section 3.3.2. Therefore for the pipes in which the volume of flow had changed, the pipe diameters and roughnesses that had been established before all the pipes were made the same size were reverted to. This means that the parameters used in the equation no longer have physical meaning. Details are shown in Table 4.20.

Table 4.20: Pipe Diameters and Roughness Coefficient Values used in the Colebrook-White Runs.

Connections	Pipe Diameter (m)	Roughness Coefficient (mm)
Wellesley - Michael	0.12 (also 0.5 and 0.1 for seepage faces)	31 (also 20 and 4 for seepage faces)
Randolph - Michael	0.26	120
Balgonie - Michael	0.26	120
Frances - Michael	0.12 (0 for lower pipe)	11.633
Randolph - Frances	0.32	150
Balgonie - Randolph	0.12	0.03

The calibration statistics show that the fit to the real data is overall slightly better, than with the Prandtl-Nikuradse equation. See Table 4.21.

Table 4.21: Calibration Statistics using the Colebrook-White Equation

Pond	Residual Mean	Absolute Residual Mean
Wellesley	-0.172	0.714
Michael	-4.017	4.658
Frances	-	-
Randolph	0.046	0.923
Balgonie	0.466	1.471

The results of both the deterministic and stochastic runs are very similar to those produced by the Prandtl-Nikuradse equation. The volumes of flow are generally slightly larger in the Colebrook-White runs and the times of discharges, slightly slower from Wellesley and Michael and slightly faster from Frances, Randolph and Balgonie. The data produced by GRAM with the Colebrook-White equation are shown in Tables 4.22 - 4.25 (for a more detailed set see Appendix 4).

Table 4.22: Deterministic Analysis of Volume of Flow using the Colebrook-White Equation

Pond	Volume of Flow (Ml/d)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	8.978	9.796	10.264
Michael	6.719	7.505	1.108
Frances	5.806	5.864	1.211
Randolph	-	-	2.034
Balgonie	1.211	-	7.473
Total	22.714	23.166	22.090

Table 4.23: Deterministic Analysis of Time of First Surface Discharge using the Colebrook-White Equation

Pond	Time of First Discharge (years)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	22.98	22.98	24.59
Michael	21.85	21.86	27.57
Frances	19.29	19.29	26.66
Randolph	-	-	27.31
Balgonie	28.24	-	25.69

Table 4.24: Stochastic Analysis of Volume of Flow using the Colebrook-White Equation

Pond	Volume of Flow (Ml/d)			
	Mean of Intermediate Scenario		Median of Intermediate Scenario	
	Of No.	Of 1000 Runs	Of No.	Of 1000 Runs
Wellesley	8.993		9.03	
Michael	6.858	6.778	6.871	6.79
Frances	5.150	5.078	5.162	5.056
Randolph	0.0026	2.02e-4	0.0016	0
Balgonie	1.471	1.356	1.460	1.191
Total	22.475	22.205	22.525	22.067

Table 4.25: Stochastic Analysis of Time to First Surface Discharge using the Colebrook-White Equation

Pond	Time of First Discharge (years)	
	Mean of Intermediate Scenario	Median of Intermediate Scenario
Wellesley	22.85	22.78
Michael	22.07	21.95
Frances	17.60	17.87
Randolph	39.42	35.76
Balgonie	29.16	28.23

The main criticism of the Colebrook-White component of GRAM is the length of time it takes to run. It takes approximately 30 times as long as the Prandtl and Nikuradse equation, which makes it inappropriate for use on a PC. Even on a mainframe the time that the simulations take to run far outweighs the advantages of using the Colebrook-White equation. Therefore only the intermediate scenario was run stochastically.

4.2.9 Application of the Varying Storage Component

Data for the storage coefficient of each worked seam was calculated from the volume of extraction from each seam, the average seam height and the area of each pond. The seams actually have a relatively high gradient, however, it is assumed that the seams are horizontal at the height at which they intersect the main shaft of each colliery. The storage coefficient of the remaining strata was calibrated against the data for the period January 1985 to March 1994.

This produced a value for the storage coefficient for the strata between the seams of 0.02. This is only marginally smaller than the previous value for the entire pond. The fit is only insignificantly better than the one produced without the vertically varying storage coefficient. Table 4.26 shows the calibration statistics. The absolute residual mean is only better than previous runs for Randolph and Balgonie. Figures 4.17 - 4.19 show the fit of synthetic data to recorded.

Table 4.26: Calibration Statistics using a Varying Storage Coefficient

Pond	Residual Mean	Absolute Residual Mean
Wellesley	-0.474	0.772
Michael	-4.300	4.857
Frances	-	-
Randolph	-0.107	0.832
Balgonie	1.193	1.398

Figure 4.17: Fit of Synthetic Data to the Real Hydrograph for January 1985 to March 1994 with Varying Storage Coefficient

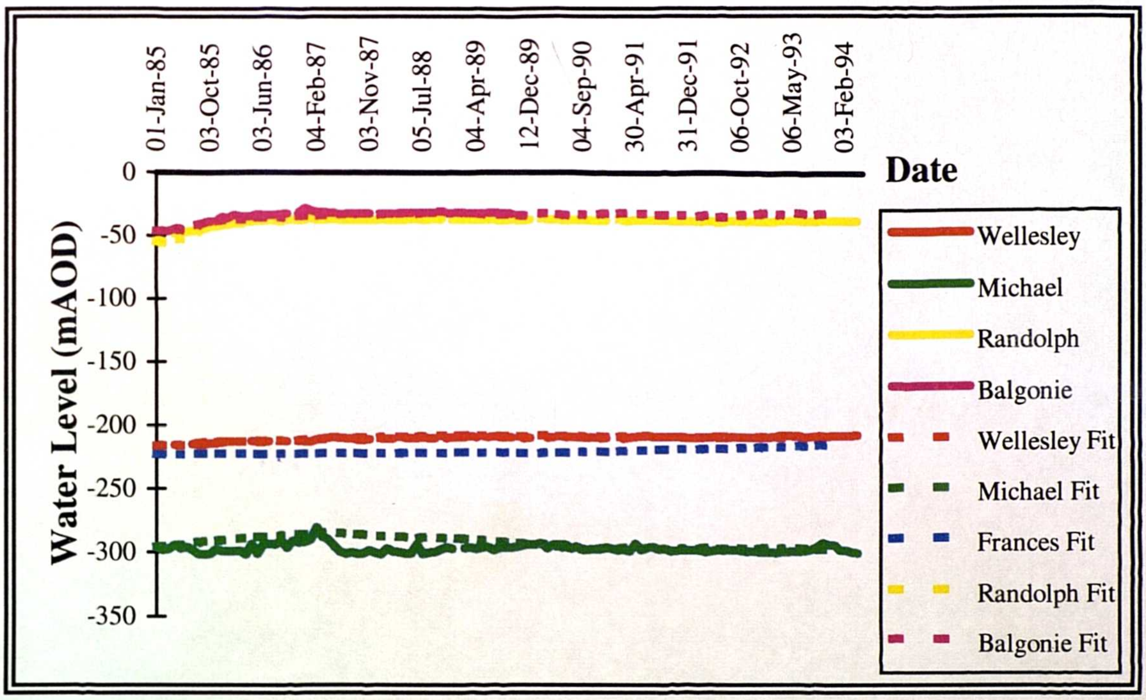


Figure 4.18: Fit of Synthetic Data to the Real Hydrograph for Randolph and Balgonie with Varying Storage Coefficient

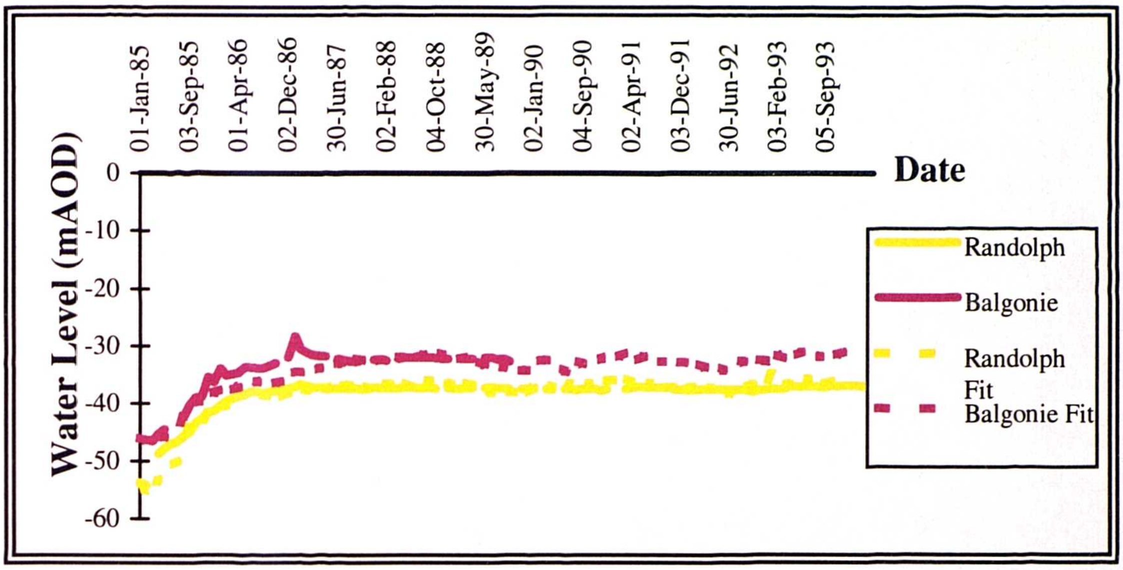
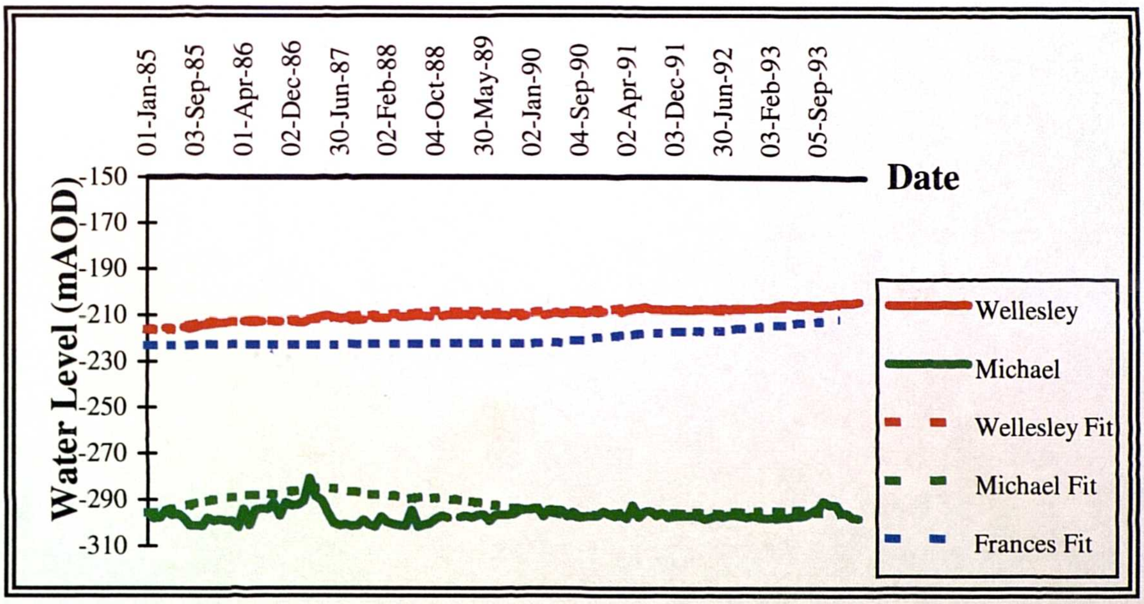


Figure 4.19: Fit of Synthetic Data to the Real Hydrograph for Wellesley, Michael and Frances with Varying Storage Coefficient



The peaks of water level in Balgonie and Michael were not recreated. The peaks could be associated with strata of low storage coefficient as described in Section 4.2.3. If so, then GRAM is not able to recreate this.

The water level in Michael although peaky remains mainly in the range -300 m to -290 m (although there is one peak on 1 March 1987 when the water level reaches -280 m). In the Michael pond the pavements of the Wood, Wemyss Parrot and Bush seams are at -311.79 m, -294.44 m and -245.09 m respectively. The water level is therefore passing through the Wemyss Parrot seam as it varies between -300 m and -290 m.

The Wemyss Parrot was not worked from the Michael shaft, which partially explains the low storage coefficient type behaviour. However, the Victoria Pit which lies to the south-west of Michael did work a small area of the seam; (an area of 0.4 km^2 was mined, extracting 324000 m^3 of coal). The Victoria Pit workings fall within the Michael pond; workings in seams above and below the Wemyss Parrot are connected to the Michael workings. It is possible that there is an overspill mechanism from the Victoria Pit - Wemyss Parrot workings to the main workings within the Michael pond and it is this that is causing the peaks in water level.

Figure 4.20 shows the predicted water levels after pumping is ceased. These rebound curves recreate the stepped nature of the curves for Ladysmith and Tindale shafts as described by Lancaster (1995). The results of both deterministic and stochastic simulations are shown in Tables 4.27 - 4.30. A detailed set of results is shown in Appendix 5. The Monte Carlo simulations show smaller standard deviations than the original model, for the time of discharge, this can partially be explained by the removal of the stochastic storage coefficient. Compared to the results of the original model the values tend to show a smaller discharge and a time to discharge which is longer by several years.

Figure 4.20: Rebound Curves for the Intermediate Scenario

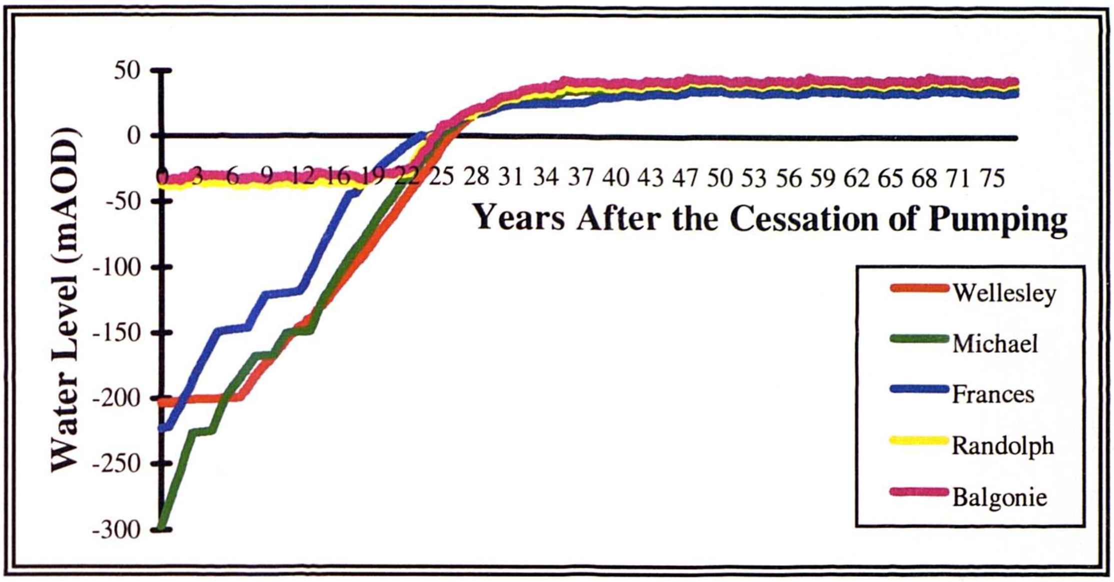


Table 4.27: Deterministic Analysis of Volume of Flow using a Varying Storage Coefficient

Pond	Volume of Flow (Ml/d)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	8.886	9.716	9.949
Michael	6.649	7.260	1.033
Frances	5.193	5.201	1.092
Randolph	0	-	1.867
Balgonie	0.921	-	7.365
Total	21.65	22.18	21.31

Table 4.28: Deterministic Analysis of Time of First Surface Discharge using a Varying Storage Coefficient

Pond	Time of First Discharge (years)		
	Intermediate Scenario	Maximum Flow to the Sea Scenario	No Flow to the Sea Scenario
Wellesley	26.25	26.25	28.04
Michael	25.99	25.99	33.03
Frances	24.94	24.94	33.68
Randolph	-	-	34.01
Balgonie	34.94	-	31.69

Table 4.29: Stochastic Analysis of Volume of Flow using a Varying Storage Coefficient

Pond	Volume of Flow (Ml/d)			
	Mean of Intermediate Scenario		Median of Intermediate Scenario	
	Of No.	Of 1000 Runs	Of No.	Of 1000 Runs
Wellesley	8.889		8.922	
Michael	6.787	6.715	6.769	6.696
Frances	5.297	5.247	5.300	5.266
Randolph	0.0024	2e-4	0.0009	0
Balgonie	1.324	1.115	1.286	1.045
Total	22.299	21.996		

Table 4.30: Stochastic Analysis of Time to First Surface Discharge using a Varying Storage Coefficient

Pond	Time of First Discharge (years)	
	Mean of Intermediate Scenario	Median of Intermediate Scenario
Wellesley	26.14	26.01
Michael	25.79	25.62
Frances	24.91	24.74
Randolph	46.75	46.74
Balgonie	35.13	34.89

4.2.10 Limitations of the GRAM Dysart-Leven Model

Accuracy of Individual Discharge Volumes

The data regarding discharges are limited. In the intermediate scenario all the discharge points have been given the same pipe properties. There are no data to support any other approach. Therefore the relative volumes of discharge are dependant only on the relative height of the discharge. It is entirely possible that one discharge may be blocked, or another pathway may transmit large quantities of water. Therefore the predicted total discharge from each pond is a more useful piece of information than the specific discharge volumes predicted to arise from each pipe.

Estimation of Marine Inflow

A major element of doubt in this model is the estimate of marine inflow. It has been calibrated to fit the model; however, it is probable that there is not a unique solution to the calibration. For example, it is possible that the marine inflow to Wellesley is greater and the roughness coefficient for the pipes to Michael are smoother, thereby giving the same net recharge to both ponds. If a way of measuring the marine inflow could be found it would greatly enhance the accuracy of the model, particularly for the Frances pond, where marine inflow forms such a large component of the recharge.

The slight rise in water level in Frances during both the calibration period and the checking period indicates that there is probably too much marine inflow to that pond, if the water level is assumed to stay at approximately -223 mAOD. However, the additional inflow to Frances is necessary to maintain the water balance. The lack of data for this pond means that it is hard to quantify how far water levels in Frances might vary from -223 mAOD and how far pumping rates might vary from 9.03 Ml/d to maintain this water level.

Water Level Data from the Forth River Purification Board

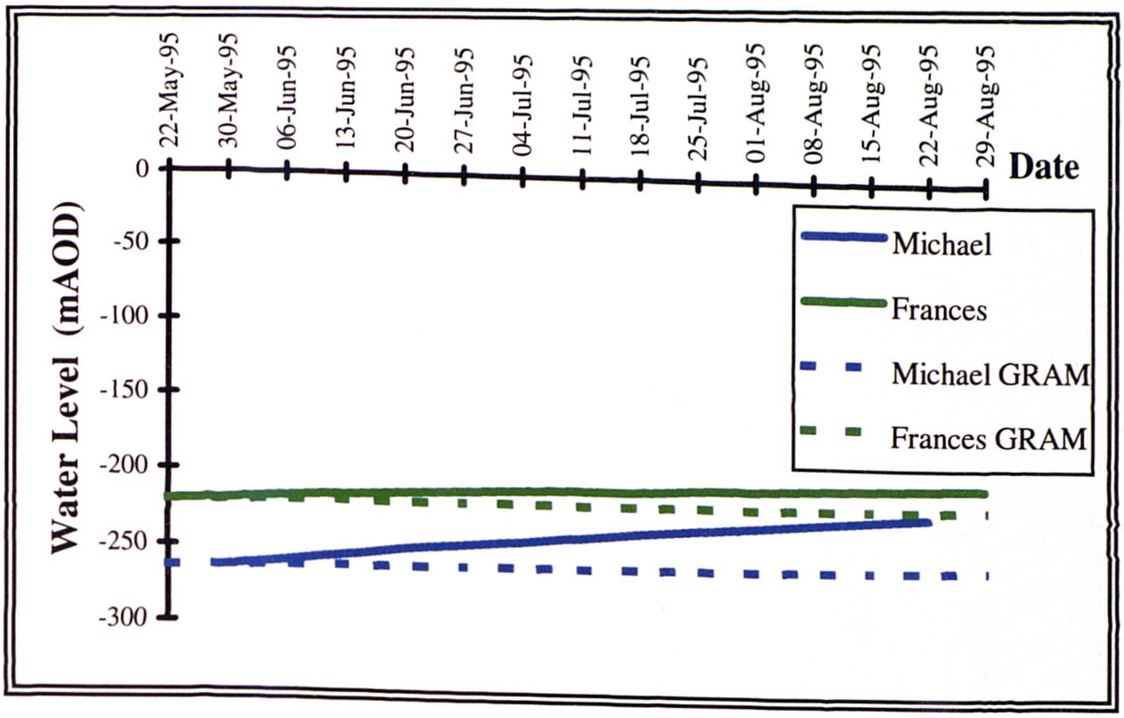
The pumps were turned off at Michael and Frances in May 1995. The rise in water levels is recorded in Table 4.31 and shown graphically in Figure 4.21. The rise is far faster than previously predicted by GRAM.

Table 4.31 Recorded Data for Frances and Michael Shafts

Date	Water Level in Michael	Water Level in Frances
22/5/95		-220.67
30/5/95	-263.55	-219.73
6/6/95	-259.89	-217.60
13/6/95	-255.66	-215.60
20/6/95	-250.76	-213.64
27/6/95	-247.27	-212.01
4/7/95	-244.23	-210.24
11/7/95	-240.18	-208.93
18/7/95	-236.22	-208.50
25/7/95	-233.28	-206.43
1/8/95	-230.27	-205.29
8/8/95	-227.49	-204.36
15/8/95	-224.44	-203.40
22/8/95	-221.75	-202.52
29/8/95		-201.87

The flat hydraulic gradient assumed over the ponds, creates a very flat rebound curve (see Section 3.3). Initially the rebound is likely to be far faster than predicted by GRAM as the cone of depression caused by the abstraction fills. This will be reflected in water level estimates which are lower than those recorded. However, as stated in Section 3.3; the estimate of the time taken for rebound to reach the surface probably remains valid as the most significant factors controlling the system are recharge and the total storage volume. In other words, the initial rate of rise observed in the two shafts is unlikely to be maintained throughout the period of rebound.

Figure 4.21: Observed and Predicted Rebound of Water Levels in Michael and Frances Shafts



The initial water level predictions are worse for Michael than for Frances, this is likely to be caused by the abstraction rate at Michael which was 23.5 Ml/d compared to 9.03 Ml/d at Frances. The cone of depression caused by pumping in Michael is therefore likely to be far greater than the one in Frances. Hence the local hydraulic gradients will be greater and the water level will rise at a faster rate.

4.3 Applying Standard Groundwater Modelling Techniques to the Dysart-Leven Coalfield

4.3.1 Introduction

In order to assess the advantages / disadvantages of GRAM compared with standard modelling approaches, the results of the GRAM model of the Dysart-Leven Coalfield will be compared with those produced using a standard groundwater modelling package, MODFLOW. To obtain MODFLOW output a completely new conceptual model of the coalfield will be necessary. It must be assumed that the strata in the coalfield can be represented by an equivalent porous medium (EPM), through which flow is laminar.

The intention is to develop a series of models. Firstly, a steady state model of the area with the abstraction wells in operation. Secondly, a steady state model as if rebound had already occurred. Finally, a transient model of the rebound occurring.

MODFLOW is the world's most widely used quasi-three-dimensional, groundwater modelling program (McDonald and Harbaugh, 1988; Anderson and Woessner, 1992). It uses block-centred finite difference equations in a backward difference form. The code is modular; a discussion of the modules that have been used in this study follows.

4.3.2 MODFLOW

The Basic Package

The grid of the model is defined in the Basic Package. The number of row, columns, layers, the initial heads, the number of stress periods, the calculation of a water budget and which other packages will be used are input into this package.

The Block Centred Flow Package

The three-dimensional flow of groundwater is traditionally described by the partial differential equation, shown in Equation 4.1.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad \textbf{Eqn: 4.1}$$

Where:

x, y and z are rectangular co-ordinates,

K is the hydraulic conductivity,

h is the head,

W is the volumetric flux, representing all the sources and sinks of water to the system,

S_S is the storage coefficient and

t is time.

In MODFLOW this is represented by the finite difference approximation for a cell for one timestep. This is represented by Equation 4.2. **Eqn: 4.2**

$$\begin{aligned}
&CR_{i,j-\frac{1}{2},k}\left(h^2_{i,j-1,k}-h^2_{i,j,k}\right)+CR_{i,j+\frac{1}{2},k}\left(h^2_{i,j+1,k}-h^2_{i,j,k}\right)+\\
&CC_{i-\frac{1}{2},j,k}\left(h^2_{i-1,j,k}-h^2_{i,j,k}\right)+CC_{i+\frac{1}{2},j,k}\left(h^2_{i+1,j,k}-h^2_{i,j,k}\right)+\\
&CV_{i,j,k-\frac{1}{2}}\left(h^2_{i,j,k-1}-h^2_{i,j,k}\right)+CV_{i,j,k+\frac{1}{2}}\left(h^2_{i,j,k+1}-h^2_{i,j,k}\right)+\\
&P_{i,j,k}h^2_{i,j,k}+Q_{i,j,k}=SS_{i,j,k}\frac{\left(\Delta r_j\Delta c_i\Delta v_k\right)\left(h^2_{i,j,k}-h^1_{i,j,k}\right)}{t_2-t_1}
\end{aligned}$$

Where:

i, j and k are the indexing system for rows, columns and layers,

h^1 and h^2 are the heads at time 1 and time 2,

Q and P are the flows to and from the cell through the packages (e.g. a river),

SS is the specific storage,

$\Delta r_j \Delta c_i \Delta v_k$ is the volume of the cell,

t_1 and t_2 are times 1 and 2 and

CR, CC and CV are conductances between the nodes which represent the hydraulic conductances combined with the grid dimensions. An example is shown in Equation 4.3.

$$CR_{i,j-\frac{1}{2},k} = KR_{i,j-\frac{1}{2},k} \frac{\Delta c_i \Delta v_k}{\Delta r_{j-\frac{1}{2}}}$$ **Eqn: 4.3**

Where:

KR is the hydraulic conductivity in the row (j) direction,

Δr_j is the length of the cell in the row (j) direction,

Δc_i is the length of the cell in the column (i) direction and

Δv_k is the height of the cell.

MODFLOW uses an iterative method to solve this equation. It sets an arbitrary value for the new set of heads and iterates until the heads satisfy the set of equations.

Four types of layers are recognised by the package, confined, unconfined and two layer types which can swap between confined and unconfined. The first of these assumes that the saturated thickness is a high fraction of the layer thickness and therefore transmissivity does not need to be recalculated. The other layer which swaps between confined and unconfined recalculates transmissivity at each iteration.

The Block Centred Flow Package 2: The WETDRY Function

The original Basic Package of MODFLOW does not allow a cell to be wetted once it has become a no-flow cell. This is a considerable disadvantage when, for example, looking at the recovery of groundwater levels when a well is turned off, or where cells incorrectly go dry as part of the iteration process. Therefore a new Basic Package (BCF2) was developed to allow 'wetting' to occur. The decision as to when to wet a cell can be made based either on the head of the cell immediately below or on the head in that cell and in the four surrounding cells. The head in the newly wetted cell can be decided in one of two ways, represented by either Equation 4.4 or 4.5.

$$h = BOT + WETFCT(hn - BOT)$$ **Eqn: 4.4**

$$h = BOT + WETFCT(THRESH)$$ **Eqn: 4.5**

Where:

h is the new head,

hn is the head in the cell that causes the wetting,

BOT is the elevation of the bottom of the cell and

WETFCT and *THRESH* are user specified constants.

Equation 4.4 intuitively seems to be the most realistic and is therefore the favoured method. However, it can promote instability which is a problem when using the 'wetting' capability of BCF2. Convergence problems are more likely to occur when using the wetting capacity (McDonald *et al*, 1991). A situation highlighting this problem is described by McDonald *et al* (1991); a cell which has a well in it goes dry, the stress of abstraction is then removed, allowing it to become wet, when abstraction is resumed it goes dry and abstraction ceases until it becomes wet again. There is also a problem when a single aquifer is being modelled by multiple layers, where the vertical conductance would vary between zero when a cell is dry and a constant when it is wetted.

The amount of data that is required by a multi-layer model which uses the wetting capability means that the occurrence of errors is likely and of their being difficult to trace. (McDonald *et al*, 1991).

The Recharge Package

The Recharge Package is designed to simulate recharge from precipitation. Recharge can be applied to the model in one of three ways. Firstly, recharge is only applied to layer 1 of the model. Secondly, the user specifies which cell in the vertical column recharge is applied to. Under these two options, should the cell that recharge will be applied to, become dry then recharge is not applied. This is the advantage of the third option where recharge is applied to the top active or constant head cell in each column. The volume of recharge is given by Equation 4.6.

$$Q_{Ri,j} = I_{i,j} DELR_j DELC_i \qquad \textbf{Eqn: 4.6}$$

Where:

$Q_{Ri,j}$ is the recharge applied to the cell at location i, j,

$I_{i,j}$ is the recharge (lt^{-1}) and

$DELR_j DELC_i$ is the area of the cell.

The Well Package

The Well Package is designed to model both abstraction and recharge wells. The data required are the row, column and layer of the cell and the rate of flow (either recharge or discharge). More than one well can be located in each cell. It is assumed that each well is only open to one layer of the model. However, a well which drains more than one layer can be modelled using a group of single layer wells.

The Drain Package

The Drain Package was designed to model agricultural drains. It removes water from the aquifer when the head of the groundwater exceeds a fixed elevation (such as the level of an agricultural drain). This package can also be used to represent gaining rivers or springs. The discharge (*QD*) is calculated using either Equation 4.7 or 4.8.

$$QD_{i,j,lk} = CD_{i,j,k}\left(h_{i,j,k} - d_{i,j,k}\right) \qquad \text{for } h_{i,j,k} > d_{i,j,k} \qquad \textbf{Eqn: 4.7}$$

$$QD_{i,j,lk} = 0 \qquad \text{for } h_{i,j,k} <= d_{i,j,k} \qquad \textbf{Eqn: 4.8}$$

Where:

$h_{i,j,k}$ is the head in the cell,

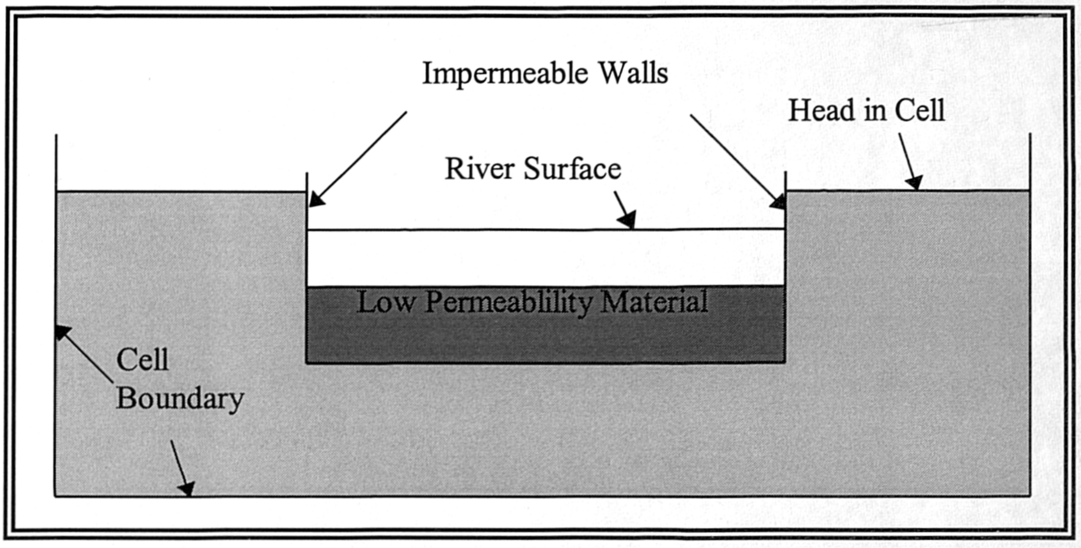
$d_{i,j,k}$ is the head in the drain which is approximated by the median drain invert elevation and

$CD_{i,j,k}$ is the lumped conductance describing all the headloss between the drain and the cell.

The River Package

The River Package represents rivers, streams or water bodies which can either contribute to the groundwater system or drain from it depending on the groundwater head. Figure 4.22 shows a cross-sectional representation of a river in MODFLOW.

Figure 4.22: The Conceptualisation of a River Package Cell



After McDonald and Harbaugh (1988)

The hydraulic conductance of the stream-river connection (*CRIV*) is given by Equation 4.9.

$$CRIV = \frac{KLW}{M}$$ **Eqn: 4.9**

Where:

L is the length of the reach,

W is the width of the river,

K is the hydraulic conductivity of the river bed and

M is the thickness of the river bed.

The flow between the stream and the aquifer (*QRIV*) is given by Equation 4.10 when the head in the cell is above the bottom of the river.

$$QRIV = CRIV\left(HRIV - h_{i,j,k}\right)$$ **Eqn: 4.10**

Where:

HRIV is the head in the river and

$h_{i,j,k}$ is the head in the cell.

When the head in the cell is below the bottom of the river the flow from the stream to the aquifer is given by Equation 4.11.

$$QRIV = CRIV(HRIV - RBOT) \quad \textbf{Eqn: 4.11}$$

Where:

RBOT is the height of the base of the river.

Solvers

MODFLOW offers a range of solvers. The Strongly Implicit Procedure (SIP) and the Slice-Successive Overrelaxation (SOR) packages were included in the original MODFLOW. Subsequently, the Preconditioned Conjugate Gradient (PCG2) package has been developed. This solver has two options the Modified Incomplete Cholesky Preconditioner and the Least Squares Polynomial Preconditioner.

SIP and PCG2 have both been used successfully with the wetting option of BCF2 (McDonald *et al*, 1991), although Winston (1996) indicates that PCG2 is generally the better choice when using the wetting option.

SIP

The speed at which SIP converges to a solution is controlled by three factors: the iteration parameter seed, the acceleration parameter and the number of iteration parameters. The optimum combination of these three factors is different for every model. The iteration parameter seed can be estimated by MODFLOW; however if the head changes between iterations are too large then the seed value should be increased and vice versa. The acceleration parameter is usually set at 1. If the model diverges from solution then this value should be reduced. The number of iteration parameters is generally set at 5.

PCG2

There has been considerable interest in the conjugate gradient method as a device for solving groundwater flow equations. It has proven to be efficient and capable of solving large, difficult problems (Meijerink and van der Vorst, 1977; Saad, 1985). When used in MODFLOW, PCG2 tends to perform better than either SIP or SOR (Hill, 1990a). Kuiper (1981) tested PCG2 against SIP and found that the performance of PCG2 was either better or comparable to SIP.

Meyer *et al* (1989) tested the conjugate gradient method on three-dimensional steady state groundwater flow in randomly heterogeneous porous media. It was found to be efficient, particularly with Polynomial Preconditioning. It is therefore perfect for solving the large sparse linear systems that are associated with modelling groundwater flow. When compared with SIP it was found to be 13 times faster.

Hill (1990a & b) argues that one of the reasons that it is successful is that the iteration parameters are calculated internally and need not be estimated by the user. For these reasons PCG2 was chosen as the most appropriate solver for the present application.

Pre-processor

MODFLOW was run through Groundwater Vistas v. 1.5. This package is both a pre- and postprocessor to MODFLOWwin32 (Environmental Simulations Inc., 1996). Groundwater Vistas allows the user to view the model in both plan and cross-section. This facility was particularly useful, with the steep gradients of both the aquifer geometry and the groundwater surface, in the Dysart-Leven Coalfield.

4.3.3 The Conceptual Model

The Water Balance

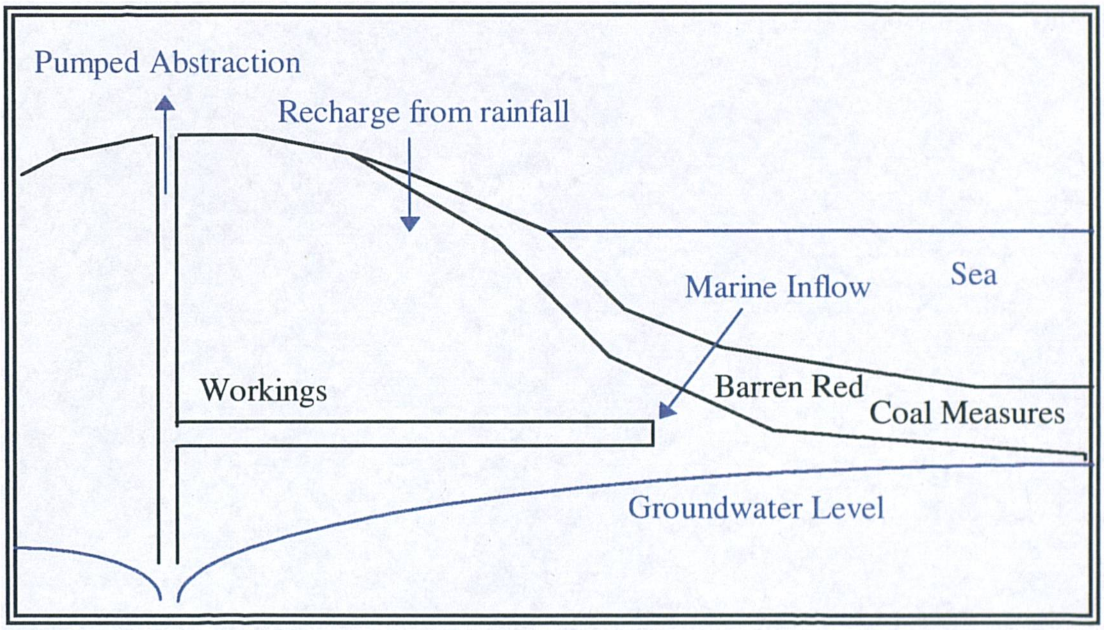
The water balance has 3 main components: recharge from rainfall, marine inflow and the abstraction from Michael and Frances (see Figure 4.23). The rivers are assumed to be isolated from the Coal Measures and therefore do not provide recharge, (as was assumed in the conceptual model used by GRAM; see Section 3.6).

The study described in Section 4.2.2 calculated recharge to be 22.64 Ml/d. Abstraction values from 1987 (after completion of the slight rebound in water levels) can be regarded as steady state. The steady state abstraction rate at Michael is 23.50 Ml/d and at Frances is 9.03 Ml/d.

Marine inflow, in the GRAM calibration (for the period January 1985 to March 1994) and inflow from the Whin Dooks amounted to approximately 11.80 Ml/d. This estimate includes the period prior to 1987 when there was a gain in storage. Therefore, it does not represent steady state conditions.

With a total inflow of 34.44 Ml/d (22.64 + 11.80) and a total abstraction of 32.53 (23.50 + 9.03), there would be a gain in storage of approximately 1.91 Ml/d. This is inappropriate for a steady state model. Therefore, the marine inflow was reduced to 9.89 Ml/d, to approximate steady state conditions.

Figure 4.23: Cross Section of Conceptual Model

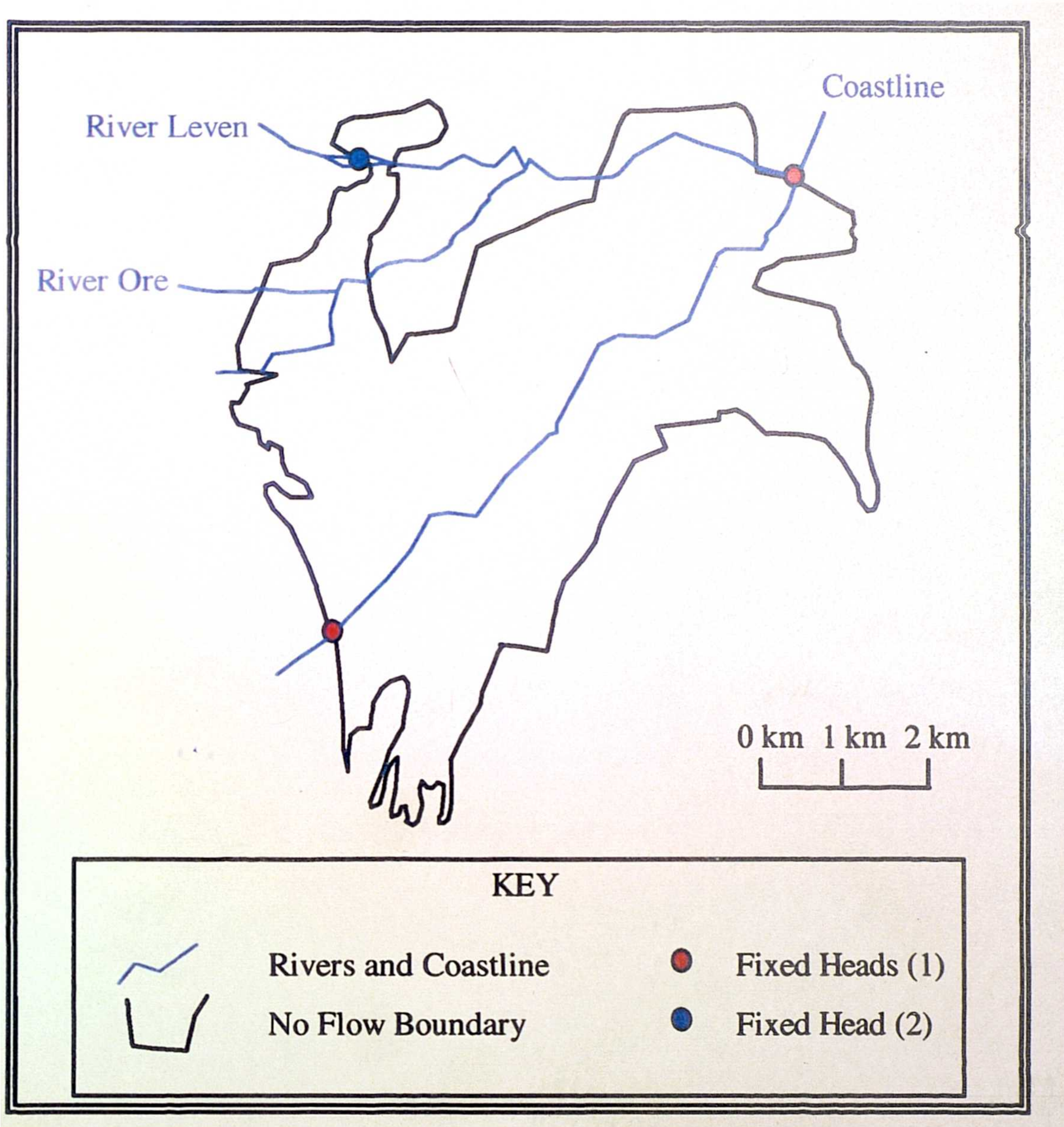


The Hydrostratigraphic Units

The Coal Measures will be regarded as one layer, therefore the model will be a two-dimensional areal model. Defining the hydrostratigraphic units in any more detail would be problematic. There are sixteen worked seams in the coalfield. Each seam could be treated as an individual hydrostratigraphic unit, with its cyclothem as an associated confining layer. However, this would lead to massive grid requirements, exorbitant run-times and the increased risk of non-convergence where the geometry becomes too complex.

When faced with such a problem McDonald *et al* (1991) recommend starting with a simple model and gradually making it more complex, rather than starting with a complex model. Although, Toran and Bradbury (1988) found errors in assuming two-dimensional flow for a minewater problem they also found that the use of a quasi-three-dimensional flow model did not significantly improve their calibration (see Section 2.6.4).

Figure 4.24: Boundaries of the Conceptual Model



The Boundary Conditions

The boundaries of the model are shown in Figure 4.24. The Passage Group is used as a no-flow boundary around the inland workings. Out to sea the outer limit of the workings is used as a no-flow boundary (due to the very different nature of the two environments); however, it will be necessary to verify this assumption with a sensitivity analysis.

The Fixed Heads

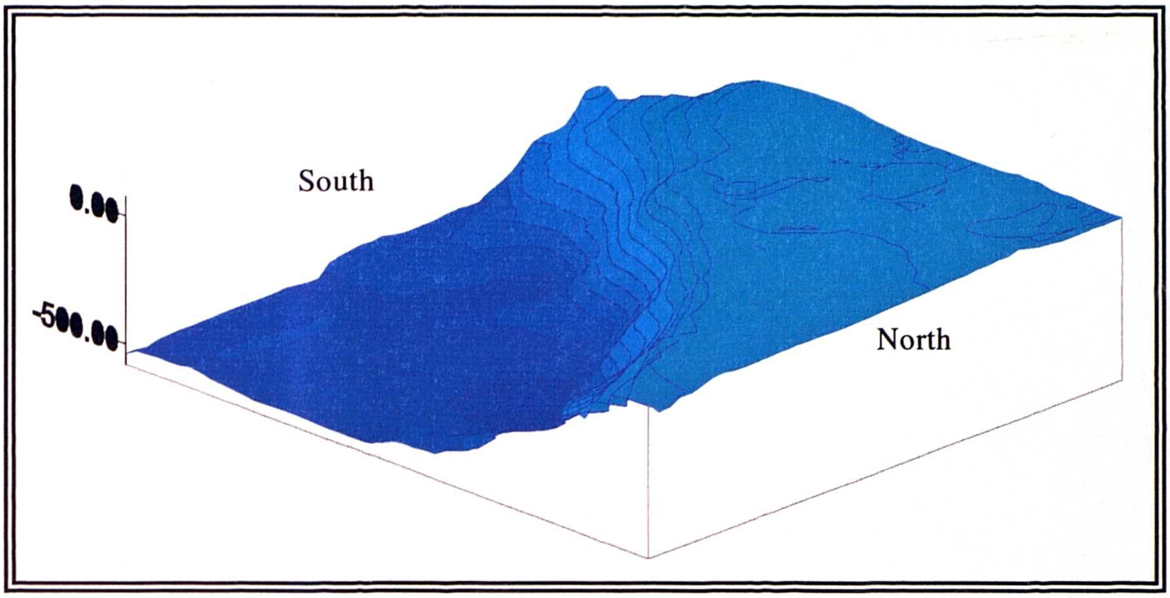
A fundamental constraint of using MODFLOW (or any other finite difference or finite element code) is the obligation, imposed by mathematical limitations, to define a fixed-head somewhere within the domain.

A cross section of the conceptual model is shown in Figure 4.23. This shows the difficulty faced in defining fixed heads, the best option seems to be to use sea level where the no-flow boundary meets the sea. (See Fixed Heads (1) in Figure 4.24.) Another option would be a fixed head on one of the rivers, however, the assumption that there is no interaction between the aquifer and surface water bodies makes this option dubious.

Aquifer Properties

The Coal Measures will be regarded as a single layer (see Hydrostratigraphic Units section). The aquifer top will be set as the top of the Pilkembare seam and the aquifer base will be the bottom of the Lower Dysart seam. See Figure 4.25.

Figure 4.25: The Top of the Coal Measures Aquifer, Viewed from the North-East



The value of effective hydraulic conductivity will be difficult to estimate. Bullens Consultants give a range of values for this coalfield of 0.09 m/d to 100 m/d depending on the state of the strata (see Section 4.1.5).

Secondary permeability is likely to be a major factor when estimating the effective hydraulic conductivity of this system. Gale (1982) states that the secondary permeability can increase the effective hydraulic conductivity of a fractured rock system by up to five orders of magnitude. Anderson and Woessner (1992) note that the influence of the secondary permeability on effective hydraulic conductivity is dependant on the type of material and the number, width and interconnection of the fractures.

The value of hydraulic conductivity will be calibrated, starting from initial estimates within the range estimated by Bullen Consultants.

The Flow System

The direction of groundwater flow in the model is predominantly from the points of recharge (either due to rainfall or marine inflow) to the abstraction wells in the middle of the model domain. There are seven abstraction wells in the model. Details of the six abstraction locations within the Frances Colliery were available in the British Coal archives (Table 4.32). The abstraction rate was split evenly between the six abstraction wells. (No data was available to allow the abstraction rate to be split more accurately.) The description of the pumping regime at Michael in the British Coal archives detailed only one abstraction location at the base of the Michael No. 2 shaft.

Table 4.32: Location of Abstraction Wells

Colliery	Model Co-ordinates	Abstraction Rate (Ml/d)
Michael	333555 : 696100	23.50 Ml/d
Frances	331000 : 693885	1.51 Ml/d
	332000 : 692100	1.51 Ml/d
	332500 : 692200	1.51 Ml/d
	332100 : 331800	1.51 Ml/d
	331800 : 692700	1.51 Ml/d
	331300 : 693000	1.51 Ml/d

The Head Targets

The only data available to be used as head targets are the water levels in the shafts. The targets are listed in Table 4.33. Therefore, the head targets include the water levels at the Michael and Frances shafts. These are not ideal as they coincide with abstraction wells. However, the lack of data means that no other target heads are available.

Table 4.33: Target Heads

Name	Model Co-ordinates	Target Head (m)
Balgonie	330700 : 698800	-32.948
Randolph	330300 : 695800	-37.0728
Frances	331000 : 693885	-223.114
Michael	333555 : 696100	-297.79
Wellesley	336640 : 698790	-204.064

4.3.1 Setting up the Model

The units of the model are days and metres. The bottom left of the model domain is at 328895 : 689650 (NT329897) and the top right at 340090 : 701800 (NO401018). The grid is orientated parallel to the ordinate. The minimum grid spacing is 10 m by 10 m at the abstraction wells, this expands by a maximum of a 1.5 multiplier to a maximum size cell of 50 m by 50 m. The grid spacing is necessarily small due to the steep gradients in both the aquifer geometry and the target head distribution. The grid consisted of 289 rows and 275 columns.

The marine inflow is likely to be a function of thickness of Barren Red Coal Measures (see Figure 4.23). Ultimately, the marine inflow will be represented using the river function (see Figure 4.22 and Section 4.3.2). The width of the river being the entire width of the cell and the depth of the river sediment being the thickness of the Barren Red Coal Measures. However, the marine inflow will initially be represented as evenly distributed recharge. It will be represented as a function of the thickness of the Barren Red Coal Measures, when this level of detail proves necessary.

The PCG2 solver, could not be used with this model. The Cholesky Preconditioning method produced the error message: "Cholesky diagonal is less than zero; therefore, the simulation has been aborted." The Polynomial Preconditioning method simply crashed prior to any iterations. Therefore, the SIP solver was used, with an iteration parameter seed of 0.5, an acceleration parameter of 1 and 5 iteration parameters.

4.3.2 Calibration of MODFLOW

Initial calibration used a uniform hydraulic conductivity distribution. With values of high hydraulic conductivity, the heads were not low enough in the coastal ponds. With low values of hydraulic conductivity the abstraction well at Michael dried out. The hydraulic conductivity was slowly lowered until the head at Michael was approximately correct (at 0.27 m/d). However, a cone of depression with a relatively small radius was created and the heads at all the other targets were too high, particularly at Wellesley and Frances.

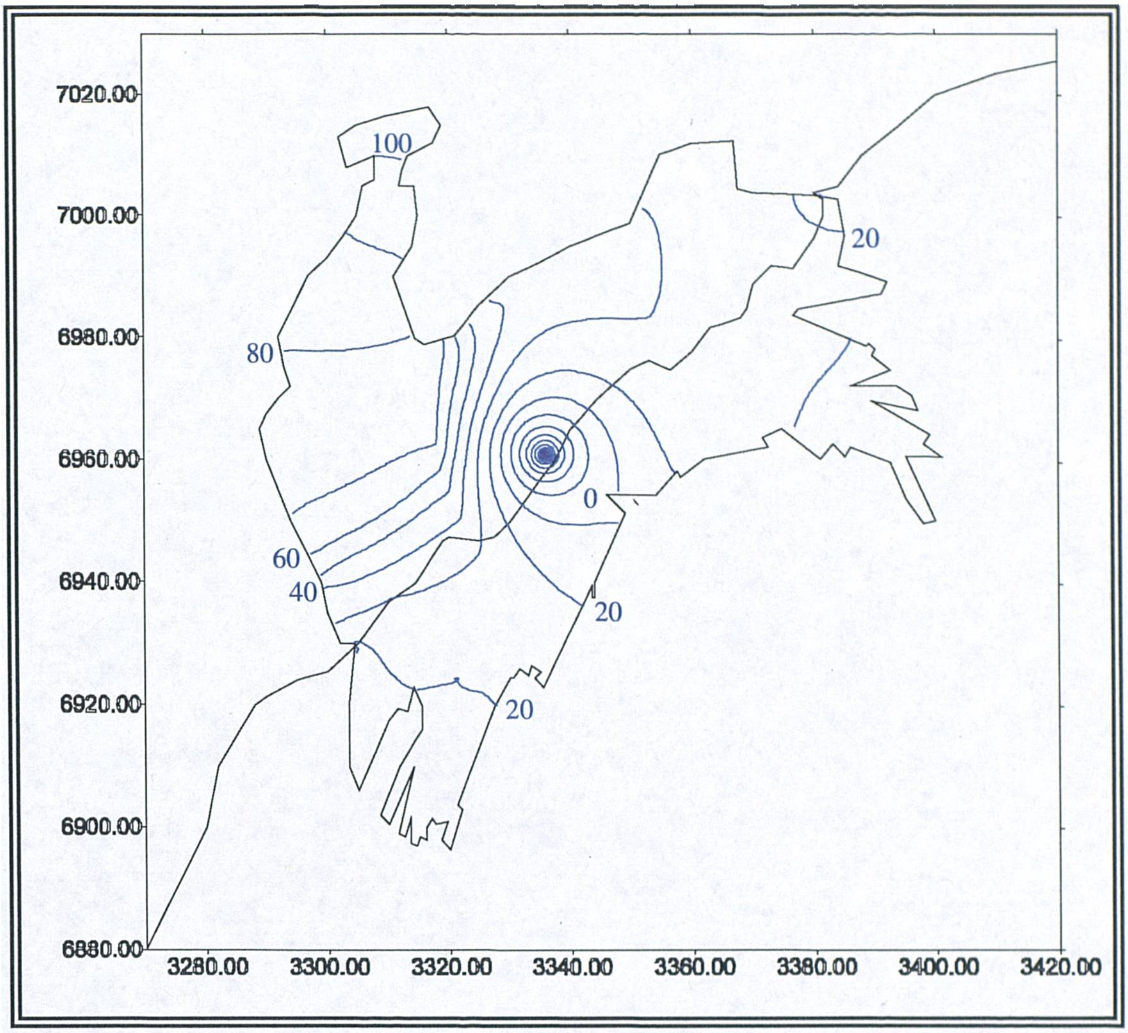
Therefore, the use of a uniform hydraulic conductivity distribution was abandoned. The hydraulic conductivity in the area of the Randolph and Balgonie collieries was increased. The heads improved with increasing hydraulic conductivity, until 10 m/d was reached. At this point the improvement to the heads proved to be finite. The heads at Randolph and Balgonie were being adversely affected by the high heads in the rest of the coalfield.

The hydraulic conductivities in the area of the Frances and Wellesley collieries were increased. This resulted in improved heads in that area and also in the Randolph and Balgonie area, but the head at Michael increased. With a hydraulic conductivity distribution that consisted of 0.27 m/d in the Michael workings and 10 m/d in the rest of the coalfield, the heads across the whole model were too high. One factor that was preventing the heads from being lowered was the fixed heads at sea level. See Figure 4.26. The error between the target heads and the calibrated heads was still hundreds of metres (see Table 4.34).

Table 4.34: Error in Calibration to Target Heads

Name	Target Head (m)	Error in Calibration (m)	Calibration Heads (m)
Balgonie	-32.948	-117.98	85.03
Randolph	-37.0728	-108.24	71.17
Frances	-223.114	-252.46	29.35
Michael	-297.79	-83.65	-214.14
Wellesley	-204.064	-232.27	28.06

Figure 4.26: Head Distribution



Localised areas of very low hydraulic conductivity were introduced around the fixed heads. This did not significantly lower the heads at Wellesley or Frances.

The fixed heads were removed from the intersection between the edge of the model and sea level. The assumption that there is no interaction between the surface water bodies and the aquifer was ignored and a fixed head was introduced where the River Leven crosses the model boundary. See Fixed Head (2) in Figure 4.24. This did result in an improvement in the head distribution. Lowering the hydraulic conductivities around Frances and Wellesley did now result in a lowering of the heads in that area.

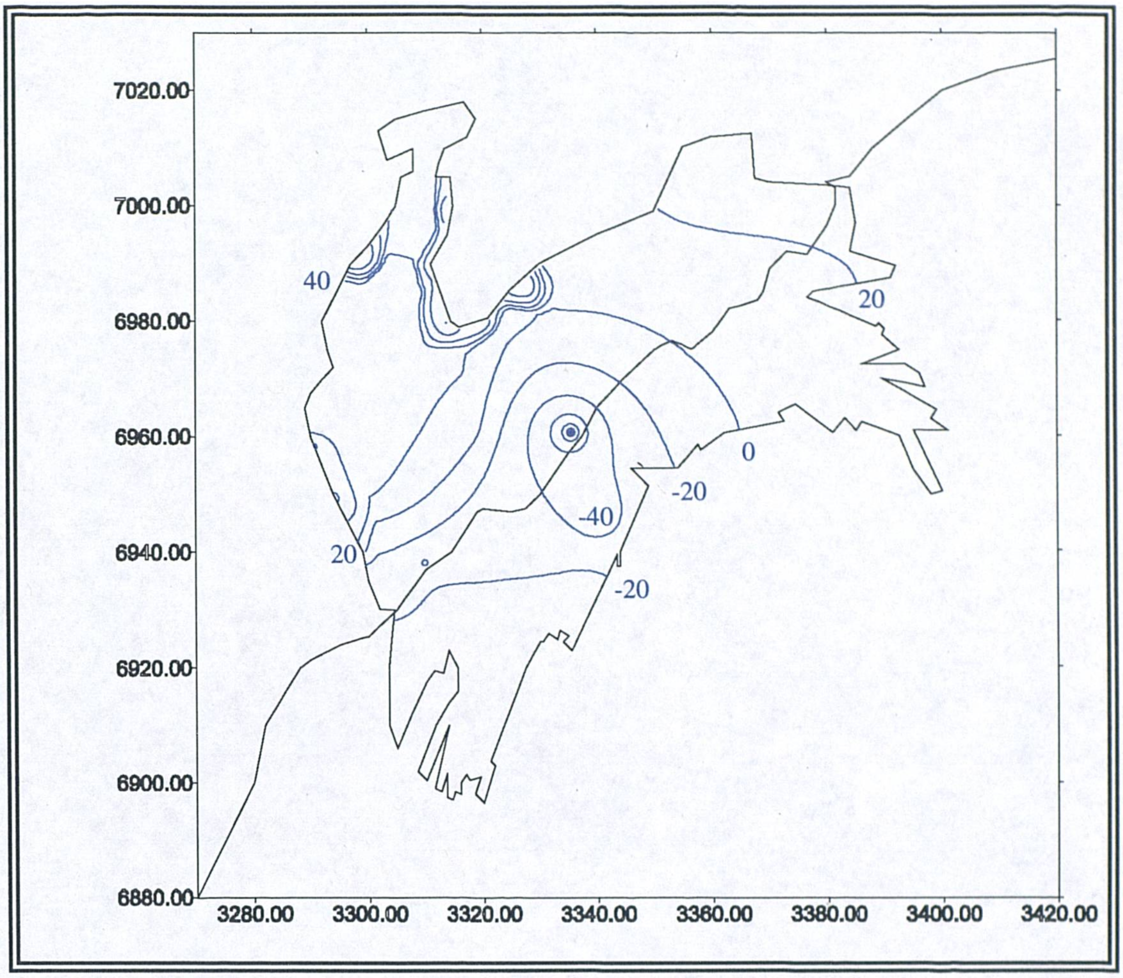
As the hydraulic conductivities around Frances and Wellesley were lowered, there was a problem with drying of cells at the edges of the aquifer. Therefore, where the cell drying problem occurred, the hydraulic conductivities were set to low values to retain water in those cells. As the heads over the coalfield improved more cells became subject to the drying problem. The model became unstable as large areas of cells dried out and the area defined by the Barnslee-Treaton Basin became separated from the rest of the model causing MODFLOW to crash.

The best heads that could be obtained before the model became unviably unstable are shown in Table 4.35. These are still hundreds of metres different from the observed heads. The modelled head distribution is shown in Figure 4.27. The hydraulic conductivity distribution that achieved these heads was 0.4 m/d in the workings from the coastal collieries and 5 m/d in the workings of the inland collieries. The edges of the aquifer that had been subject to drying, had hydraulic conductivities of 0.01 m/d. The exception to this was the western edge of the Randolph workings, where drying was less of a problem and the hydraulic conductivity was set to 0.02 m/d. These areas show up clearly in the head distribution; see Figure 4.27.

Table 4.35: Error in Calibration to Target Heads with Reduced Hydraulic Conductivities at the Edges of the Model

Name	Target Head (m)	Error in Calibration (m)	Calibration Heads (m)
Balgonie	-32.948	-67.27	34.32
Randolph	-37.0728	-58.95	21.88
Frances	-223.114	-166.23	-56.88
Michael	-297.79	-76.93	-220.86
Wellesley	-204.064	-219.70	15.36

Figure 4.27: Head Distribution with Reduced Hydraulic Conductivities at the Edges of the Model



It was decided that varying marine inflow as a function of the thickness of the Barren Red Coal Measures would not significantly improve the heads, or the stability of the model. The amount of marine inflow would vary to a degree with the thickness of these strata. However, the proximity of faults is likely to be a more critical factor. Detailed data on the location of faults is not available nor is data on the varying marine inflow to different faces. The head distribution is therefore considered too poor to be improved by changing the marine inflow distribution.

At this point the calibration of the model was abandoned. Achieving an improvement in the head distribution was thought to be unlikely. Should calibration be achieved, the memory requirements of a transient model with this grid spacing would be large enough to make it unfeasible on a standard PC.

4.3.6 Criticisms of MODFLOW Dysart-Leven Model

A major problem with modelling the Dysart-Leven Coalfield using MODFLOW is the lack of data, particularly for the spatial distribution of pumping within the workings. Toran and Bradbury (1988) found that it was necessary to have field data for before, during and after mining. If only one or two of these data sets is available, they predict large uncertainties associated with modelling.

The location of fixed heads was a difficulty. There is nowhere to site a fixed head that is truly appropriate. The fixed heads at the edge of the aquifer at the coast, do not represent the heads in the aquifer itself, but that of the sea. The fixed head where the River Leven crosses the northern area of the model, means rejecting the assumption that there is no interconnection between the surface water courses and the aquifer.

The complex geometry and the high gradients of the strata that make up the aquifer, made retaining water at the edge of the aquifer difficult. The instability that resulted from these areas drying out, prevented a good calibration from being achieved.

The relative water levels in the collieries suggests that there must be very steep hydraulic gradients in parts of the coalfield, particularly in the area between the inland collieries and the workings from Frances and Michael. This hydraulic gradient is very difficult to recreate with a model of this sort.

These difficulties are symptomatic of a fundamental problem: standard groundwater modelling approaches are inappropriate for the coal mining environment (see also Section 2.6.6). This is particularly true when the coalfield covers a relatively small area and has steeply dipping geology. The assumptions necessary in the EPM conceptual model make the model result in a gross simplification. It seems likely that in this case the size of the minimum valid REV is excessively large, possibly infinite. If further modelling with off the shelf packages was deemed necessary, then a discrete fracture or dual porosity model would perhaps be more appropriate. Although parameterisation of such a complex model would be virtually impossible.

5 Developing an Iron Content Component for GRAM

5.1 Introduction

GRAM's value as a tool for managing acid mine drainage was limited by the fact that it was solely a flow model and had no water quality component. This was initially overcome by using it in parallel with PHREEQE, which is a geochemical modelling code. This has been used successfully to give an indication of the iron and sulphate content of first flush discharges (Younger *et al*, 1995).

Younger (1997) has developed a theory of AMD generation; dividing the source of pollution into vestigial and juvenile acidity. This can be adapted to form a conceptual model, and ultimately a component of GRAM. The model will only address the iron content of AMD, which is undoubtedly the most important element and will also give an indication of the overall water quality.

5.2 Vestigial and Juvenile Acidity

Pyrite oxidation mainly occurs before inundation by groundwater rebound. In the absence of dissolved oxygen pyrite oxidation can only occur when large concentrations of strong oxidants are present, which is unlikely in inundated mine workings (Younger, 1997). However, seasonal pyrite oxidation can occur by two methods:

- the formation of iron hydroxysulphate solids by pyrite oxidation in the unsaturated zone, which is later followed by dissolution of these iron hydroxysulphate solids when the water level rises,
- pyrite oxidation of seasonally exposed mineral surface in the unsaturated zone.

This means that a low level of AMD generation can carry on almost indefinitely. Therefore, Younger (1997) divides AMD according to when the pyrite was oxidised. 'Vestigial acidity' is caused by the inundation of the mineworkings by groundwater rebound. This leads to the first flush of heavily polluted water. 'Juvenile acidity' is caused by seasonal fluctuations in the water level, as described above. Juvenile acidity can be dominated by mineral acidity as opposed to proton acidity, see Section 2.1.5.

How enduring a discharge of AMD may be is dependent on the rate of reduction of the vestigial acidity and the rate of production of juvenile acidity (Younger, 1997).

5.3 Conceptual Model

The GRAM conceptual model includes iron associated with the vestigial acidity and the juvenile acidity. Each pond in the GRAM model has an iron content, which is assumed to be homogeneously distributed within the water. There are four sources of this iron: recharge, marine inflow, flow from other ponds and contact with the oxidised pyritic sulphur in the Coal Measures.

The iron content of flow to and from ponds can be calculated according to the ratio of the volume of water that flows in the pipe to the volume of water that is in the pond of origin.

The iron content which results from contact with oxidised pyritic sulphur is a function of: the sulphur content, the percentage of the sulphur which is pyritic, the density of the rock and the percentage of the pyritic sulphur which is oxidised and available to be dissolved.

If the vertically varying storage coefficient option is used in GRAM, the areas of increased storage coefficient represent the coal seams (see Section 3.3.3). The coal seams (areas of increased storage coefficient), have pyritic sulphur available to be dissolved. Therefore, as the water levels rise through the coal seams the iron content of the water is increased.

If 1 m^3 of water is in contact with a coal seam with an effective porosity of n, then it will be in contact with $1/n$ m^3 of rock. Assuming a density of D kg/m^3 the mass of rock in contact with 1 m^3 of water (M) would be $1/n * D$ kg. Data for the sulphur content percentage (by weight) of coal seams ($\%S_W$) is often available. However, not all of the sulphur is in pollution-generating pyritic form.

Casagrande (1987) found that high and medium sulphur-content coals associated with marine or brackish depositional environments have approximately equal proportions of pyritic and non-pyritic sulphur. On the other hand, in low sulphur-content coals associated with freshwater depositional environments the pyritic sulphur amounts to only 20 - 30 % of the total sulphur content.

Morrison *et al* (1990) worked on the Alleghenian coal bearing strata and assumed that all the total sulphur content was an approximation of the pyritic sulphur content because the Alleghenian shales are typically low in sulphate and organic sulphur. However, they found that freshwater sequences had low pyritic sulphur contents, compared to brackish sequences.

For the Dysart-Leven Coalfield, Bullen Consultants (1994) used the values found by Casagrande (1987). They assumed that 25 % of the sulphur content of low sulphur coal was pyritic and 50 % of the sulphur content of intermediate or high sulphur content coals was pyritic.

Multiplying the estimated proportion that is pyritic by the $\%S_W$ and M (in grams) provides an estimate of the weight of the pyritic sulphur with which 1 m^3 of water can come into contact. However, only a small proportion of the pyritic sulphur will have been oxidised and the water will not be able to dissolve all of it, due to the variable porosity of the coal measures.

There is considerable uncertainty when estimating the proportion of the pyritic sulphur which is oxidised and thus available to be dissolved. Bullen Consultants (1994) used values in the range 0.1 - 10 % of the total pyritic sulphur, but stated that 10 % was probably an excessively high estimate.

The pyritic sulphur which has been oxidised and come into contact with the 1 m^3 of water can be divided by the atomic weight of sulphur (32.06) to get the number of moles of sulphur. Pyrite is represented as FeS_2, hence the number of moles of iron dissolved into the 1 m^3 of water, will be half the number of moles of sulphur.

The data is stored as moles of iron per pond until the time of discharge. At the time of the first discharge from each pond a ‘mixing zone’ is defined. The iron content of the mixing zone is defined by the ratio of the volume of water in the mixing zone to the volume of water in the pond at the time of the first discharge. The iron content of discharges is based only on the iron content of the mixing zone. The mixing zone gains iron from recharge, flow between ponds and the generation of juvenile acidity and loses it by discharges to the surface.

The number of moles of iron discharged is calculated according to the ratio of the volume of discharge to the volume of water in the mixing zone. The number of moles of iron discharged, is divided by the volume of water and multiplied by the atomic weight of iron (55.847) to get the iron content in g/m^3 which is equivalent to mg/l. This means that the iron concentration will decline with time, until only iron from juvenile acidity is discharged.

5.4 FORTRAN Code

The FORTRAN code closely follows the conceptual model, described in Section 5.3. The main limitation of the code is the number of layer types that can become inundated within one timestep. A maximum of 3 types of layer in each change in height, is all the code can cope with. Therefore, in one time step the height of the water table can pass from strata below a seam, through the seam and into the strata above the seam. Considering the distances between most coal seams this should be sufficient with a timestep of one day.

The input data required by GRAM for iron modelling is as follows:

- rock density (g/cm^3),
- atomic weight of sulphur,
- atomic weight of iron,
- fraction of the rock mass that has been exposed to oxidation,
- iron content of recharge (g/l),
- iron content of marine inflow (g/l),
- height of the base of the mixing zone for each pond (m),
- for each change between coal seam and coal measures strata:
    - height (mAOD),
    - volume of sulphur,
    - fraction of sulphur that is pyritic.

GRAM outputs the following data from the iron component:

- the volume of iron in each surface discharge over time and
- the average volume of iron in the flow from each surface discharge point.

The obvious parameter to vary by Monte Carlo simulation is the proportion of the pyritic sulphur which is oxidised and available to be dissolved. However, there is limited data to form a distribution of the likelihood of different proportions. Strömberg and Banwart (1994) developed a geochemical model of water-rock interactions in waste heaps at a copper mine in northern Sweden. They concluded that the physical surface area which is available to be oxidised is approximately constant per volume of rock and independent of the particle size distribution. The reactive surface area was $1 \pm 0.4\ m^2/g$ (of rock). At a rock density of $2800\ kg/m^3$ and an assumed porosity of 35 % the physical surface area is the order of $2 \times 10^6\ m^2/m^3$ (of rock).

5.5 Applying the Iron Content Component to the Dysart-Leven Coalfield.

5.5.1 Previous Predictions

Previous predictions of the quality of discharges in the Dysart-Leven Coalfield have been included for comparison to the iron content of the discharges produced by GRAM. Bullen Consultants (1994) used PHREEQE to predict the quality of discharges. In the valleys of the Rivers Ore and Leven the predicted water quality of the initial discharges are shown in Table 5.1. However, subsequent experience indicates that the upper limit of the iron content is likely to approximately 1400 mg/l (Younger, P.L., University of Newcastle upon Tyne, Personal Communication, 1997).

This initial first flush would pass after the first year or two of discharge. The metal concentration would fall to the lower end of the ranges shown in Table 5.1 and the pH would rise to 4.5 or 5.

Table 5.1: Predicted Water Quality of the Initial Discharges to the Rivers Ore and Leven

Water Quality Indicator	Range
pH	3.5 - 5.0
Fe	500 - 2800 mg/l
Al	10 - 1000 mg/l
SO_4	1600 - 5400 mg/l

After: Bullen Consultants (1994)

At the coast the predicted discharges are of a better quality. The pH of these discharges is likely to stay above 5, the iron concentration is unlikely to exceed 580 mg/l and the aluminium concentration is likely to be less than 1 mg/l. The water quality would eventually improve to levels in the ranges shown in Table 5.2.

Table 5.2: Water Quality of Discharges to Coast

Water Quality Indicator	Range
pH	5.0 - 6.5
Fe	10 - 250 mg/l
SO_4	500 - 1000 mg/l

After: Bullen Consultants (1994)

5.5.2 Data Required by the Iron Content Component

The iron content of the recharge is assumed to be 0.01 mg/l (Stunell, J., University of Newcastle upon Tyne, Personal Communication, 1996). Marine inflow is assumed to contain 2 μg/l of iron (Drever, 1982). The atomic weights of sulphur and iron are 32.06 and 55.847 respectively. The rock density was estimated as 2.65 g/cm^3.

The heights of the coal seams have already been estimated, when the varying storage coefficient was applied to the Dysart-Leven Coalfield (see Section 4.2.9). Data regarding the sulphur content of the seams was available and is shown in Table 5.3.

Table 5.3: Sulphur Contents of Seams in the Dysart-Leven Coalfield

Seam	Pond	Total Sulphur (wt %)
Pilkembare	Wellesley	1.15
Wall	Wellesley Frances	1.50 1.65
Barncraig	Wellesley Michael Frances	0.7 - 3.16 (median 1.50) 0.80 0.72
Coxtool	Wellesley Michael Frances	1.00 0.80 0.60
Den	Wellesley	0.88
Chemiss	Wellesley Michael Frances	1.00 0.90 0.72
Bush	Michael	1.40
Wemyss Parrot	Michael	1.20
Wood	Michael	0.70
Earl David's Parrot	Michael	0.55
Bowhouse	Wellesley Michael Frances	0.80 0.80 0.69
Branxton	Wellesley Michael Frances	0.80 0.70 0.60
More	Michael Frances	0.60 0.80
Boreland	Michael Frances	0.80 0.70
Sandwell	Wellesley Michael Frances	1.60 1.40 0.90
Dysart Main	Wellesley Michael Frances Balgonie	0.60 0.60 0.45 0.60
Lower Dysart	Michael Frances Randolph Balgonie	2.1 1.5 0.5 - 4.65 2.20

After Bullen Consultants (1994)

As noted in Section 4.1.6 the most polluting discharges of AMD are expected from areas of shallow workings in seams with a high pyritic sulphur content. Specifically, the Lower Dysart seam and to a lesser extent the Wemyss Parrot, Bush, Pilkembare, Wall, Bowhouse and Sandwell seams. In all these seams the highest sulphur contents are inland, in the area of the Randolph and Balgonie ponds.

The fraction of the rock mass that is exposed to oxidation will be estimated. As will the height of the base of the mixing zone. The fraction of sulphur which is pyritic will be based on the 50 % for high and intermediate sulphur coal seams and 25 % for low sulphur coal seams used by Bullen Consultants (1994).

5.5.3 Applying the Iron Content Component

The three areas of uncertainty are the percentage of the sulphur which is pyritic, the percentage of the pyritic sulphur which comes into contact with air and is oxidised and the height of the mixing zone.

In the first run of model, the percentage of sulphur which is pyritic, was 25 % for the low sulphur seams and 50 % for the high sulphur seams. The percentage of pyritic sulphur which comes into contact with air and is oxidised was estimated as 1 % which is the middle of the range of values used by Bullen Consultants (1994). The height of the bottom of the mixing zone was taken to be 10 cm below the height of the lowest discharge.

This produced a first flush with a value of 1087830.7 mg/l at the Leven Harbour discharge from the Wellesley pond, this latterly fell to 784.7117 mg/l. Some of the worst UK AMD pollution cases have first flush iron contents of up to 1500 mg/l (Younger, P., University of Newcastle upon Tyne, Personal Communication, 1997), therefore, this value is far too high.

The percentage of the pyritic sulphur which comes into contact with air and is oxidised was therefore reduced to 0.01 %. This produced a first flush with a value of 1087.351 mg/l at the Leven Harbour discharge from the Wellesley pond, this latterly fell to 7.846 mg/l. This is larger than the first flush predicted at the coast by Bullen Consultants (1994), however it is the correct order of magnitude.

The necessary reduction in this percentage to obtain commonly observed values indicates that the range of values previously used for the Dysart-Leven Coalfield (0.1 - 10 %) was too high. Further application of the model to other coalfields would help to establish a more appropriate range of values.

5.5.4 Sensitivity Analysis

A sensitivity analysis was performed on the discharge at Leven Harbour. The three areas of uncertainty were varied. The results are shown in Table 5.4.

Table 5.4: Sensitivity Analysis

Percentage of the sulphur which is pyritic (Low : High)	Percentage of Pyritic Sulphur which is oxidised	Distance Between Base of Mixing Zone and First Discharge Point(m)	Iron Concentration of Discharge from Leven Harbour (mg/l)	
			First Flush	After 100 years
25:50	0.01	0.1	1087.35	7.85
5:10	0.01	0.1	217.47	1.57
50:75	0.01	0.1	2174.70	15.69
25:50	0.001	0.1	108.74	0.79
25:50	0.1	0.1	10873.15	78.43
25:50	0.01	0.01	458.82	2.37
25:50	0.01	1	2246.958	61.55

The percentage of the pyritic sulphur which is oxidised affects the value of the first flush and the level of pollution after a century. As one would expect an order of magnitude change in the percentage results in an order of magnitude change in iron content. This is also true of the percentage of the sulphur which is pyritic. Both percentages apply to both the vestigial acidity and the juvenile acidity.

The impact of altering the distance of the base of the mixing zone below the lowest point of discharge is more complex. The iron content after a century has a direct relationship with the thickness of the mixing zone. However, the iron content of the first flush, does increases with increasing height of the mixing zone. However, unlike the other results, it does not form a straight line graph when it is plotted. Increasing the thickness of the mixing zone by an order of magnitude approximately doubles the iron content of the first flush discharge.

This is because the iron content of the first flush of the first discharge from a pond is dependent on the volume of the mixing zone. In all the sensitivity runs, the volume of water in the pond and the volume of water discharged was constant. The iron content of the first flush is calculated by the volume of water which is removed from the mixing zone (as it assumes a homogenous mix in the mixing zone). The initial iron content in the mixing zone is also calculated according to the relative volumes of water in the pond and the mixing zone. Therefore, varying the volume of the mixing zone results in iron contents in the discharge which form an asymptotic curve.

5.5.5 The Predicted Iron Content of Discharges over Time

The model was run using the intermediate values in the sensitivity analysis (see Table 5.4). The predicted iron content of the discharge from the Wellesley shafts is shown in Figure 5.1. The total iron content of all discharges from the Wellesley pond is shown in Figure 5.2. The peaks are caused by the first flows from different discharges.

Figure 5.1: The Iron Content of the Discharge from the Wellesley shafts.

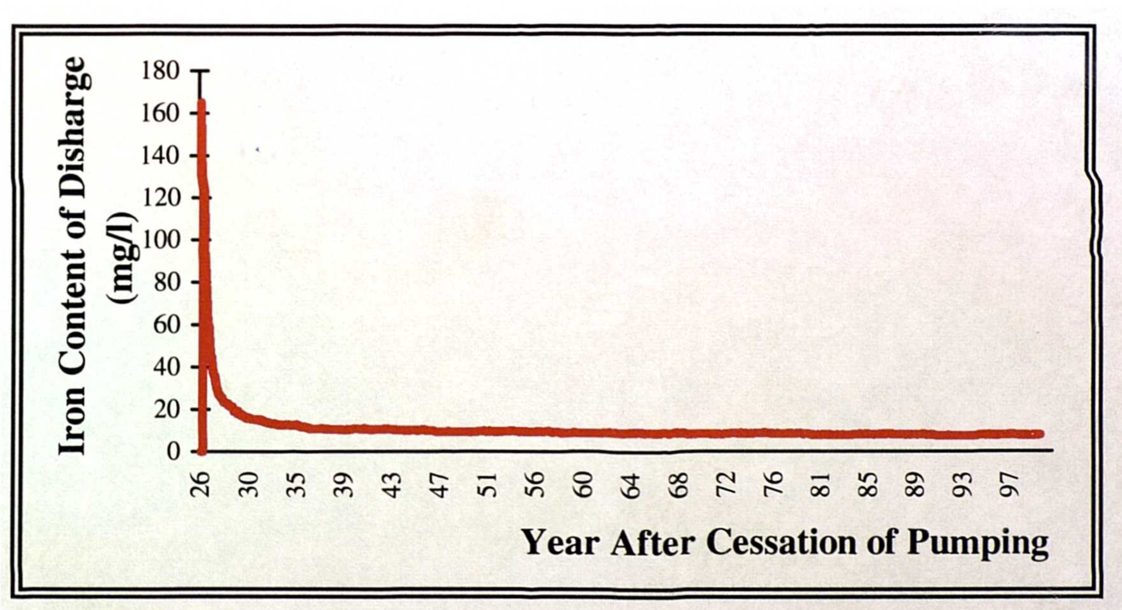
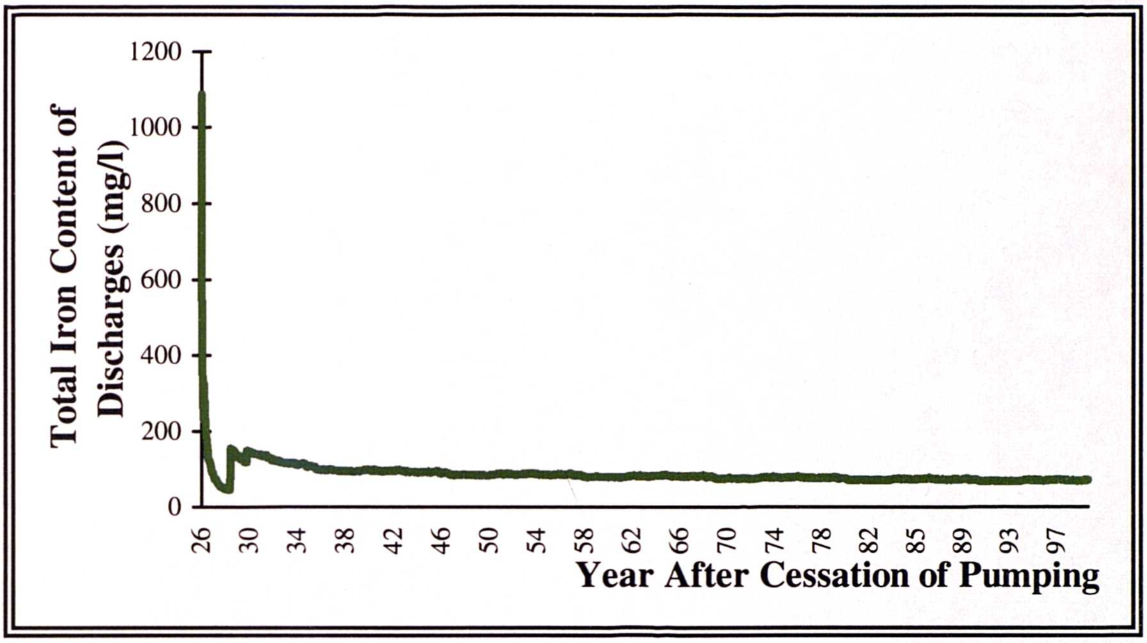


Figure 5.1 shows both the quality of the first flush and the time taken for the vestigial acidity to be exhausted. A few years after the discharge is initiated the iron content solely consists of iron associated with juvenile acidity. The rate of decay will be dependent on the height of the mixing zone, and hence the amount of iron in the discharge that is associated with vestigial acidity.

Figure 5.2: The Total Iron Content of all the Discharges from the Wellesley Pond.



Application of this model to a series of discharges that have already occurred would be invaluable. This would allow good estimates of the three areas of uncertainty to be collected. These values not only control the first flush and ultimate iron content of the discharges, but how long it takes for the vestigial acidity to be exhausted.

An attempt was made to apply GRAM to the discharges from the Wheal Jane tin mine in Cornwall. However, the hydrology of the mine appears to be complex, the volume of water discharging indicates that the mine must have a very large catchment area. It was felt that there was too much uncertainty regarding the water balance particularly the recharge to the mine to apply the hydrological part of GRAM successfully and that this would devalue the results of the iron component.

6 Conclusions

6.1 Summary

With the closure of many UK deep coal mines, AMD is likely to be a continuing problem. Modelling of the potential discharges is therefore an invaluable planning tool. The ability of existing models to represent this environment using the sparse data sets that are available is limited.

A new modelling approach (GRAM) has been developed to predict the timing, location, quality and quantity of discharges by modelling groundwater rebound through abandoned mineworkings. GRAM uses the concept of ponds, long used in the coal mining industry. This simple conceptual model means that the hydraulic parameters necessary for the application of traditional modelling techniques are not necessary.

The ponds are connected by pipes. Flow through these pipes is calculated using either the Prandtl and Nikuradse or the Colebrook-White pipeflow equations. Vertically varying storage coefficients can represent the differing nature of the worked Coal Measures and the unworked strata.

An iron component to GRAM models the hydrolysis of oxidised pyritic sulphur which is associated with both vestigial and juvenile acidity. This gives an indication of the water quality of discharges.

The model takes a relatively short time to run, therefore, Monte Carlo simulation can easily be applied to variables that have most error in their estimation.

GRAM has been applied to the Dysart-Leven Coalfield producing estimates of the quantity, timing and location of discharges. MODFLOW has been unsuccessfully applied to the same coalfield.

The results of the iron component as applied to the Dysart-Leven Coalfield were inconclusive. There are three major sources of uncertainty. Estimates of the percentage of the sulphur which is pyritic, the percentage of the pyritic sulphur which is oxidised and the height of the mixing zone are difficult to obtain. A sensitivity analysis indicated that these variables have a profound impact on the iron content of discharges.

However, the percentage value that is available to be oxidised had to be reduced to 0.01 % to obtain commonly observed discharge values. This gives an indication that the range of values previous used on the Dysart-Leven Coalfield (0.1 - 10 %) was too high and a more appropriate estimate for future work.

6.2 Attainment of Aims

The main aim of this study was to develop a new approach for modelling groundwater rebound through abandoned mineworkings. This has been achieved in the form of GRAM, a simple model that has modest data requirements and uses Monte Carlo simulation to account for the inaccuracies in the estimation of data.

GRAM has been used to predict the timing, location and quantity of discharges from the Dysart-Leven Coalfield. The accuracy of these predictions is unlikely to be verified by time because the results of the model have been used by the FRPB (latterly SEPA) to negotiate a solution with the Coal Authority. The water levels in the workings will be maintained at a low enough level to prevent further discharges at the surface (Sargent R., SEPA, Personal Communication, 1995).

A comparison of GRAM and MODFLOW as applied to the Dysart-Leven Coalfield illustrated the strengths and weaknesses of both approaches (see Section 6.3).

Before the GRAM iron component can be used to predict the water quality of discharges, calibration of the three areas of uncertainty must be carried out on existing discharges. The results of the iron component have therefore not been compared with the those of a geochemical model.

6.3 Strengths and Weaknesses of GRAM and MODFLOW

The conceptual model used in GRAM is essentially a hybrid of a Discrete Fracture model which includes a storage component, whereas, the work done with MODFLOW assumed an EPM (Equivalent Porous Medium). This meant that GRAM was better able to deal with the steep hydraulic gradients in the Dysart-Leven Coalfield than MODFLOW.

However, although confidence in the estimates of the timing and volume of discharges produced by GRAM is good on a pond-by-pond basis, detailed information regarding the conductances of potential discharges is necessary to give a fair representation on a discharge-by-discharge basis. This has been overcome in the Dysart-Leven Coalfield by using three scenarios which vary the conductances of different groups of discharges.

It is likely that the water levels at the location of the pumps will initially rise faster than predicted by GRAM. This is due to the steep hydraulic gradient in the ponds which GRAM assumes is flat. This assumption does not however, affect the ultimate estimates of total time taken to rebound.

The results of GRAM (particularly the timing of discharges) are dependent on the estimation of the storage coefficient. This is particularly difficult to estimate. Though it can be represented as a probability distribution using Monte Carlo simulation it is still likely to be the greatest source of error.

GRAM (even using the vertically varying storage coefficient) is unable to recreate the peaks evident in the water level time series for the Dysart-Leven Coalfield. The peaks may be the result of changes in water level local to the shafts, whereas GRAM tries to reproduce them over the whole pond.

Surface water bodies are not represented in GRAM. The only interaction between ground and surface waters that GRAM can represent are recharge, marine inflow and discharge via pipeflow. It is therefore assumed that baseflow and recharge from surface waters to the Coal Measures are a negligible part of the water balance. The estimates of marine inflow for the Dysart-Leven Coalfield are a source of error, as they have been only established by calibration.

GRAM only allows flow through pipes when they are immersed and hence flow full. This means that a few centimetres of flow in the bottom of an intact roadway must be represented by a small pipe.

The use of the Prandtl and Nikuradse equation assumes that all flow is in the rough-turbulent zone. However, replacing this with the Colebrook-White equation increases the run time by over 30 times and did not significantly improve the model fit.

The MODFLOW model of the Dysart-Leven Coalfield was limited by the lack of appropriate data. The assumption that an EPM could represent flow seems ill founded, particularly when one considers the relative size of the conduits of flow. The steep gradients in the aquifer top and base complicate modelling; as do the steep hydraulic gradients in the target head distribution. The failure of the MODFLOW application is therefore unsurprising. MODFLOW would be better able to represent a large coalfield which does not have steep slopes in geology or hydraulic gradient. GRAM is far better suited to this type of coalfield.

6.4 Recommendations

6.4.1 Data Collection During and After Mining

Accurate maps of mineworkings are essential to work of this type. Particularly important are the locations of major roadways and their condition. A detailed knowledge of the distribution of different methods of extraction would enable more enlightened assessment of flow regimes and likely storage capacity.

The storage coefficient is likely to be the most important parameter in any model of mineworkings. Data regarding changes in water level are therefore invaluable, whether from deliberate temporary cessation of pumping or pump failure. Values of hydraulic conductivity in different parts of a coalfield would help to define the flow regime and are essential for some types of modelling approach. A detailed head distribution would also be invaluable for calibration purposes.

A proper appreciation of surface hydrology would allow accurate estimates of recharge to the mineworkings over time. As would detailed data regarding inflow from the sea, adjacent aquifers and the unworked strata.

Time series of the chemistry of pumped waters prior to any treatment would help when assessing the potential for polluting discharges. The most useful data would be collected when groundwater levels rise beyond normal seasonal fluctuations due to temporary cessation of pumping.

Collection of data regarding the percentage of the sulphur which is pyritic, the percentage of the pyritic sulphur which is oxidised and the heights of mixing zones in a range of coalfields would enable estimates of these major sources of uncertainty to be made more accurately.

6.4.2 Further Work

The modelling of the Dysart-Leven Coalfield would be improved if accurate estimates of marine inflow to the workings in different collieries could be established.

If the iron component was applied to a coalfield where discharges are already occurring better estimates could be obtained of the percentage of the sulphur which is pyritic, the percentage of the pyritic sulphur which is oxidised and the height of mixing zones. These are the three parameters about which there is most uncertainty. The iron component could then be reapplied to the Dysart-Leven Coalfield.

Development of a more comprehensive water quality component would aid the planning of treatment techniques. The factors which most affect the choice of technique are: alkalinity, acidity, iron and aluminium content (see Section 2.3.2). Therefore, a water quality model which addressed all four of these factors would be of most use.

A useful development in GRAM would be the ability to model flow through partially full pipes. This would allow the diameters of the roadways to be represented in a way which is physically realistic.

In a situation where more data are available a good choice of existing model would be something of the fracture flow genre. Development of a more complex minewater model should concentrate on representing flow in three differing environments: the rock matrix, the goaf and along roadways.

A more complex model for representing flow in abandoned mineworkings is under development. This couples SHETRAN (version 4.1) to a pipe network model. SHETRAN is a physically based distributed modelling system which incorporates a Variably Saturated Subsurface (VSS) component. The VSS component is capable of simulating flow in the combination of saturated and unsaturated conditions found in abandoned mineworkings (Adams and Younger, 1997). The pipe network component will simulate turbulent flow in open roadways, shafts and adits. This model will be used in cases where more extensive data sets are available.

6.5 Concluding Comments

The availability and reliability of data will always be a limiting factor when modelling the mineworking environment. GRAM has been developed to make the best use of available data. The performance of GRAM compares favourably against that of MODFLOW, which was unable to cope with the complex environment and the limited data sets.

GRAM was able to predict the timing and quality of potential discharges from the Dysart-Leven Coalfield. The iron component could be applied successfully if good estimates of the three types of data over which there is most uncertainty are obtained. This would give an indication of overall water quality of the potential discharges.

APPENDIX 1

FORTRAN CODE

```
      PROGRAM WINGRAM

*     THIS IS THE GENERIC VERSION OF GRAM
*     THIS IS A LUMPED PARAMETER MODEL OF GROUNDWATER REBOUND
*     THROUGH WORKED COAL MEASURES

      INTEGER STEP,STOP,TIM(6,10),REPEAT,CONNN(15),NIRON(6)
      INTEGER NPCONN,NPONDS,NRAIN,EQN,STORTR,NSTOR(6),IRONTR,DSTART(6)
      INTEGER DISN(6),J,J2,STE,MC,NRSPR,PUMPTR,OUTTR,OUTV
      INTEGER CONNP1(15),CONNP2(15),MCSTR,MCRTR,MCKTR,MCPN
      INTEGER MCPID(5),MCPNC(5),NPUMP(6),NOUT,OUTA(250)
      REAL AREA(6),AREALA(6),EFRAIN(6),EVAP,HEIGHT(6)
      REAL INF(6),HLAST(6),PRSPR(31)
      REAL PDRO(6),PUMP(6),QSURF(6,10),DISKIN(6,10)
      REAL RAIN(6,30),RECH(6),SEEP(6),STORE(6),RAININ
      REAL AVSURF(6,10),TSURF(6,10),CONKIN(15,6)
      REAL CONNH(15,6),CONNK(15,6),CONND(15,6),CONNL(15,6)
      REAL DUMMY,DISH(6,10),DISK(6,10),DISD(6,10),DISL(6,10)
      REAL STORAT(6,2,100),MOLIRO(6),MOLIROZ(6),RDEN,RMASS,OHEIGHT(6)
      REAL SULPH(6,3,100),CONTAC,AWS,AWI,TEMP,IRONR,IRONS,HMIX(6)
      REAL TIRONR,TIRONS,TIRONC,SURFI(6,10),TSURFI(6,10),AVSUI(6,10)
      REAL PUMPA(6,2,250),WHIND(6)

*     DEFINITIONS
*     AREA = AREA OF POND (m2)
*     AREALA = AREA OF POND WHICH IS LAND (m2)
*     AVSUI = AVERAGE SURFACE IRON VOLUME IN DISCHARGE
*     AVSURF = AVERAGE SURFACE FLOW OVER TIME
*     AWI = ATOMIC WEIGHT OF IRON
*     AWS = ATOMIC WEIGHT OF SULPHUR
*     CONNN = ROADWAY NUMBER
*     CONNH = ROADWAY HEIGHT
*     CONNK = ROADWAY ROUGHNESS
*     CONKIN = ROADWAY KINEMATIC VISCOSITY
*     CONND = ROADWAY DIAMETER
*     CONNL = ROADWAY LENGTH
*     CONNP1 = ROADWAY CONNECTION TO POND
*     CONNP2 = ROADWAY CONNECTION TO POND
*     CONTAC = PERCENTAGE OF IRON THAT WATER COMES INTO CONTACT WITH
*     DISN = DISCHARGE NUMBER
*     DISH = DISCHARGE HEIGHT
*     DISK = DISCHARGE ROUGHNESS
*     DISKIN = DISCHARGE KINEMATIC VISCOSITY
*     DISD = DISCHARGE DIAMETER
*     DISL = DISCHARGE LENGTH
*     DSTART = IF DISCHARGE STARTED
*     DUMMY = RANDOM NUMNER SEED VALUE
*     EFRAIN = EFFECTIVE RAINFALL (m)
*     EQN = WHICH PIPEFLOW EQUATION
*     EVAP = EVAPORATION (m)
*     HEIGHT = LEVEL OF WATER IN POND (m)
*     HLAST = LEVEL OF WATER IN PREVIOUS TIME STEP (m)
*     HMIX = HEIGHT OF BOTTOM OF MIXING ZONE
*     INF = INFILTRATION INTO POND
*     IRONR = VOLUME OF IRON IN RECHARGE
*     IRONS = VOLUME OF IRON IN MARINE INFLOW
*     IRONTR = WHETHER IRON IS BEING USED
*     J = COUNTER
*     J2 = COUNTER
```

```
*   MC = LOOP
*   MCKTR = WHETHER THE ROUGHNESS OF A PIPE IS BEING USED IN MONTE CARLO
SIMULATION
*   MCPID = THE NUMBER CONNECTION BETWEEEN PONDS OF THE PIPES BEING USED IN
MONTE CARLO SIMULATION
*   MCPN = HOW MANY PIPES ARE BEING USED IN MONTE CARLO SIMULATION
*   MCPNC = THE NUMBER OF THE CONNECTION OF THE PIPES BEING USED IN MONTE
CARLO SIMULATION
*   MCRTR = WHETHER PDRO IS BEING USED IN MONTE CARLO SIMULATION
*   MCSTR = WHETHER STORAGE IS BEING USED IN MONTE CARLO SIMULATION
*   MOLIRO = MOLES OF IRON IN POND
*   MOLIROZ = MOLES OF IRON IN MIXING ZONE IN POND
*   NIRON = NUMBER OF IRON DATA
*   NOUT = NUMBER OF OUTPUT DATA
*   NPCONN = NUMBER OF POND CONNECTIONS
*   NPONDS = NUMBER OF PONDS
*   NPUMP = NUMBER OF PUMPING VALUES
*   NRAIN = NUMBER OF RAINFALL DATA
*   NRSPR = NUMBER OF RAINFALL ATTENUATION DATA
*   NSTOR = NUMBER OF STORAGE DATA
*   OHEIGHT = INITIAL WATER LEVELS
*   OUTA = ARRAY OF OUTPUT DATA TIMES
*   OUTTR = OUTPUT AT SPECIFIC VALUES ONLY
*   OUTV = OUTPUT AT MULTIPLIER ONLY
*   PDRO = PERCENTAGE DIRECT RUNOFF INTO RIVER
*   PRSPR = RAINFALL ATTENUATION ARRAY
*   PUMP = AMOUNT OF WATER PUMPED FROM EACH POND
*   PUMPA = ARRAY OF PUMPING VALUES
*   PUMPTR = PUMPING VARYING WITH TIME AT SPECIFIC VALUES
*   QSURF = SURFACE DISCHARGES IN EACH POND
*   RAIN = RAINFALL (m)
*   RAININ = RAINFALL (NOT EFFECTIVE RAINFALL)
*   RDEN = ROCK DENSITY
*   RECH = RECHARGE INTO POND (m)
*   REPEAT = WHICH MC VALUE IS IN USE
*   SEEP = AMOUNT OF SEEPAGE FROM LIMESTONE (m3)
*   STEP = COUNTER OF TIMESTEP LOOP
*   STE = TEMPORARY STEP VALUE
*   STOP = MAXIMUM VALUE OF TIMESTEP
*   STORAT = ARRAY OF VARYING STORATIVITY / SPECIFIC STORAGE OF POND
*   STORE = STORATIVITY / SPECIFIC STORAGE OF POND
*   STORTR = WHETHER STORAGE IS BEING USED
*   SULPH = SULPHUR CONTENT
*   SURFI = SURFACE IRON VOLUME DISCHARGE
*   TEMP = TEMPORARY VALUE
*   TIM = TIME TAKEN TO REBOUND TO THE SURFACE
*   TIRONC = TOTAL IRON FROM CONTACT WITH PYRITE
*   TIRONR = TOTAL IRON FROM RECHARGE
*   TIRONS - TOTAL IRON FROM MARINE INFLOW
*   TSURF = TOTAL SURFACE FLOW
*   TSURFI = TOTAL SURFACE IRON DISCHARGE
*   WHIND = FLOW OTHER MINES OR AQUIFERS

      DATA TIM,AVSURF,TSURF,REPEAT/181*0/
      DATA AREA,AREALA,EFRAIN,EVAP,HEIGHT,EQN/26*0/
      DATA INF,HLAST,RAININ/13*0/
      DATA RAIN,STE,MC,NRSPR,PRSPR/214*0/
      DATA PDRO,PUMP,QSURF,NPONDS,NPCONN,DSTART/80*0/
      DATA RECH,SEEP,STORE,NRAIN/19*0/
      DATA CONNN,CONNH,CONNK,CONND,CONNL,CONKIN/465*0/
```

```
      DATA CONNP1,CONNP2,MCPID,MCPNC/40*0/
      DATA DISN,DISH,DISK,DISD,DISL,DISKIN/306*0/
      DATA STORTR,NSTOR,STORAT/1207*0/
      DATA MOLIRO,RDEN,RMASS,CONTAC,AWS,AWI,IRONTR,NIRON/18*0/
      DATA SULPH,IRONR,IRONS,TIRONR,TIRONS,TIRONC,OHEIGHT/1811*0/
      DATA SURFI,TSURFI,AVSUI,MOLIROZ,HMIX/192*0/
      DATA PUMPTR,OUTTR,OUTV,NPUMP,NOUT,OUTA,PUMPA/3260*0/
      DATA WHIND/6*0/

*     READ IN SCENARIOS
      OPEN(10,FILE='C:\WINGRAM\INPUT\SCEN.INP')

      READ(10,*) NPONDS
      READ(10,*) NPCONN
      READ(10,*) NRAIN
      READ(10,*) MC
      READ(10,*) STOP
      READ(10,*) EQN
      READ(10,*) STORTR
      IF (STORTR.EQ.1) READ(10,*) (NSTOR(J), J=1,NPONDS)
      READ(10,*) IRONTR
      IF (IRONTR.EQ.1) READ(10,*) (NIRON(J), J=1,NPONDS)
      READ(10,*) PUMPTR
      IF (PUMPTR.EQ.1) READ(10,*) (NPUMP(J), J=1,NPONDS)
      READ(10,*) OUTTR
      IF (OUTTR.EQ.0) READ(10,*) OUTV
      CLOSE(10)

      PRINT *,'      *** WINGRAM IS RUNNING *** '

      OPEN(11,FILE='C:\WINGRAM\INPUT\RDATA.DAF',FORM='FORMATTED',
     +ACCESS='DIRECT',RECL=7)
      OPEN(12,FILE='C:\WINGRAM\DATA\TIMES.DAT')
      OPEN(13,FILE='C:\WINGRAM\DATA\AVQ.DAT')
      OPEN(29,FILE='C:\WINGRAM\DATA\AVI.DAT')
      OPEN(21,FILE='C:\WINGRAM\DATA\BAL.DAT')
      OPEN(14,FILE='C:\WINGRAM\DATA\HEIGHT.DAT')
      IF (IRONTR.EQ.0) THEN
      IF (NPONDS.GE.1) OPEN(15,FILE='C:\WINGRAM\DATA\SURF1.DAT')
      IF (NPONDS.GE.2) OPEN(16,FILE='C:\WINGRAM\DATA\SURF2.DAT')
      IF (NPONDS.GE.3) OPEN(17,FILE='C:\WINGRAM\DATA\SURF3.DAT')
      IF (NPONDS.GE.4) OPEN(18,FILE='C:\WINGRAM\DATA\SURF4.DAT')
      IF (NPONDS.GE.5) OPEN(19,FILE='C:\WINGRAM\DATA\SURF5.DAT')
      IF (NPONDS.GE.6) OPEN(20,FILE='C:\WINGRAM\DATA\SURF6.DAT')
      ELSE
      IF (NPONDS.GE.1) OPEN(30,FILE='C:\WINGRAM\DATA\IRON1.DAT')
      IF (NPONDS.GE.2) OPEN(31,FILE='C:\WINGRAM\DATA\IRON2.DAT')
      IF (NPONDS.GE.3) OPEN(32,FILE='C:\WINGRAM\DATA\IRON3.DAT')
      IF (NPONDS.GE.4) OPEN(33,FILE='C:\WINGRAM\DATA\IRON4.DAT')
      IF (NPONDS.GE.5) OPEN(34,FILE='C:\WINGRAM\DATA\IRON5.DAT')
      IF (NPONDS.GE.6) OPEN(35,FILE='C:\WINGRAM\DATA\IRON6.DAT')
      ENDIF

      DUMMY=RAN1(-13)

*     START OF MONTE CARLO LOOP
      DO 1200 REPEAT=1,MC

      DO 1210 J=1,NPONDS
      DO 1220 J2=1,10
```

```
      TSURF(J,J2)=0
      QSURF(J,J2)=0
      AVSURF(J,J2)=0
      TIM(J,J2)=0
      SURFI(J,J2)=0
      TSURFI(J,J2)=0
      AVSUI(J,J2)=0
1220 CONTINUE
      DSTART(J)=0
      MOLIRO(J)=0
      MOLIROZ(J)=0
1210 CONTINUE

*    READ IN POND DATA

   OPEN(22,FILE='C:\WINGRAM\INPUT\PONDAT.INP')
   READ(22,*) EVAP
   EVAP=EVAP/1000
   EVAP=EVAP/365
   DO 1230 J=1,NPONDS
      READ(22,*) AREA(J)
      READ(22,*) AREALA(J)
      READ(22,*) STORE(J)
      READ(22,*) HEIGHT(J)
      OHEIGHT(J) = HEIGHT(J)
      READ(22,*) PDRO(J)
      READ(22,*) PUMP(J)
      READ(22,*) SEEP(J)
      READ(22,*) WHIND(J)
1230 CONTINUE
   CLOSE(22)

*    READ IN STORATIVITY DATA

   IF (STORTR.EQ.1) THEN
      OPEN(27,FILE='C:\WINGRAM\input\stordat.inp')
      DO 1232 J = 1, NPONDS
       DO 1234 J2 = 1, NSTOR(J)
        READ(27,*) STORAT(J,1,J2),STORAT(J,2,J2)
1234   CONTINUE
1232  CONTINUE
      CLOSE(27)
   ENDIF

*    READ IN IRON DATA

   IF (IRONTR.EQ.1) THEN
      OPEN(28,FILE='C:\WINGRAM\input\IRON.inp')

      READ(28,*) RDEN
      READ(28,*) AWS
      READ(28,*) AWI
      READ(28,*) CONTAC
      READ(28,*) IRONR
      READ(28,*) IRONS
      READ(28,*) (HMIX(J), J=1,NPONDS)

      DO 1236 J = 1, NPONDS
       DO 1238 J2 = 1, NIRON(J)
        READ(28,*) SULPH(J,1,J2),SULPH(J,2,J2),SULPH(J,3,J2)
```

```
1238    CONTINUE
1236   CONTINUE
        CLOSE(28)
     ENDIF

*    READ IN FLOW DATA

     IF (NPCONN.GT.0) THEN
     OPEN(23,FILE='C:\WINGRAM\INPUT\FLODAT.INP')
     DO 1240 J=1,NPCONN
        READ(23,*) CONNP1(J),CONNP2(J)
        READ(23,*) CONNN(J)
        DO 1250 J2=1,CONNN(J)
         READ(23,*) CONNH(J,J2),CONNK(J,J2),CONND(J,J2),CONNL(J,J2),
    +CONKIN(J,J2)
          CONNK(J,J2)=CONNK(J,J2)/1000
1250 CONTINUE
1240 CONTINUE
     CLOSE(23)
     ENDIF

*    READ IN DISCHARGE DATA

     OPEN(24,FILE='C:\WINGRAM\INPUT\DIS.INP')

     DO 1260 J=1,NPONDS
        READ(24,*) DISN(J)
        DO 1270 J2=1,DISN(J)
         READ(24,*) DISH(J,J2),DISK(J,J2),DISD(J,J2),DISL(J,J2),
    +DISKIN(J,J2)
         DISK(J,J2)=DISK(J,J2)/1000
1270 CONTINUE
1260 CONTINUE
     CLOSE(24)

*    READ IN RAINFALL SPREAD DATA

     OPEN(26,FILE='C:\WINGRAM\INPUT\RSPR.INP')
        READ(26,*) NRSPR
        DO 1280 J=1,NRSPR
         READ(26,*) PRSPR(J)
1280 CONTINUE
     CLOSE(26)

*    READ IN PUMPING DATA

     IF (PUMPTR.EQ.1) THEN
        OPEN(37,FILE='C:\WINGRAM\input\pumpdat.inp')
        DO 1282 J = 1, NPONDS
         DO 1284 J2 = 1, NPUMP(J)
          READ(37,*) PUMPA(J,1,J2),PUMPA(J,2,J2)
1284    CONTINUE
1282   CONTINUE
        CLOSE(37)
     ENDIF

*    READ IN OUTPUT ARRAY DATA

     IF (OUTTR.EQ.1) THEN
     OPEN(38,FILE–'C:\WINGRAM\INPUT\OUTDAT.INP')
```

```
        READ(38,*) NOUT
        DO 1285 J=1,NOUT
         READ(38,*) OUTA(J)
 1285 CONTINUE
      ENDIF
      CLOSE(38)


*   READ IN MONTE CARLO DATA
      IF(MC.GT.1) THEN
      OPEN(36,FILE='C:\WINGRAM\INPUT\MONTE.INP')
         READ(36,*) MCSTR
         READ(36,*) MCRTR
         READ(36,*) MCKTR
         IF (MCKTR.EQ.1) THEN
          READ(36,*) MCPN
          DO 1290 J = 1,MCPN
          READ(36,*) MCPID(J)
          READ(36,*) MCPNC(J)
 1290 CONTINUE
        ENDIF
        CLOSE(36)
      ENDIF

      IF (MC.GT.1) CALL MONTE(STORE,PDRO,CONNK,NPONDS,NPCONN,MCSTR,
     +MCRTR,MCKTR,MCPN,MCPID,MCPNC)

*   TIMESTEP LOOP
      DO 1300 STEP=1,STOP

*   MOVE RAIN ARRAY ON ONE
      DO 1305 J=1,NRSPR
      DO 1307 J2=1,NPONDS
      RAIN(J2,J)=RAIN(J2,(J+1))
 1307 CONTINUE
 1305 CONTINUE

*   READ IN RAINFALL DATA
      STE=STEP
      DO 1310 J=1,(INT(STOP/NRAIN)+1)
         IF (STE.GT.NRAIN) STE=STE-NRAIN
 1310 CONTINUE
      READ(UNIT=11,FMT=1320,REC=STE) RAININ
      RAININ=RAININ/1000
 1320 FORMAT (F6.2)

      DO 1350 J=1,NPONDS
      IF (HEIGHT(J).GE.0) SEEP(J)=0
 1350 CONTINUE

      DO 1360 J=1,NPONDS
         HLAST(J)=HEIGHT(J)
      DO 1370 J2=1,NPCONN
         QSURF(J,J2)=0
 1370 CONTINUE
 1360 CONTINUE

      IF (PUMPTR.EQ.1) CALL PVALS(PUMP,STEP,NPONDS,NPUMP,PUMPA)

      IF (STORTR.EQ.1) CALL SVALS(NSTOR,STORAT,STORE,NPONDS,HEIGHT)
```

```
      DO 1380 J=1,NPONDS

      CALL RECHRG(AREALA(J),PDRO(J),RAIN,EVAP,EFRAIN(J),RECH(J),
     +AREA(J),STORE(J),INF(J),PUMP(J),SEEP(J),RAININ,NRSPR,PRSPR,J,
     +IRONR,TIRONR,IRONS,TIRONS,AWS,NPONDS,WHIND(J),IRONTR)

*     CALCULATES CHANGE IN LEVEL OF POND
      HEIGHT(J)=HLAST(J)+RECH(J)

      IF ((IRONTR.EQ.1).AND.(RECH(J).GT.0)) CALL IRON(NSTOR(J),STORAT,
     +STORE(J),HEIGHT(J),J,HLAST(J),SULPH,AWS,RDEN,CONTAC,TIRONC,
     +AREA(J),NPONDS)

      IF (DSTART(J).EQ.0) THEN
*     ADDS MOLES OF IRON FROM RECHARGE, SEEPAGE AND COAL SEAMS TO TOTAL
      MOLIRO(J) = MOLIRO(J)+TIRONR+TIRONS+TIRONC
      TIRONR = 0
      TIRONS = 0
      TIRONC = 0
      ELSE
      MOLIROZ(J) = MOLIROZ(J)+TIRONR+TIRONS+TIRONC
      TIRONR = 0
      TIRONS = 0
      TIRONC = 0
      ENDIF

 1380 CONTINUE

      IF (NPCONN.GT.0) THEN
      CALL FLOW(HEIGHT,CONNN,CONNH,CONNK,CONND,CONNL,STEP,AREA
     +,STORE,NPCONN,EQN,CONKIN,MOLIRO,OHEIGHT,NSTOR,STORAT,SULPH
     +,AWS,RDEN,CONTAC,TIRONC,IRONTR,CONNP1,CONNP2,NPONDS)
      ENDIF

      DO 1390 J=1,NPONDS

      IF (EQN.EQ.1) CALL SURFCE(HEIGHT(J),AREA(J),STORE(J),
     +QSURF,TSURF,STEP,J,TIM,REPEAT,DISN,DISH,DISK,DISD,DISL,
     +MOLIRO(J),OHEIGHT(J),SURFI,TSURFI,AWI,DSTART(J),MOLIROZ(J),
     +HMIX(J),NPONDS,NPCONN)

      IF (EQN.EQ.2) CALL SURF2(HEIGHT(J),AREA(J),STORE(J),
     +QSURF,TSURF,STEP,J,TIM,REPEAT,DISN,DISH,DISK,DISD,DISL,DISKIN,
     +MOLIRO(J),OHEIGHT(J),SURFI,TSURFI,AWI,DSTART(J),MOLIROZ(J),
     +HMIX(J),NPONDS,NPCONN)

 1390 CONTINUE

      IF (MC.EQ.1) THEN
      CALL BAL(INF,HEIGHT,HLAST,AREA,STORE,PUMP,SEEP,NPONDS,WHIND)

      IF (OUTTR.EQ.1) THEN
      CALL PREOUT(QSURF,HEIGHT,REPEAT,STEP,SURFI,NPONDS,DISN,NOUT,
     +OUTA,IRONTR)
      ELSE
      IF (MOD(STEP,OUTV).EQ.0) CALL OUT(QSURF,HEIGHT,STEP,SURFI,
     +NPONDS,DISN,IRONTR)
      ENDIF
```

```
      ENDIF

 1300 CONTINUE
*     END OF TIME STEP LOOP

      CALL AVFLO(TSURF,TIM,AVSURF,REPEAT,STOP,DISN,NPONDS,TSURFI,AVSUI,
     +NPCONN)
      print*,repeat
      CALL OUTPUT(TIM,AVSURF,AVSUI,NPONDS,DISN)

 1200 CONTINUE
*     END OF MONTE CARLO LOOP

      CLOSE(11)
      CLOSE(12)
      CLOSE(13)
      CLOSE(21)
      CLOSE(29)
      CLOSE(14)
      IF (IRONTR.EQ.0) THEN
      IF (NPONDS.GE.1) CLOSE(15)
      IF (NPONDS.GE.2) CLOSE(16)
      IF (NPONDS.GE.3) CLOSE(17)
      IF (NPONDS.GE.4) CLOSE(18)
      IF (NPONDS.GE.5) CLOSE(19)
      IF (NPONDS.GE.6) CLOSE(20)
      ELSE
      IF (NPONDS.GE.1) CLOSE(30)
      IF (NPONDS.GE.2) CLOSE(31)
      IF (NPONDS.GE.3) CLOSE(32)
      IF (NPONDS.GE.4) CLOSE(33)
      IF (NPONDS.GE.5) CLOSE(34)
      IF (NPONDS.GE.6) CLOSE(35)
      ENDIF

      STOP
      END


*     SUBROUTINES

      SUBROUTINE MONTE(S,PR,CK,NP,NC,MS,MR,MK,MP,MID,MNC)

      INTEGER Z,RD,NP,MS,MR,MK,MP
      INTEGER MID(5),MNC(5)
      REAL S(6),PR(6),CK(15,6),RRD

*     CALCULATES MC VALUES

*     DEFINITIONS
*     CK = ROADWAY ROUGHNESS
*     MID = THE NUMBER CONNECTION BETWEEEN PONDS OF THE PIPES BEING USED IN
MONTE CARLO SIMULATION
*     MK = WHETHER THE ROUGHNESS OF A PIPE IS BEING USED IN MONTE CARLO
SIMULATION
*     MP = HOW MANY PIPES ARE BEING USED IN MONTE CARLO SIMULATION
*     MNC = THE NUMBER OF THE CONNECTION OF THE PIPES BEING USED IN MONTE
CARLO SIMULATION
*     MR = WHETHER PDRO IS BEING USED IN MONTE CARLO SIMULATION
*     MS = WHETHER STORAGE IS BEING USED IN MONTE CARLO SIMULATION
```

```
*   NC = NUMBER OF CONNECTIONS
*   NP = NUMBER OF PONDS
*   PR = PERCENTAGE OF DIRECT RUN-OFF INTO RIVER
*   RD = RANDOM NUMBER
*   RRD = REAL RANDOM NUMBER
*   S = STORATIVITY
*   Z = COUNTER

*   ADD MONTE CARLO FACTOR TO STORATIVITY VALUE
    IF (MS.EQ.1) THEN
    OPEN(25,FILE='C:\WINGRAM\INPUT\NORSTOR.DAF',FORM='FORMATTED',
   +ACCESS='DIRECT',RECL=8)

    DO 2000 Z=1,NP

        RRD=RAN1(123)
        RRD=RRD*1000
        RD=INT(RRD)
        IF (RD.GT.1000) RD=RD-1000
        IF (RD.EQ.0) RD=1000
        READ(UNIT=25,FMT=2020,REC=RD) S(Z)

2000 CONTINUE
        CLOSE(25)
    ENDIF

    IF (MR.EQ.1) THEN

    OPEN(23,FILE='C:\WINGRAM\INPUT\NORPDRO.DAF',FORM='FORMATTED',
   +ACCESS='DIRECT',RECL=8)

    DO 2010 Z=1,NP

        RRD=RAN1(123)
        RRD=RRD*1000
        RD=INT(RRD)
        IF (RD.GT.1000) RD=RD-1000
        IF (RD.EQ.0) RD=1000
        READ(UNIT=23,FMT=2030,REC=RD) PR(Z)

2010 CONTINUE
        CLOSE(23)
    ENDIF


    IF (MK.EQ.1) THEN
    DO 2015 Z=1,MP
    OPEN(24,FILE='C:\WINGRAM\INPUT\NORROU.DAF',FORM='FORMATTED',
   +ACCESS='DIRECT',RECL=10)

        RRD=RAN1(123)
        RRD=RRD*1000
        RD=INT(RRD)
        IF (RD.GT.2000) RD=RD-2000
        IF (RD.GT.1000) RD=RD-1000
        IF (RD.EQ.0) RD=999
        IF (RD.LT.0) RD=999
        READ(UNIT=24,FMT=2025,REC=RD) CK(MID(MP),MNC(MP))

        IF (CK(MID(MP),MNC(MP)).LT.0) THEN
```

```
       RRD=RAN1(123)
       RRD=RRD*1000
       RD=INT(RRD)
       IF (RD.GT.2000) RD=RD-2000
       IF (RD.GT.1000) RD=RD-1000
       IF (RD.EQ.0) RD=999
       IF (RD.LT.0) RD=999
       READ(UNIT=24,FMT=2025,REC=RD) CK(MID(MP),MNC(MP))
      ENDIF

      CLOSE(24)
 2015 CONTINUE
   ENDIF

 2020 FORMAT (F7.5)
 2025 FORMAT (F9.4)
 2030 FORMAT (F7.4)

   RETURN
   END

   SUBROUTINE RECHRG(AL,PR,R,E,ER,RE,A,S,I,PU,SE,RI,NRS,PRS,Y8,
  +IR,TIR,IS,TIS,AW,NP,WD,IT)
   INTEGER Y7,NRS,Y8,NP,IT
   REAL AL,PR,R(6,30),E,ER,RE,A,S,I,PU,SE,RI,PRS(31),IR,TIR,IS,TIS
   REAL AW,WD

*   CALCULATES RECHARGE INTO POND

*   DEFINITIONS
*   A = AREA OF POND
*   AL = AREA OF LAND
*   AW = ATOMIC WEIGHT OF SULPHUR
*   E = EVAPORATION
*   ER = EFFECTIVE RAINFALL
*   I = INFILTRATION
*   IR = VOLUME OF IRON IN RECHARGE
*   IS = VOLUME OF IRON IN MARINE INFLOW
*   IT = WHETHER IRON IS BEING USED
*   NP = NUMBER OF PONDS
*   NRS = NUMBER OF RAINFALL IN ATTENUATION DATA
*   PU = AMOUNT PUMPED
*   PR = PERCENTAGE OF DIRECT RUN-OFF INTO RIVER
*   PRS = RAINFALL ATTENUATION ARRAY
*   R = RAINFALL
*   RE = RECHARGE
*   RI = RAINFALL
*   S = STORATIVITY
*   SE = SEEPAGE
*   TIR = TOTAL IRON FROM RECHARGE
*   TIS = TOTAL IRON FROM MARINE INFLOW
*   WD = FLOW FROM OTHER MINES OR AQUIFERS
*   Y7 = COUNTER
*   Y8 = COUNTER OF PONDS

   ER=RI-E
   IF (ER.LT.0) ER=0

   DO 2050 Y7=1,NRS
```

```
      R(Y8,Y7)=R(Y8,Y7)+(ER*PRS(Y7))
 2050 CONTINUE

      I=R(Y8,1)*(1-(PR/100))*AL
      RE=I/(A*S)

*     REMOVES PUMPED WATER FROM RECHARGE

      IF (PU.LT.-0.5) THEN
         RE=0
      ELSE
         RE=RE - SPREAD(A,PU,S)
      ENDIF

*     ADDS SEEPAGE FROM SEA

      IF (SE.GT.0) THEN
         RE=RE + SPREAD(A,SE,S)
      ENDIF

*     ADDS WATER FROM OTHER MINES OR AQUIFERS

      IF (WD.GT.0) THEN
         RE=RE + SPREAD(A,WD,S)
      ENDIF


*     CALCULATES VOLUMES OF IRON FROM RECHARGE AND SEEPAGE
      IF (IT.EQ.1) THEN

      IF (I.GT.0) THEN
      TIR =((IR*I)/AW)/2
      ELSE
      TIR = 0
      ENDIF

      IF (SE.GT.0) THEN
      TIS = ((IS*SE)/AW)/2
      ELSE
      TIS = 0
      ENDIF

      ENDIF
      RETURN
      END


      SUBROUTINE FLOW(H,CN,CH,CK,CD,CL,N,A,S,NPC,E,CKIN,MI,OH,NS,STO,
     +SUL,AW,RD,CT,TIC,IT,CP1,CP2,NP)

      INTEGER NP,NPC
      INTEGER CN(15),N,Y2,Y,E,IT,CP1(15),CP2(15)
      REAL H(6),CH(15,6),CK(15,6),CD(15,6),CL(15,6)
      REAL CKIN(15,6)
      REAL HA,HB,J,A(6),S(6),Q,MI(6),OH(6),NS(6),STO(6,2,100)
      REAL SUL(6,2,100),AW,RD,CT,TIC

*     CALCULATES FLOW BETWEEN PONDS

*     DEFINITIONS
```

```
*   A = AREA OF POND
*   AW = ATOMIC WEIGHT OF SULPHUR
*   CN = ROADWAY NUMBER
*   CH = ROADWAY HEIGHT
*   CK = ROADWAY ROUGHNESS
*   CKIN = ROADWAY KINEMATIC VISCOSITY
*   CD = ROADWAY DIAMETER
*   CL = ROADWAY LENGTH
*   CP1 = ROADWAY POND 1
*   CP2 = ROADWAY POND 2
*   CT = PERECENTAGE OF IRON THAT WATER COMES INTO CONTACT WITH
*   DST = WHETHER DISCHARGE HAS STARTED
*   E = WHICH PIPEFLOW EQUATION
*   H = LEVEL OF WATER IN POND (m)
*   HA = LEVEL OF WATER IN POND (m)
*   HB = LEVEL OF WATER IN POND (m)
*   IT = WHETHER IRON IS BEING USED
*   MI = MOLES OF IRON IN POND
*   N = STEP
*   NP = NUMBER OF PONDS
*   NPC = NUMBER OF POND CONNECTIONS
*   NS = NUMBER OF STORAGE DATA
*   OH = INITIAL WATER LEVELS
*   Q = DISCHARGE THROUGH ROADWAY
*   RD = ROCK DENSITY
*   S = STORATIVITY
*   STO = ARRAY OF VARYING STORATIVITY
*   SUL = SULPHUR CONTENT
*   TIC = TOTAL IRON FROM CONTACT WITH PYRITE
*   VEL = VELOCITY THROUGH ROADWAY
*   Y = COUNTER
*   Y2 = COUNTER

      DO 2100 Y2=1,NPC
      DO 2110 Y=1,CN(Y2)
      IF (CD(Y2,Y).GT.0) THEN
      IF (E.EQ.1) Q = PFLOW(H(CP1(Y2)),H(CP2(Y2)),CD(Y2,Y),CH(Y2,Y),
     +CL(Y2,Y),CK(Y2,Y))
      IF (E.EQ.2) Q = PFLW2(H(CP1(Y2)),H(CP2(Y2)),CD(Y2,Y),CH(Y2,Y),
     +CL(Y2,Y),CK(Y2,Y),CKIN(Y2,Y))

      H(CP1(Y2)) = H(CP1(Y2)) - SPREAD(A(CP1(Y2)),Q,S(CP1(Y2)))
      H(CP2(Y2)) = H(CP2(Y2)) + SPREAD(A(CP2(Y2)),Q,S(CP2(Y2)))

      IF ((MI(CP1(Y2)).GT.0).AND.(Q.GT.0)) THEN
      MI(CP1(Y2)) = MI(CP1(Y2))-((Q/((H(CP1(Y2))-OH(CP1(Y2)))*
     +A(CP1(Y2))))*MI(CP1(Y2)))
      MI(CP2(Y2)) = MI(CP2(Y2))+((Q/((H(CP1(Y2))-OH(CP1(Y2)))*
     +A(CP1(Y2))))*MI(CP1(Y2)))
      CALL IRON(NS(CP2(Y2)),STO,S(CP2(Y2)),H(CP2(Y2)),CP2(Y2),HB,
     +SUL,AW,RD,CT,TIC,A(CP2(Y2)),NP)
      MI(CP2(Y2)) = MI(CP2(Y2))+TIC
      TIC = 0
      ENDIF

      IF ((MI(CP2(Y2)).GT.0).AND.(Q.LT.0)) THEN
      MI(CP1(Y2))   MI(CP1(Y2))-((Q/((H(CP2(Y2))-OH(CP2(Y2)))*
     +A(CP2(Y2))))*MI(CP2(Y2)))
      MI(CP2(Y2))   MI(CP2(Y2))+((Q/((H(CP2(Y2))-OH(CP2(Y2)))*
     +A(CP2(Y2))))*MI(CP2(Y2)))
```

```
      CALL IRON(NS(CP1(Y2)),STO,S(CP1(Y2)),H(CP1(Y2)),CP1(Y2),HA,
     +SUL,AW,RD,CT,TIC,
     +A(CP1(Y2)),NP)
      MI(CP1(Y2)) = MI(CP1(Y2))+TIC
      TIC = 0
      ENDIF

      ENDIF
 2110 CONTINUE
 2100 CONTINUE

      RETURN
      END


      SUBROUTINE SURFCE(H,A,S,QS,TS,N,Y,T,REP,DN,DH,DK,DD,DL,MI,OH,
     +SI,TSI,AW,DST,MIZ,MH,NP,NPC)

      INTEGER NP,NPC
      INTEGER N,Y,T(6,10),REP,DN(6),J4,DST
      REAL H,A,S,DH(6,10),DK(6,10),DD(6,10),DL(6,10),AW,MIZ,MH
      REAL APIPE,LAMBDA,VEL,QS(6,10),TS(6,10),MI,OH,SI(6,10)
      REAL TSI(6,10)

*     DEFINITIONS
*     A = AREA OF POND
*     APIPE = CROSS-SECTIONAL AREA OF PIPE
*     AW = ATOMIC WEIGHT OF SULPHUR
*     DN = NUMBER OF DISCHARGES
*     DH = HEIGHT OF DISCHARGES
*     DK = ROUGHNESS OF DISCHARGES
*     DD = DIAMETER OF DISCHARGES
*     DL = LENGTH OF DISCHARGES
*     DST = WHETHER DISCHARGE HAS STARTED
*     H = LEVEL OF WATER IN POND
*     HP = LEVEL OF WATER BELOW WHICH THERE IS NO SURFACE FLOW
*     HS = LEVEL OF WATER ABOVE SURFACE OF POND
*     J4 = COUNTER
*     LAMBDA = LAMBDA
*     MH = HEIGHT OF BOTTOM OF MIXING ZONE
*     MI = MOLES OF IRON IN POND
*     MIZ = MOLES OF IRON IN MIXING ZONE IN POND
*     N = STEP
*     NP = NUMBER OF PONDS
*     NPC = NUMBER OF POND CONNECTIONS
*     OH = INITIAL WATER LEVELS
*     QS = DISCHARGE AT SURFACE
*     REP = WHICH MC VALUE IS IN USE
*     S = STORATIVITY
*     SI = SURFACE IRON VOLUME DISCHARGE
*     T = TIME TAKEN TO REBOUND TO THE SURFACE
*     TS = TOTAL SURFACE FLOW
*     TSI = TOTAL SURFACE IRON DISCHARGE
*     VEL = VELOCITY
*     Y = POND

      DO 2200 J4=1,DN(Y)

*     STORES TIME WHEN POND REBOUNDS TO SURFACE AND CREATES MIXING ZONE
      IF (H.GT.DH(Y,J4)) THEN
```

```
      IF (T(Y,J4).EQ.0) T(Y,J4)=N
      IF (DST.EQ.0) THEN
      DST = 1
      MIZ = ((H-MH)/(H-OH))*MI
      MI = MI - MIZ
      ENDIF
   ENDIF

*   CALCULATES DISCHARGE AT SURFACE OF POND

   IF (H.GE.(DH(Y,J4)+DD(Y,J4))) THEN
   IF (DD(Y,J4).GT.0) THEN
      APIPE = (3.14159*DD(Y,J4)*DD(Y,J4))/4
      LAMBDA = (1/(2*(ALOG10(3.7*DD(Y,J4)/DK(Y,J4)))))
  +*(1/(2*(ALOG10(3.7*DD(Y,J4)/DK(Y,J4)))))
      VEL = SQRT((2*9.81*(H-DH(Y,J4)))/(1.5+(LAMBDA*DL(Y,J4)/
  +DD(Y,J4))))
      QS(Y,J4) = (APIPE*VEL)
      QS(Y,J4)=QS(Y,J4)*60*60*24
*    CONVERTED TO M3/DAY
      H = H-SPREAD(A,QS(Y,J4),S)
   ENDIF
   ENDIF

*   CALCULATES TOTAL SURFACE FLOW
   TS(Y,J4)=TS(Y,J4)+QS(Y,J4)

*   CALCULATES VOLUME OF IRON IN SURFACE FLOW

   IF (QS(Y,J4).GT.0) THEN
   IF (MIZ.GT.0) THEN
      SI(Y,J4) = (QS(Y,J4)/((H-MH)*A))*MIZ
      MIZ = MIZ - SI(Y,J4)
   ELSE
      SI(Y,J4) = 0
   ENDIF
   ELSE
      SI(Y,J4) = 0
   ENDIF

   IF (SI(Y,J4).GT.0) THEN

*   CONVERT MOLES TO G/M3 = MG/L
      SI(Y,J4) = (SI(Y,J4)/QS(Y,J4))*AW

*   SUMS TOTAL TO BE AVERAGED
      TSI(Y,J4) = TSI(Y,J4)+SI(Y,J4)

   ENDIF

2200 CONTINUE

   RETURN
   END


   SUBROUTINE SURF2(H,A,S,QS,TS,N,Y,T,REP,DN,DH,DK,DD,DL,DKIN,MI,
  +OH,SI,TSI,AW,DST,MIZ,MH,NP,NPC)

   INTEGER NP,NPC
```

```
      INTEGER N,Y,T(6,10),REP,DN(6),J4,Y2,J6,DST
      REAL H,A,S,DH(6,10),DK(6,10),DD(6,10),DL(6,10)
      REAL DKIN(6,10),MIZ,MH,MI,AW
      REAL QS(6,10),TS(6,10),DS,APIP,HM,OH,SI(6,10),TSI(6,10)
      DOUBLE PRECISION DVEL,DVEL2

*     DEFINITIONS
*     A = AREA OF POND
*     APIP = CROSS-SECTIONAL AREA OF PIPE
*     AW = ATOMIC WEIGHT OF SULPHUR
*     DN = NUMBER OF DISCHARGES
*     DH = HEIGHT OF DISCHARGES
*     DK = ROUGHNESS OF DISCHARGES
*     DKIN = KINEMATIC VISCOSITY OF DISCHARGES
*     DD = DIAMETER OF DISCHARGES
*     DL = LENGTH OF DISCHARGES
*     DN = NUMBER OF DISCHARGES
*     DS = HEAD GRADIENT
*     DST = WHETHER DISCHARGE HAS STARTED
*     DVEL =  VELOCITY
*     DVEL2 = VELOCITY
*     H = LEVEL OF WATER IN POND
*     HM = MINOR HEAD LOSS
*     HP = LEVEL OF WATER BELOW WHICH THERE IS NO SURFACE FLOW
*     HS = LEVEL OF WATER ABOVE SURFACE OF POND
*     J4 = COUNTER
*     J6 = COUNTER
*     MH = HEIGHT OF BOTTOM OF MIXING ZONE
*     MI = MOLES OF IRON IN POND
*     MIZ = MOLES OF IRON IN MIXING ZONE IN POND
*     N = STEP
*     OH = INITIAL WATER LEVELS
*     QS = DISCHARGE AT SURFACE
*     REP = WHICH MC VALUE IS IN USE
*     S = STORATIVITY
*     SI = SURFACE IRON VOLUME DISCHARGE
*     T = TIME TAKEN TO REBOUND TO THE SURFACE
*     TS = TOTAL SURFACE FLOW
*     TSI = TOTAL SURFACE IRON DISCHARGE
*     Y = POND

      DO 2210 J4=1,DN(Y)

*     STORES TIME WHEN POND REBOUNDS TO SURFACE
      IF (H.GT.DH(Y,J4)) THEN
         IF (T(Y,J4).EQ.0) T(Y,J4)=N
         IF (DST.EQ.0) THEN
         DST = 1
         MIZ = ((H-MH)/(H-OH))*MI
         MI = MI - MIZ
         ENDIF
      ENDIF

*     CALCULATES DISCHARGE AT SURFACE OF POND
      IF (H.GE.(DH(Y,J4)+DD(Y,J4))) THEN
      IF (DD(Y,J4).GT.0) THEN
         DVEL2 = 0
         APIP = (3.14159*DD(Y,J4)*DD(Y,J4))/4
         DS = (H-DH(Y,J4))/DL(Y,J4)
         CONV = 0
```

```
      DO 2220 J6 = 1,1000
        IF (CONV.EQ.0) THEN
      DVEL = -2*(SQRT(19.62*DD(Y,J4)*DS))*(ALOG10((DK(Y,J4)/(3.7*
     +DD(Y,J4)))+((2.51*DKIN(Y,J4))/(DD(Y,J4)*SQRT(19.62*DD(Y,J4)*
     +DS)))))
        HM = (1.5*DVEL*DVEL)/19.62
        DS = (H-DH(Y,J4)-HM)/DL(Y,J4)
          IF (DS.LE.0) THEN
          PRINT*,'HEADLOSS DUE TO ENTRY AND EXIT LOSS IS GREATER
     +THAN THE TOTAL HEAD.  THINK ABOUT YOUR CALIBRATION.  THE PIPE
     +PROPERTIES ARE    ',H,DH(Y,J4),DD(Y,J4),DK(Y,J4),DKIN(Y,J4)
          DVEL=0
          CONV=1
          ENDIF
        IF (ABS(DVEL2-DVEL).LT.0.00001) THEN
          CONV = 1
        ELSE
        IF (J6.EQ.1000.AND.CONV.EQ.0) PRINT*,'SF ITERATION HAS NOT
     +CONVERGED',N,DH(Y,J4),H,DVEL,DVEL2,DS,Y,J4,A
           DVEL2=DVEL
          ENDIF
          ENDIF
 2220    CONTINUE

        QS(Y,J4) = (APIP*DVEL)
        QS(Y,J4)=QS(Y,J4)*60*60*24
*      CONVERTED TO M3/DAY
         H = H-SPREAD(A,QS(Y,J4),S)
      ENDIF
      ENDIF

*     CALCULATES TOTAL SURFACE FLOW
      TS(Y,J4)=TS(Y,J4)+QS(Y,J4)

*     CALCULATES VOLUME OF IRON IN SURFACE FLOW

      IF (QS(Y,J4).GT.0) THEN
      IF (MIZ.GT.0) THEN
          SI(Y,J4) = (QS(Y,J4)/((H-MH)*A))*MIZ
          MIZ = MIZ - SI(Y,J4)
       ELSE
          SI(Y,J4) = 0
       ENDIF
       ELSE
          SI(Y,J4) = 0
        ENDIF

        IF (SI(Y,J4).GT.0) THEN

*       CONVERT MOLES TO G/M3 = MG/L
           SI(Y,J4) = (SI(Y,J4)/QS(Y,J4))*AW

*       SUMS TOTAL TO BE AVERAGED
            TSI(Y,J4) = TSI(Y,J4)+SI(Y,J4)

         ENDIF

 2210 CONTINUE

         RETURN
```

```
      END


      SUBROUTINE AVFLO(TS,T,AVS,REP,ST,DN,NP,TSI,AVSI,NPC)
      INTEGER NP,NPC
      REAL TS(6,10),AVS(6,10),AVSI(6,10),TSI(6,10)
      INTEGER Y,T(6,10),REP,DN(6),ST

*     CALCULATES AVERAGE FLOW

*     DEFINITIONS
*     AVS = AVERAGE SURFACE FLOW
*     AVSI = AVERAGE SURFACE IRON VOLUME IN DISCHARGE
*     DN = NUMBER OF DISCHARGES
*     NP = NUMBER OF PONDS
*     REP = WHICH MC VALUE IS IN USE
*     ST =  MAXIMUM VALUE OF TIMESTEP
*     TS = TOTAL SURFACE FLOW
*     TSI = TOTAL SURFACE IRON DISCHARGE
*     T = TIME
*     Y = POND

      DO 2300 Y=1,NP
      DO 2310 J4=1,DN(Y)
      AVS(Y,J4)=(TS(Y,J4)/((ST-T(Y,J4))))
*     IN m3/d

      AVSI(Y,J4)=(TSI(Y,J4)/((ST-T(Y,J4))))

 2310 CONTINUE
 2300 CONTINUE

      RETURN
      END


      SUBROUTINE PREOUT(QS,H,REP,ST,SI,NP,DN,NO,OA,IT)
      INTEGER NP,DN(6),NO
      REAL QS(6,10),H(6),SI
      INTEGER ST,REP,Y,OA(250)

*     CALCULATES WHEN TO OUTPUT DATA

*     DEFINITIONS
*     H = WATER LEVEL
*     IT = WHETHER IRON IS BEING USED
*     NP = NUMBER OF PONDS
*     NPC = NUMBER OF POND CONNECTIONS
*     NO = NUMBER OF OUTPUT DATA
*     OA = ARRAY OF OUTPUT DATA
*     PT = ARRAY OF PUMPING VALUES USED
*     QS = SURFACE DISCHARGE IN EACH POND
*     REP = WHICH MC VALUE IS IN USE
*     ST = STEP
*     SI = SURFACE IRON VOLUME DISCHARGE
*     Y = COUNTER

      DO 2600 Y=1,NO
         IF(ST.EQ.OA(Y)) CALL OUT(QS,H,REP,SI,NP,DN,IT)
 2600 CONTINUE
```

```
      RETURN
      END


      SUBROUTINE OUT(QS,H,N,SI,NP,DN,IT)
      INTEGER NP,DN(6)
      REAL QS(6,10),H(6),SI(6,10)
      INTEGER N,Y2,Y3,Y4

*     OUTPUTS DATA ON EACH CYCLE

*     DEFINITIONS
*     H = WATER LEVEL
*     IT = WHETHER IRON IS BEING USED
*     N = WHICH MC VALUE IS IN USE
*     NP = NUMBER OF PONDS
*     NPC = NUMBER OF POND CONNECTIONS
*     QS = SURFACE DISCHARGE IN EACH POND
*     SI = SURFACE IRON VOLUME DISCHARGE

      WRITE(14,*) N,(H(Y2),Y2=1,NP)

      IF (NP.GE.1) THEN
      IF (IT.EQ.0) WRITE(15,*) (QS(1,Y2),Y2=1,DN(1))
      IF (IT.EQ.1) WRITE(30,*) (SI(1,Y3),Y3=1,DN(1))
      ENDIF
      IF (NP.GE.2) THEN
      IF (IT.EQ.0) WRITE(16,*) (QS(2,Y2),Y2=1,DN(2))
      IF (IT.EQ.1) WRITE(31,*) (SI(2,Y3),Y3=1,DN(2))
      ENDIF
      IF (NP.GE.3) THEN
      IF (IT.EQ.0) WRITE(17,*) (QS(3,Y2),Y2=1,DN(3))
      IF (IT.EQ.1) WRITE(32,*) (SI(3,Y3),Y3=1,DN(3))
      ENDIF
      IF (NP.GE.4) THEN
      IF (IT.EQ.0) WRITE(18,*) (QS(4,Y2),Y2=1,DN(4))
      IF (IT.EQ.1) WRITE(33,*) (SI(4,Y3),Y3=1,DN(4))
      ENDIF
      IF (NP.GE.5) THEN
      IF (IT.EQ.0) WRITE(19,*) (QS(5,Y2),Y2=1,DN(5))
      IF (IT.EQ.1) WRITE(34,*) (SI(5,Y3),Y3=1,DN(5))
      ENDIF
      IF (NP.GE.6) THEN
      IF (IT.EQ.0) WRITE(20,*) (QS(6,Y2),Y2=1,DN(6))
      IF (IT.EQ.1) WRITE(35,*) (SI(6,Y3),Y3=1,DN(6))
      ENDIF


      RETURN
      END


      SUBROUTINE OUTPUT(T,AVS,AVSI,NP,DN)
      INTEGER NP,DN(6)
      REAL AVS(6,10),AVSI(6,10)
      INTEGER T(6,10),Y2,Y3,Y4

*     OUTPUTS DATA TO FILES

*     DEFINITIONS
```

```
*    AVS = AVERAGE SURFACE FLOW OVER TIME
*    AVSI = AVERAGE SURFACE IRON VOLUME IN DISCHARGE
*    T = TIME

      DO 3000 Y4=1,NP
      WRITE(12,*) (T(Y4,Y2),Y2=1,DN(Y4))
      WRITE(13,*) (AVS(Y4,Y3),Y3=1,DN(Y4))
      WRITE(29,*) (AVSI(Y4,Y3),Y3=1,DN(Y4))
 3000 CONTINUE

      RETURN
      END


      SUBROUTINE BAL(I,H,HL,A,S,P,SE,NP,WD)
      INTEGER Y,NP
      REAL I(6),H(6),HL(6),A(6),S(6),P(6),SE(6),TOTAL(12),TOT(2),WD(6)


*    OUTPUTS DATA TO FILES

*    DEFINITIONS
*    A = AREA OF POND
*    H = WATER LEVEL
*    HL = LAST WATER LEVEL
*    I = INFILTRATION
*    NP = NUMBER OF PONDS
*    P = PUMPING
*    S = STORATIVITY
*    SE = SEEPAGE
*    TOTAL = TOTAL WATER VOLUME
*    WD = INFLOW FROM OTHER AQUIFERS OR MINES
*    Y = COUNTER

      TOT(1)=0
      TOT(2)=0

      DO 2400 Y = 1,NP
      TOTAL(Y) = (H(Y)-HL(Y))*(A(Y)*S(Y))
      TOT(1)=TOT(1)+TOTAL(Y)
      TOTAL(Y+NP) = I(Y)+SE(Y)-P(Y)+WD(Y)
      TOT(2)=TOT(2)+TOTAL(Y+NP)
 2400 CONTINUE
      WRITE(21,*) TOT(1),TOT(2)

      RETURN
      END


      SUBROUTINE PVALS(PU,N,NP,PN,PA)
      INTEGER N,Y2,NP,Y3
      INTEGER PN(6)
      REAL PU(6),PA(6,2,250)

*    INPUTS PUMPING DATA

*    DEFINITIONS
*    N = STEP
*    NP = NUMBER OF PONDS
```

```
*    PA = ARRAY OF PUMPING VALUES
*    PD = PUMPING DATA ARRAY
*    PN = NUMBER OF PUMPING VALUES
*    PU = PUMPING VALUE
*    Y2 = COUNTER

      DO 2500 Y2=1,NP
      DO 2510 Y3=1,PN(Y2)
      IF(N.GE.PA(Y2,1,Y3)) PU(Y2)=PA(Y2,2,Y3)
 2510 CONTINUE
 2500 CONTINUE

      RETURN
      END


      SUBROUTINE SVALS(NS,STO,S,NP,H)
      INTEGER NP
      INTEGER NS(6),Y,Y2
      REAL STO(6,2,100),S(6),H(6)

*    OUTPUTS DATA TO FILES

*    DEFINITIONS
*    H = WATER LEVEL
*    NS = NUMBER OF STORAGE DATA
*    NP = NUMBER OF PONDS
*    S = STORATIVITY
*    STO = ARRAY OF VARYING STORATIVITY
*    Y = COUNTER
*    Y2 = COUNTER

      DO 2800 Y = 1,NP
      DO 2810 Y2=1,NS(Y)
         IF (STO(Y,2,Y2).GT.H(Y)) S(Y)=STO(Y,1,Y2)
 2810 CONTINUE
 2800 CONTINUE

      RETURN
      END


      SUBROUTINE IRON(NS,STO,S,II,Y,HL,SUL,AW,RD,CT,TIC,A,NP)
      INTEGER NP
      INTEGER NS,Y,Y2
      REAL S,H,HL,SUL(6,3,100),AW,RD,CT,TIC,A,RC,RCP,RCP2,RCP3

*    CALCULATES IRON

*    DEFINITIONS
*    A = AREA OF POND
*    AW = ATOMIC WEIGHT OF SULPHUR
*    CT = PERECENTAGE OF IRON THAT WATER COMES INTO CONTACT WITH
*    H = WATER LEVEL
*    HL = LAST WATER LEVEL
*    NS = NUMBER OF STORAGE DATA
*    NP = NUMBER OF PONDS
*    RC = KG OF ROCK IN CONTACT WITH EACH M3 OF WATER
*    RCP = KG OF OXIDSED PYRITE IN CONTACT WITH EACH M3 OF WATER
*    RD = ROCK DENSITY  g/cm3
```

```
*    S = STORATIVITY
*    SUL = SULPHUR CONTENT
*    TIC = TOTAL IRON FROM CONTACT WITH PYRITE
*    Y = COUNTER
*    Y2 = COUNTER

      DO 2900 Y2=1,NS
         IF (SUL(Y,3,Y2).GT.HL) THEN
          IF (SUL(Y,3,Y2).GT.H) THEN
           IF(SUL(Y,1,Y2).GT.0) THEN
            RC = (1/S)*RD*1000
            RCP = RC*SUL(Y,1,Y2)*SUL(Y,2,Y2)*CT
            TIC = (((RCP*1000)/AW)/2)*((H-HL)*A)
           ELSE
            TIC = 0
           ENDIF
          ELSE
           IF(SUL(Y,3,(Y2-1)).GT.H) THEN
            RC = (1/S)*RD*1000
            RCP = RC*SUL(Y,1,Y2)*SUL(Y,2,Y2)*CT
            RCP2 = RC*SUL(Y,1,(Y2-1))*SUL(Y,2,(Y2-1))*CT
            TIC = ((((RCP*1000)/AW)/2)*((SUL(Y,3,Y2)-HL)*A))+
     +((((RCP2*1000)/AW)/2)*(H-(SUL(Y,3,Y2))*A))
           ELSE
            RC = (1/S)*RD*1000
            RCP = RC*SUL(Y,1,Y2)*SUL(Y,2,Y2)*CT
            RCP2 = RC*SUL(Y,1,(Y2-1))*SUL(Y,2,(Y2-1))*CT
            RCP3 = RC*SUL(Y,1,(Y2-2))*SUL(Y,2,(Y2-2))*CT
            TIC = ((((RCP*1000)/AW)/2)*(((SUL(Y,3,Y2)-HL)*A))+
     +((((RCP2*1000)/AW)/2)*((SUL(Y,3,(Y2-1))-SUL(Y,3,Y2))*A))+
     +((((RCP3*1000)/AW)/2)*(H-(SUL(Y,3,(Y2-1)))*A)))
           ENDIF
          ENDIF
         ENDIF
 2900 CONTINUE

      RETURN
      END


*     FUNCTIONS


      REAL*4 FUNCTION RAN1(IDUM)

*     BY PROF G PEGRAM UNIVERSITY OF NATAL, DURBAN, SOUTH AFRICA

      INTEGER IX,IY,IZ
      IF(IDUM.LT.0) THEN
         IX=17-IDUM
         IY=63-IDUM
         IZ=30307+IDUM/303
      ENDIF
      IX=MOD(171*IX,30269)
      IY=MOD(172*IX,30307)
      IZ=MOD(170*IX,30323)
      RAN1=MOD(REAL(IX)/30269.0D0+REAL(IY)/30307.0D0+REAL(IZ)/30323.0D0
     +,1.0D0)

      RETURN
```

```
      END

      REAL*4 FUNCTION PFLOW(HA,HB,PDIAM,PHEIGHT,PLEN,PROUGH)

      REAL APIPE,LAMBDA,VEL,DISCH
      INTEGER DONE
      DISCH = 0
      DONE = 0
      PFLOW = 0

*     CALCULATES PIPEFLOW USING PRANDTL AND NIKURADSE

*     DEFINITIONS
*     APIPE = CROSS-SECTIONAL AREA OF PIPE
*     DISCH = DISCHARGE
*     DONE = ITERATION CONVERGED
*     HA = WATER LEVEL
*     HB = WATER LEVEL
*     LAMBDA = LAMBDA
*     PDIAM = PIPE DIAMETER
*     PFLOW = PIPEFLOW VOLUME
*     PHEIGHT = PIPE HEIGHT
*     PLEN = PIPE LENGTH
*     PROUGH = PIPE ROUGHNESS
*     VEL = VELOCITY

      IF ((HA.GE.(PHEIGHT+PDIAM)).AND.(HB.GE.(PHEIGHT+PDIAM))) THEN
         APIPE = (3.14159*PDIAM*PDIAM)/4
         LAMBDA = (1/(2*(ALOG10(3.7*PDIAM/PROUGH))))
     +*(1/(2*(ALOG10(3.7*PDIAM/PROUGH))))
         VEL = SQRT((2*9.81*ABS(HA-HB))/(1.5+(LAMBDA*PLEN/PDIAM)))
         IF (HB.GE.HA) VEL = VEL*(-1)
         DISCH = (APIPE*VEL)
         PFLOW=DISCH*60*60*24
*     CONVERTED TO M3/DAY
         DONE = 1

      ELSEIF ((HA.GE.(PHEIGHT+PDIAM)).AND.(HB.LT.(PHEIGHT+PDIAM))) THEN
         IF (DONE.EQ.0) THEN
         APIPE = (3.14159*PDIAM*PDIAM)/4
         LAMBDA = (1/(2*(ALOG10(3.7*PDIAM/PROUGH))))
     +*(1/(2*(ALOG10(3.7*PDIAM/PROUGH))))
         VEL = SQRT((2*9.81*(HA-PHEIGHT))/(1.5+(LAMBDA*PLEN/PDIAM)))
         DISCH = (APIPE*VEL)
         PFLOW=DISCH*60*60*24
*     CONVERTED TO M3/DAY
         DONE = 1
      ENDIF

      ELSEIF ((HB.GE.(PHEIGHT+PDIAM)).AND.(HA.LT.(PHEIGHT+PDIAM))) THEN
         IF (DONE.EQ.0) THEN
         APIPE = (3.14159*PDIAM*PDIAM)/4
         LAMBDA = (1/(2*(ALOG10(3.7*PDIAM/PROUGH))))
     +*(1/(2*(ALOG10(3.7*PDIAM/PROUGH))))
         VEL = SQRT((2*9.81*(HB-PHEIGHT))/(1.5+(LAMBDA*PLEN/PDIAM)))
         VEL = VEL*(-1)
         DISCH = (APIPE*VEL)
         PFLOW=DISCH*60*60*24
*     CONVERTED TO M3/DAY
```

```
      DONE = 1
      ENDIF
   ENDIF
   RETURN
   END


   REAL*4 FUNCTION PFLW2(HA,HB,PDIAM,PHEIGHT,PLEN,PROUGH,PKIN)

   DOUBLE PRECISION DVEL,DVEL2
   REAL DS,HM,APIP,DISCH
   INTEGER DONE, CONV,J5

*   CALCULATES PIPEFLOW USING COLEBROOK-WHITE

*   DEFINITIONS
*   APIP = CROSS-SECTIONAL AREA OF PIPE
*   CONV =  HAVE ITERATIONS CONVERGED?
*   DISCH = DISCHARGE
*   DONE = ITERATION CONVERGED
*   DVEL = VELOCITY
*   DVEL2 = VELOCITY
*   HA = WATER LEVEL
*   HB = WAATER LEVEL
*   HM = MINOR HEAD LOSS
*   J5 = COUNTER
*   LAMBDA = LAMBDA
*   PDIAM = PIPE DIAMETER
*   PFLOW = PIPEFLOW VOLUME
*   PHEIGHT = PIPE HEIGHT
*   PLEN = PIPE LENGTH
*   PROUGH = PIPE ROUGHNESS

   DVEL2 = 0
   DISCH = 0
   DONE = 0
   PFLW2 = 0

   IF ((HA.GE.(PHEIGHT+PDIAM)).AND.(HB.GE.(PHEIGHT+PDIAM))) THEN
      IF (HA.GE.HB) THEN
      DVEL2 = 0
      DS = (HA-HB)/PLEN
      APIP = (3.14159*PDIAM*PDIAM)/4
      CONV = 0

      IF (DS.GT.0) THEN
      DO 2700 J5 = 1,1000
        IF (CONV.EQ.0) THEN
         DVEL = -2*(SQRT(19.62*PDIAM*DS))*(ALOG10((PROUGH/(3.7*
  +PDIAM))+((2.51*PKIN)/(PDIAM*SQRT(19.62*PDIAM*DS)))))
         HM = (1.5*DVEL*DVEL)/19.62
         DS = (HA-HB-HM)/PLEN
         IF (DS.LE.0) THEN
         DVEL = 0
         CONV = 1
         PRINT*,'HEADLOSS DUE TO ENTRY AND EXIT LOSS IS GREATER
  +THAN THE TOTAL HEAD.  THINK ABOUT YOUR CALIBRATION.  THE PIPE
  +PROPERTIES ARE H= ',PHEIGHT,' D= ',PDIAM,' R= ',PROUGH,' K= ',
  +PKIN,' HA= ',HA,' HB= ',HB
         ENDIF
```

```
          IF (ABS(DVEL2-DVEL).LT.0.00001) THEN
           CONV = 1
          ELSE
           IF (J5.EQ.1000.AND.CONV.EQ.0) PRINT*,'ITERATION HAS NOT
     +CONVERGED PH= ',PHEIGHT,' HA= ',HA,' HB= ',HB,' V1= ',DVEL,
     +' V2= ',DVEL2,' DS= ',DS
          DVEL2 = DVEL
         ENDIF
        ENDIF
 2700  CONTINUE
       ENDIF

       ELSE

       DVEL2 = 0
       DS = (HB-HA)/PLEN
       APIP = (3.14159*PDIAM*PDIAM)/4
       CONV = 0

       DO 2710 J5 = 1,1000
        IF (CONV.EQ.0) THEN
         DVEL = -2*(SQRT(19.62*PDIAM*DS))*(ALOG10((PROUGH/(3.7*
     +PDIAM))+((2.51*PKIN)/(PDIAM*SQRT(19.62*PDIAM*DS)))))
         HM = (1.5*DVEL*DVEL)/19.62
         DS = (HB-HA-HM)/PLEN
         IF (DS.LE.0) THEN
         DVEL = 0
         CONV = 1
         PRINT*,'HEADLOSS DUE TO ENTRY AND EXIT LOSS IS GREATER
     +THAN THE TOTAL HEAD.  THINK ABOUT YOUR CALIBRATION.  THE PIPE
     +PROPERTIES ARE H= ',PHEIGHT,' D= ',PDIAM,' R= ',PROUGH,' K= ',
     +PKIN,' HA= ',HA,' HB= ',HB
         ENDIF
         IF (ABS(DVEL2-DVEL).LT.0.00001) THEN
          CONV = 1
         ELSE
          IF (J5.EQ.1000.AND.CONV.EQ.0) PRINT*,'ITERATION HAS NOT
     +CONVERGED PH= ',PHEIGHT,' HA= ',HA,' HB= ',HB,' V1= ',DVEL,
     +' V2= ',DVEL2,' DS= ',DS
          DVEL2 = DVEL
         ENDIF
        ENDIF

 2710  CONTINUE

       DVEL = DVEL*(-1)
       ENDIF

       DISCH = (APIP*DVEL)
       PFLW2=DISCH*60*60*24
*     CONVERTED TO M3/DAY
       DONE = 1

     ELSEIF ((HA.GE.(PHEIGHT+PDIAM)).AND.(HB.LT.(PHEIGHT+PDIAM))) THEN
       IF (DONE.EQ.0) THEN
       DVEL2 = 0
       APIP = (3.14159*PDIAM*PDIAM)/4
       DS = (HA-PHEIGHT)/PLEN
       CONV = 0
```

```
      DO 2720 J5 = 1,1000
        IF (CONV.EQ.0) THEN
          DVEL = -2*(SQRT(19.62*PDIAM*DS))*(ALOG10((PROUGH/(3.7*
     +PDIAM))+((2.51*PKIN)/(PDIAM*SQRT(19.62*PDIAM*DS)))))
          HM = (1.5*DVEL*DVEL)/19.62
          DS = (HA-PHEIGHT-HM)/PLEN
          IF (DS.LE.0) THEN
          DVEL = 0
          CONV = 1
          PRINT*,'HEADLOSS DUE TO ENTRY AND EXIT LOSS IS GREATER
     +THAN THE TOTAL HEAD.  THINK ABOUT YOUR CALIBRATION.  THE PIPE
     +PROPERTIES ARE H= ',PHEIGHT,' D= ',PDIAM,' R= ',PROUGH,' K= ',
     +PKIN,' HA= ',HA,' HB= ',HB
          ENDIF
          IF (ABS(DVEL2-DVEL).LT.0.00001) THEN
           CONV = 1
          ELSE
           IF (J5.EQ.1000.AND.CONV.EQ.0) PRINT*,'ITERATION HAS NOT
     +CONVERGED PH= ',PHEIGHT,' HA= ',HA,' HB= ',HB,' V1= ',DVEL,
     +' V2= ',DVEL2,' DS= ',DS
           DVEL2 = DVEL
          ENDIF
        ENDIF

 2720 CONTINUE

      DISCH = (APIP*DVEL)
      PFLW2=DISCH*60*60*24
*     CONVERTED TO M3/DAY
      DONE = 1
      ENDIF

   ELSEIF ((HB.GE.(PHEIGHT+PDIAM)).AND.(HA.LT.(PHEIGHT+PDIAM))) THEN
      IF (DONE.EQ.0) THEN
      DVEL2 = 0
      APIP = (3.14159*PDIAM*PDIAM)/4
      DS = (HB-PHEIGHT)/PLEN
      CONV = 0

      DO 2730 J5 = 1,1000
        IF (CONV.EQ.0) THEN
          DVEL = -2*(SQRT(19.62*PDIAM*DS))*(ALOG10((PROUGH/(3.7*
     +PDIAM))+((2.51*PKIN)/(PDIAM*SQRT(19.62*PDIAM*DS)))))
          HM = (1.5*DVEL*DVEL)/19.62
          DS = (HB-PHEIGHT-HM)/PLEN
          IF (DS.LE.0) THEN
          DVEL = 0
          CONV = 1
          PRINT*,'HEADLOSS DUE TO ENTRY AND EXIT LOSS IS GREATER
     +THAN THE TOTAL HEAD.  THINK ABOUT YOUR CALIBRATION.  THE PIPE
     +PROPERTIES ARE H= ',PHEIGHT,' D= ',PDIAM,' R= ',PROUGH,' K= ',
     +PKIN,' HA= ',HA,' HB= ',HB
          ENDIF
          IF (ABS(DVEL2-DVEL).LT.0.00001) THEN
           CONV = 1
          ELSE
           IF (J5.EQ.1000.AND.CONV.EQ.0) PRINT*,'ITERATION HAS NOT
     +CONVERGED PH= ',PHEIGHT,' HA= ',HA,' HB= ',HB,' V1= ',DVEL,
     +' V2= ',DVEL2,' DS= ',DS
           DVEL2 = DVEL
```

```
          ENDIF
         ENDIF

2730   CONTINUE

        DVEL = DVEL*(-1)
        DISCH = (APIP*DVEL)
        PFLW2=DISCH*60*60*24
*      CONVERTED TO M3/DAY
        DONE = 1
        ENDIF
      ENDIF
      RETURN
      END


      REAL*4 FUNCTION SPREAD(PAREA,DIS,PSTOR)

*     CALCULATES SPREAD OF VOLUMES ACCROSS POND

*     DEFINITIONS
*     DIS = VOLUME
*     PAREA =  AREA
*     PSTOR =  STORATIVITY

      SPREAD = (DIS/(PAREA*PSTOR))

      RETURN
      END
```

APPENDIX 2

RESULTS USING THE PRANDTL AND NIKURADSE EQUATION

Deterministic Analysis using Intermediate Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	1.275	22.51
Old Shaft at 20m	NT348999	0.952	24.48
Old Shaft at 25m	NO354002	0.793	25.36
Duniface Adit to Kennoway Burn at 20m	NO352005	0.952	24.48
Bowhouse Outcrops at 20m	NO360008	0.952	24.48
Chemiss Outcrops at 20m	NO364006	0.952	24.48
Kirkland Shafts at 20m	NO367004	0.952	24.48
Leven Shafts at 25m	NO374002	0.793	25.36
Drainage Level in Leven Harbour at 5m	NO383003	1.311	22.32
Michael			
Victoria Shaft at 7.3m	NT322947	1.265	21.55
Lady Shaft at 15m	NT324947	1.092	23.05
Reservoir Shaft at 15m	NT326947	1.092	23.05
Coxtool Shaft at 15m	NT326947	1.092	23.05
Windmill Shaft at 20m	NT329951	0.964	24.27
Michael Shafts at 11.6m	NT336962	1.172	22.35
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.136	21.33
Foreshore below Frances Colliery at 10m	NT310937	1.136	21.33
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.245	20.26
Blair Den shafts at 15m	NT314943	1.014	22.77
Blair Den shafts at 25m	NT314943	0.706	26.01
Blair Den shafts at 35m	NT314943	0.084	37.81
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	0	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	0	-
Kingslaw Burn at 85m	NT294952	0	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.403	30.02
Old Shaft at 40m	NO307009	0.403	30.02
Discharge to Lochty Burn at 45m	NT301982	0.005	35.73
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.118	34.89
Furnace Shaft at Lochty Farm at 45m	NT296983	0.005	35.73
River Ore near Tullybreck at 45m	NT313986	0.005	35.73
Julian Shaft at 48m	NT306987	0	-
Lochty Side Shaft at 50m	NT298986	0	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	0	-
Total		22.685	

Deterministic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	4.672	22.65
Old Shaft at 20m	NT348999	-	-
Old Shaft at 25m	NO354002	-	-
Duniface Adit to Kennoway Burn at 20m	NO352005	-	-
Bowhouse Outcrops at 20m	NO360008	-	-
Chemiss Outcrops at 20m	NO364006	-	-
Kirkland Shafts at 20m	NO367004	-	-
Leven Shafts at 25m	NO374002	-	-
Drainage Level in Leven Harbour at 5m	NO383003	5.083	22.33
Michael			
Victoria Shaft at 7.3m	NT322947	2.221	21.55
Lady Shaft at 15m	NT324947	1.137	23.84
Reservoir Shaft at 15m	NT326947	1.136	23.84
Coxtool Shaft at 15m	NT326947	1.136	23.84
Windmill Shaft at 20m	NT329951	-	-
Michael Shafts at 11.6m	NT336962	1.704	22.42
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.346	21.38
Foreshore below Frances Colliery at 10m	NT310937	1.345	21.38
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.724	20.26
Blair Den shafts at 15m	NT314943	0.802	23.87
Blair Den shafts at 25m	NT314943	-	-
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	-	-
Old Shaft at 40m	NO307009	-	-
Discharge to Lochty Burn at 45m	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	-	-
Furnace Shaft at Lochty Farm at 45m	NT296983	-	-
River Ore near Tullybreck at 45m	NT313986	-	-
Julian Shaft at 48m	NT306987	-	-
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	-	-
Total		22.306	

Deterministic Analysis using No Flow to the Sea Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	-	-
Old Shaft at 20m	NT348999	1.460	24.10
Old Shaft at 25m	NO354002	1.366	24.73
Duniface Adit to Kennoway Burn at 20m	NO352005	1.460	24.10
Bowhouse Outcrops at 20m	NO360008	1.460	24.10
Chemiss Outcrops at 20m	NO364006	1.460	24.10
Kirkland Shafts at 20m	NO367004	1.460	24.10
Leven Shafts at 25m	NO374002	1.366	24.73
Drainage Level in Leven Harbour at 5m	NO383003	-	-
Michael			
Victoria Shaft at 7.3m	NT322947	-	-
Lady Shaft at 15m	NT324947	-	-
Reservoir Shaft at 15m	NT326947	-	-
Coxtool Shaft at 15m	NT326947	-	-
Windmill Shaft at 20m	NT329951	-	-
Michael Shafts at 11.6m	NT336962	-	-
Wemyss Den Burn at 45m:	NT338977	1.033	27.59
Frances			
North Foreshore at Dysart at 10m	NT307933	-	-
Foreshore below Frances Colliery at 10m	NT310937	-	-
Frances Shaft at 45m	NT309938	1.081	27.30
Blair Den shafts at 5m	NT314943	-	-
Blair Den shafts at 15m	NT314943	-	-
Blair Den shafts at 25m	NT314943	-	-
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	0.951	27.78
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	0.900	29.03
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.973	26.04
Old Shaft at 40m	NO307009	0.973	26.04
Discharge to Lochty Burn at 45m	NT301982	0.820	27.09
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.884	26.63
Furnace Shaft at Lochty Farm at 45m	NT296983	0.820	27.09
River Ore near Tullybreck at 45m	NT313986	0.820	27.09
Julian Shaft at 48m	NT306987	0.713	28.22
Lochty Side Shaft at 50m	NT298986	0.634	29.16
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	0.713	28.22
Total		21.347	

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Mean Volume of Discharge (Ml/day)		Standard Deviation of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.278		0.065	
Old Shaft at 20m	1000	NT348999	0.953		0.088	
Old Shaft at 25m	1000	NO354002	0.795		0.108	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.953		0.088	
Bowhouse Outcrops at 20m	1000	NO360008	0.953		0.088	
Chemiss Outcrops at 20m	1000	NO364006	0.953		0.088	
Kirkland Shafts at 20m	1000	NO367004	0.953		0.088	
Leven Shafts at 25m	1000	NO374002	0.795		0.108	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.313		0.063	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.274		0.055	
Lady Shaft at 15m	1000	NT324947	1.102		0.063	
Reservoir Shaft at 15m	1000	NT326947	1.102		0.063	
Coxtool Shaft at 15m	1000	NT326947	1.102		0.063	
Windmill Shaft at 20m	1000	NT329951	0.973		0.072	
Michael Shafts at 11.6m	1000	NT336962	1.181		0.059	
Wemyss Den Burn at 45m:	24	NT338977	0.066	0.002	0.431	0.040
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.135		0.040	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.135		0.040	
Frances Shaft at 45m	0	NT309938	0		0	
Blair Den shafts at 5m	1000	NT314943	1.243		0.036	
Blair Den shafts at 15m	1000	NT314943	1.013		0.046	
Blair Den shafts at 25m	1000	NT314943	0.704		0.067	
Blair Den shafts at 35m	684	NT314943	0.157	0.107	0.138	0.103
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	103	NT294973	0.002	0.0002	0.008	0.001
River Ore, north-east of Balbeggie Cottage at 50m:	8	NT286966	0.0005	4e-6	0.006	6e-5
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	997	NO308004	0.402	0.401	0.126	0.126
Old Shaft at 40m	997	NO307009	0.402	0.401	0.126	0.126
Discharge to Lochty Burn at 45m	797	NT301982	0.051	0.040	0.065	0.058
River Ore between Lochty Burn confluence and New Bridge at 43m	954	NT307984	0.173	0.165	0.127	0.124
Furnace Shaft at Lochty Farm at 45m	797	NT296983	0.050	0.040	0.065	0.057
River Ore near Tullybreck at 45m	797	NT313986	0.050	0.040	0.065	0.057
Julian Shaft at 48m	954	NT306987	0.072	0.018	0.126	0.033
Lochty Side Shaft at 50m	34	NT298986	0.064	0.002	0.347	0.013
Discharge between Ore Bridge and Railway Viaduct at 48m	954	NT294973	0.072	0.018	0.126	0.033
Total			22.472	22.144		

Stochastic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Mean Volume of Discharge (Ml/day)		Standard Deviation of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	4.678		0.452	
Old Shaft at 20m	196	NT348999	0.011	0.002	0.028	0.008
Old Shaft at 25m	0	NO354002	-		-	
Duniface Adit to Kennoway Burn at 20m	196	NO352005	0.011	0.002	0.028	0.008
Bowhouse Outcrops at 20m	196	NO360008	0.011	0.002	0.028	0.008
Chemiss Outcrops at 20m	196	NO364006	0.011	0.002	0.028	0.008
Kirkland Shafts at 20m	196	NO367004	0.073	0.0143	0.150	0.031
Leven Shafts at 25m	0	NO374002	-		-	
Drainage Level in Leven Harbour at 5m	1000	NO383003	5.095		0.412	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	2.244		0.097	
Lady Shaft at 15m	1000	NT324947	1.164		0.195	
Reservoir Shaft at 15m	1000	NT326947	1.163		0.195	
Coxtool Shaft at 15m	1000	NT326947	1.162		0.195	
Windmill Shaft at 20m	404	NT329951	0.042	0.017	0.081	0.045
Michael Shafts at 11.6m	1000	NT336962	1.734		0.126	
Wemyss Den Burn at 45m:	0	NT338977	-	-	-	-
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.362		0.087	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.361		0.087	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.735		0.066	
Blair Den shafts at 15m	1000	NT314943	0.816		0.153	
Blair Den shafts at 25m	0	NT314943	-		-	
Blair Den shafts at 35m	0	NT314943	-		-	
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	0	NT294973	-		-	
River Ore, north-east of Balbeggie Cottage at 50m:	0	NT286966	-		-	
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	34	NO308004	0.013	0.0005	0.074	0.004
Old Shaft at 40m	34	NO307009	0.013	0.0005	0.074	0.004
Discharge to Lochty Burn at 45m	0	NT301982	-	-	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	7	NT307984	0.0006	5e-6[4]	0.008	7e-5
Furnace Shaft at Lochty Farm at 45m	0	NT296983	-	-	-	-
River Ore near Tullybreck at 45m	0	NT313986	-	-	-	-
Julian Shaft at 48m	0	NT306987	-	-	-	-
Lochty Side Shaft at 50m	0	NT298986	-	-	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	0	NT294973	-	-	-	-
Total			22.700	22.560		

Stochastic Analysis using No Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Mean Volume of Discharge (Ml/day)		Standard Deviation of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	0	NT366986	-		-	
Old Shaft at 20m	1000	NT348999	1.468		0.103	
Old Shaft at 25m	1000	NO354002	1.375		0.110	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	1.468		0.103	
Bowhouse Outcrops at 20m	1000	NO360008	1.468		0.103	
Chemiss Outcrops at 20m	1000	NO364006	1.468		0.103	
Kirkland Shafts at 20m	1000	NO367004	1.468		0.103	
Leven Shafts at 25m	1000	NO374002	1.375		0.110	
Drainage Level in Leven Harbour at 5m	0	NO383003	-		-	
Michael						
Victoria Shaft at 7.3m	0	NT322947	-		-	
Lady Shaft at 15m	0	NT324947	-		-	
Reservoir Shaft at 15m	0	NT326947	-		-	
Coxtool Shaft at 15m	0	NT326947	-		-	
Windmill Shaft at 20m	0	NT329951	-		-	
Michael Shafts at 11.6m	0	NT336962	-		-	
Wemyss Den Burn at 45m:	1000	NT338977	1.054		0.104	
Frances						
North Foreshore at Dysart at 10m	0	NT307933	-		-	
Foreshore below Frances Colliery at 10m	0	NT310937	-		-	
Frances Shaft at 45m	1000	NT309938	1.104		0.093	
Blair Den shafts at 5m	0	NT314943	-		-	
Blair Den shafts at 15m	0	NT314943	-		-	
Blair Den shafts at 25m	0	NT314943	-		-	
Blair Den shafts at 35m	0	NT314943	-		-	
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	1000	NT294973	0.973		0.099	
River Ore, north-east of Balbeggie Cottage at 50m:	1000	NT286966	0.916		0.105	
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	1000	NO308004	0.985		0.060	
Old Shaft at 40m	1000	NO307009	0.984		0.060	
Discharge to Lochty Burn at 45m	1000	NT301982	0.833		0.071	
River Ore between Lochty Burn confluence and New Bridge at 43m	1000	NT307984	0.897		0.066	
Furnace Shaft at Lochty Farm at 45m	1000	NT296983	0.833		0.071	
River Ore near Tullybreck at 45m	1000	NT313986	0.832		0.071	
Julian Shaft at 48m	1000	NT306987	0.727		0.081	
Lochty Side Shaft at 50m	1000	NT298986	0.647		0.092	
Discharge between Ore Bridge and Railway Viaduct at 48m	1000	NT294973	0.727		0.081	
Total			21.602			

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Mean Time of Discharge (Years)	Standard Deviation of Time of Discharge
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	22.37	2.65
Old Shaft at 20m	1000	NT348999	24.32	2.86
Old Shaft at 25m	1000	NO354002	25.58	3.13
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	24.32	2.86
Bowhouse Outcrops at 20m	1000	NO360008	24.32	2.86
Chemiss Outcrops at 20m	1000	NO364006	24.32	2.86
Kirkland Shafts at 20m	1000	NO367004	24.32	2.86
Leven Shafts at 25m	1000	NO374002	25.58	3.13
Drainage Level in Leven Harbour at 5m	1000	NO383003	22.16	2.63
Michael				
Victoria Shaft at 7.3m	1000	NT322947	21.26	2.29
Lady Shaft at 15m	1000	NT324947	22.69	2.39
Reservoir Shaft at 15m	1000	NT326947	22.69	2.39
Coxtool Shaft at 15m	1000	NT326947	22.69	2.39
Windmill Shaft at 20m	1000	NT329951	23.87	2.54
Michael Shafts at 11.6m	1000	NT336962	22.04	2.34
Wemyss Den Burn at 45m:	24	NT338977	41.60	271.11
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	20.89	2.17
Foreshore below Frances Colliery at 10m	1000	NT310937	20.89	2.17
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	19.67	2.20
Blair Den shafts at 15m	1000	NT314943	22.25	2.21
Blair Den shafts at 25m	1000	NT314943	25.88	2.74
Blair Den shafts at 35m	684	NT314943	36.60	25.78
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	103	NT294973	40.11	119.15
River Ore, north-east of Balbeggie Cottage at 50m:	8	NT286966	39.87	474.70
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	997	NO308004	29.57	5.07
Old Shaft at 40m	997	NO307009	29.57	5.07
Discharge to Lochty Burn at 45m	797	NT301982	35.85	19.15
River Ore between Lochty Burn confluence and New Bridge at 43m	954	NT307984	33.07	9.38
Furnace Shaft at Lochty Farm at 45m	797	NT296983	35.85	19.15
River Ore near Tullybreck at 45m	797	NT313986	35.85	19.15
Julian Shaft at 48m	255	NT306987	38.71	66.58
Lochty Side Shaft at 50m	34	NT298986	40.60	219.78
Discharge between Ore Bridge and Railway Viaduct at 48m	255	NT294973	38.71	66.58

Stochastic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Mean Time of Discharge (Years)	Standard Deviation of Time of Discharge
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	22.41	2.66
Old Shaft at 20m	196	NT348999	30.82	62.88
Old Shaft at 25m	0	NO354002	-	-
Duniface Adit to Kennoway Burn at 20m	196	NO352005	30.82	62.88
Bowhouse Outcrops at 20m	196	NO360008	30.82	62.88
Chemiss Outcrops at 20m	196	NO364006	30.82	62.88
Kirkland Shafts at 20m	196	NO367004	30.82	62.88
Leven Shafts at 25m	0	NO374002	-	-
Drainage Level in Leven Harbour at 5m	1000	NO383003	22.17	2.63
Michael				
Victoria Shaft at 7.3m	1000	NT322947	21.28	2.29
Lady Shaft at 15m	1000	NT324947	23.24	2.46
Reservoir Shaft at 15m	1000	NT326947	23.24	2.46
Coxtool Shaft at 15m	1000	NT326947	23.24	2.46
Windmill Shaft at 20m	404	NT329951	31.52	38.78
Michael Shafts at 11.6m	1000	NT336962	22.20	2.36
Wemyss Den Burn at 45m:	0	NT338977	-	-
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	21.02	2.17
Foreshore below Frances Colliery at 10m	1000	NT310937	21.02	2.17
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	19.67	2.20
Blair Den shafts at 15m	1000	NT314943	23.34	2.33
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	0	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	0	NT286966	-	-
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	34	NO308004	34.47	186.55
Old Shaft at 40m	34	NO307009	34.47	186.55
Discharge to Lochty Burn at 45m	0	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	7	NT307984	35.75	459.86
Furnace Shaft at Lochty Farm at 45m	0	NT296983	-	-
River Ore near Tullybreck at 45m	0	NT313986	-	-
Julian Shaft at 48m	0	NT306987	-	-
Lochty Side Shaft at 50m	0	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	0	NT294973	-	-

Stochastic Analysis using No Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Mean Time of Discharge (Years)	Standard Deviation of Time of Discharge
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	0	NT366986	-	-
Old Shaft at 20m	1000	NT348999	23.97	2.77
Old Shaft at 25m	1000	NO354002	24.73	2.84
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	23.97	2.77
Bowhouse Outcrops at 20m	1000	NO360008	23.97	2.77
Chemiss Outcrops at 20m	1000	NO364006	23.97	2.77
Kirkland Shafts at 20m	1000	NO367004	23.97	2.77
Leven Shafts at 25m	1000	NO374002	24.73	2.84
Drainage Level in Leven Harbour at 5m	0	NO383003	-	-
Michael				
Victoria Shaft at 7.3m	0	NT322947	-	-
Lady Shaft at 15m	0	NT324947	-	-
Reservoir Shaft at 15m	0	NT326947	-	-
Coxtool Shaft at 15m	0	NT326947	-	-
Windmill Shaft at 20m	0	NT329951	-	-
Michael Shafts at 11.6m	0	NT336962	-	-
Wemyss Den Burn at 45m:	1000	NT338977	27.44	2.99
Frances				
North Foreshore at Dysart at 10m	0	NT307933	-	-
Foreshore below Frances Colliery at 10m	0	NT310937	-	-
Frances Shaft at 45m	1000	NT309938	26.99	2.73
Blair Den shafts at 5m	0	NT314943	-	-
Blair Den shafts at 15m	0	NT314943	-	-
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	1000	NT294973	27.51	2.87
River Ore, north-east of Balbeggie Cottage at 50m:	1000	NT286966	28.13	2.98
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	1000	NO308004	25.70	2.60
Old Shaft at 40m	1000	NO307009	25.70	2.60
Discharge to Lochty Burn at 45m	1000	NT301982	26.78	2.80
River Ore between Lochty Burn confluence and New Bridge at 43m	1000	NT307984	26.31	2.71
Furnace Shaft at Lochty Farm at 45m	1000	NT296983	26.78	2.80
River Ore near Tullybreck at 45m	1000	NT313986	26.78	2.80
Julian Shaft at 48m	1000	NT306987	27.80	3.00
Lochty Side Shaft at 50m	1000	NT298986	28.81	3.24
Discharge between Ore Bridge and Railway Viaduct at 48m	1000	NT294973	27.80	3.00

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Median Volume of Discharge (Ml/day)		Quartile Range	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.280		0.091	
Old Shaft at 20m	1000	NT348999	0.956		0.122	
Old Shaft at 25m	1000	NO354002	0.802		0.147	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.956		0.122	
Bowhouse Outcrops at 20m	1000	NO360008	0.956		0.122	
Chemiss Outcrops at 20m	1000	NO364006	0.956		0.122	
Kirkland Shafts at 20m	1000	NO367004	0.956		0.122	
Leven Shafts at 25m	1000	NO374002	0.801		0.147	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.315		0.088	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.272		0.075	
Lady Shaft at 15m	1000	NT324947	1.102		0.088	
Reservoir Shaft at 15m	1000	NT326947	1.102		0.088	
Coxtool Shaft at 15m	1000	NT326947	1.102		0.088	
Windmill Shaft at 20m	1000	NT329951	0.973		0.100	
Michael Shafts at 11.6m	1000	NT336962	1.181		0.081	
Wemyss Den Burn at 45m:	24	NT338977	0.073	0	0.009	0
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.139		0.050	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.139		0.050	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.247		0.046	
Blair Den shafts at 15m	1000	NT314943	1.018		0.058	
Blair Den shafts at 25m	1000	NT314943	0.713		0.085	
Blair Den shafts at 35m	684	NT314943	0.130	0.094	0.123	0.158
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	103	NT294973	0.0009	0	0.003	0
River Ore, north-east of Balbeggie Cottage at 50m:	8	NT286966	0.0003	0	0.0006	0
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	997	NO308004	0.432	0.431	0.152	0.153
Old Shaft at 40m	997	NO307009	0.432	0.431	0.152	0.153
Discharge to Lochty Burn at 45m	797	NT301982	0.024	0.045	0.073	0.061
River Ore between Lochty Burn confluence and New Bridge at 43m	954	NT307984	0.168	0.051	0.214	0.223
Furnace Shaft at Lochty Farm at 45m	797	NT296983	0.024	0.045	0.073	0.060
River Ore near Tullybreck at 45m	797	NT313986	0.024	0.045	0.073	0.060
Julian Shaft at 48m	255	NT306987	0.077	0.033	0.007	0
Lochty Side Shaft at 50m	34	NT298986	0.077	0.018	0.011	0
Discharge between Ore Bridge and Railway Viaduct at 48m	255	NT294973	0.077	0.033	0.007	0
Total			22.505	22.192		

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Volume of Discharge		Upper Quartile of Volume of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.234		1.324	
Old Shaft at 20m	1000	NT348999	0.893		1.015	
Old Shaft at 25m	1000	NO354002	0.725		0.872	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.893		1.015	
Bowhouse Outcrops at 20m	1000	NO360008	0.893		1.015	
Chemiss Outcrops at 20m	1000	NO364006	0.893		1.015	
Kirkland Shafts at 20m	1000	NO367004	0.893		1.015	
Leven Shafts at 25m	1000	NO374002	0.725		0.872	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.270		1.358	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.238		1.313	
Lady Shaft at 15m	1000	NT324947	1.060		1.148	
Reservoir Shaft at 15m	1000	NT326947	1.060		1.148	
Coxtool Shaft at 15m	1000	NT326947	1.060		1.148	
Windmill Shaft at 20m	1000	NT329951	0.926		1.026	
Michael Shafts at 11.6m	1000	NT336962	1.143		1.224	
Wemyss Den Burn at 45m:	24	NT338977	0.070	0	0.079	0
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.111		1.162	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.111		1.162	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.222		1.267	
Blair Den shafts at 15m	1000	NT314943	0.986		1.044	
Blair Den shafts at 25m	1000	NT314943	0.664		0.749	
Blair Den shafts at 35m	684	NT314943	0.091	0	0.214	0.158
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	103	NT294973	0.0003	0	0.003	0
River Ore, north-east of Balbeggie Cottage at 50m:	8	NT286966	0.0001	0	0.0007	0
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	997	NO308004	0.342		0.493	
Old Shaft at 40m	997	NO307009	0.342		0.493	
Discharge to Lochty Burn at 45m	797	NT301982	0.006	0.0006	0.079	0.061
River Ore between Lochty Burn confluence and New Bridge at 43m	954	NT307984	0.060	0.048	0.274	0.214
Furnace Shaft at Lochty Farm at 45m	797	NT296983	0.006	0.0006	0.079	0.073
River Ore near Tullybreck at 45m	797	NT313986	0.006	0.0006	0.079	0.073
Julian Shaft at 48m	255	NT306987	0.074	0	0.081	0.007
Lochty Side Shaft at 50m	34	NT298986	0.070	0	0.082	0.011
Discharge between Ore Bridge and Railway Viaduct at 48m	255	NT294973	0.074	0	0.081	0.007

Stochastic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Median Volume of Discharge (Ml/day)		Quartile Range	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	4.719		0.641	
Old Shaft at 20m	196	NT348999	0.005	0	0.013	0
Old Shaft at 25m	0	NO354002	-	-	-	-
Duniface Adit to Kennoway Burn at 20m	196	NO352005	0.005	0	0.013	0
Bowhouse Outcrops at 20m	196	NO360008	0.005	0	0.013	0
Chemiss Outcrops at 20m	196	NO364006	0.005	0	0.013	0
Kirkland Shafts at 20m	196	NO367004	0.075	0	0.009	0
Leven Shafts at 25m	0	NO374002	-	-	-	-
Drainage Level in Leven Harbour at 5m	1000	NO383003	5.128		0.587	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	2.238		0.146	
Lady Shaft at 15m	1000	NT324947	1.167		0.280	
Reservoir Shaft at 15m	1000	NT326947	1.166		0.280	
Coxtool Shaft at 15m	1000	NT326947	1.166		0.280	
Windmill Shaft at 20m	404	NT329951	0.019	0	0.045	0.011
Michael Shafts at 11.6m	1000	NT336962	1.729		0.189	
Wemyss Den Burn at 45m:	0	NT338977	-		-	
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.359		0.117	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.358		0.117	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.734		0.088	
Blair Den shafts at 15m	1000	NT314943	0.820		0.200	
Blair Den shafts at 25m	0	NT314943	-		-	
Blair Den shafts at 35m	0	NT314943	-		-	
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	0	NT294973	-		-	
River Ore, north-east of Balbeggie Cottage at 50m:	0	NT286966	-		-	
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	34	NO308004	0.007	0	0.011	0
Old Shaft at 40m	34	NO307009	0.007	0	0.011	0
Discharge to Lochty Burn at 45m	0	NT301982	-		-	
River Ore between Lochty Burn confluence and New Bridge at 43m	7	NT307984	0.006	0	0.0008	0
Furnace Shaft at Lochty Farm at 45m	0	NT296983	-		-	
River Ore near Tullybreck at 45m	0	NT313986	-		-	
Julian Shaft at 48m	0	NT306987	-		-	
Lochty Side Shaft at 50m	0	NT298986	-		-	
Discharge between Ore Bridge and Railway Viaduct at 48m	0	NT294973	-		-	
Total			22.718	22.584		

Stochastic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Volume of Discharge		Upper Quartile of Volume of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	4.365		5.006	
Old Shaft at 20m	196	NT348999	0.001	0	0.015	0
Old Shaft at 25m	0	NO354002	0	0	0	0
Duniface Adit to Kennoway Burn at 20m	196	NO352005	0.001	0	0.015	0
Bowhouse Outcrops at 20m	196	NO360008	0.001	0	0.015	0
Chemiss Outcrops at 20m	196	NO364006	0.001	0	0.015	0
Kirkland Shafts at 20m	196	NO367004	0.071	0	0.081	0
Leven Shafts at 25m	0	NO374002	0	0	0	0
Drainage Level in Leven Harbour at 5m	1000	NO383003	4.803		5.390	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	2.173		2.319	
Lady Shaft at 15m	1000	NT324947	1.033		1.313	
Reservoir Shaft at 15m	1000	NT326947	1.033		1.312	
Coxtool Shaft at 15m	1000	NT326947	1.033		1.312	
Windmill Shaft at 20m	404	NT329951	0.004	0	0.049	0.011
Michael Shafts at 11.6m	1000	NT336962	1.643		1.832	
Wemyss Den Burn at 45m:	0	NT338977	-		-	
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.303		1.420	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.303		1.420	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.691		1.778	
Blair Den shafts at 15m	1000	NT314943	0.722		0.922	
Blair Den shafts at 25m	0	NT314943	-		-	
Blair Den shafts at 35m	0	NT314943	-		-	
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	0	NT294973	-		-	
River Ore, north-east of Balbeggie Cottage at 50m:	0	NT286966	-		-	
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	34	NO308004	0.001	0	0.012	0
Old Shaft at 40m	34	NO307009	0.001	0	0.012	0
Discharge to Lochty Burn at 45m	0	NT301982	-		-	
River Ore between Lochty Burn confluence and New Bridge at 43m	7	NT307984	0.0001	0	0.0009	0
Furnace Shaft at Lochty Farm at 45m	0	NT296983	-		-	
River Ore near Tullybreck at 45m	0	NT313986	-		-	
Julian Shaft at 48m	0	NT306987	-		-	
Lochty Side Shaft at 50m	0	NT298986	-		-	
Discharge between Ore Bridge and Railway Viaduct at 48m	0	NT294973	-		-	

Stochastic Analysis using No Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Median Volume of Discharge (Ml/day)	Quartile Range
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	0	NT366986	-	-
Old Shaft at 20m	1000	NT348999	1.473	0.143
Old Shaft at 25m	1000	NO354002	1.382	0.153
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	1.473	0.143
Bowhouse Outcrops at 20m	1000	NO360008	1.473	0.143
Chemiss Outcrops at 20m	1000	NO364006	1.473	0.143
Kirkland Shafts at 20m	1000	NO367004	1.472	0.143
Leven Shafts at 25m	1000	NO374002	1.381	0.153
Drainage Level in Leven Harbour at 5m	0	NO383003	-	-
Michael				
Victoria Shaft at 7.3m	0	NT322947	-	-
Lady Shaft at 15m	0	NT324947	-	-
Reservoir Shaft at 15m	0	NT326947	-	-
Coxtool Shaft at 15m	0	NT326947	-	-
Windmill Shaft at 20m	0	NT329951	-	-
Michael Shafts at 11.6m	0	NT336962	-	-
Wemyss Den Burn at 45m:	1000	NT338977	1.053	0.148
Frances				
North Foreshore at Dysart at 10m	0	NT307933	-	-
Foreshore below Frances Colliery at 10m	0	NT310937	-	-
Frances Shaft at 45m	1000	NT309938	1.101	0.126
Blair Den shafts at 5m	0	NT314943	-	-
Blair Den shafts at 15m	0	NT314943	-	-
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				-
Discharge between Ore Bridge and Railway viaduct at 48m	1000	NT294973	0.971	0.135
River Ore, north-east of Balbeggie Cottage at 50m:	1000	NT286966	0.915	0.144
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	1000	NO308004	0.984	0.084
Old Shaft at 40m	1000	NO307009	0.983	0.084
Discharge to Lochty Burn at 45m	1000	NT301982	0.833	0.100
River Ore between Lochty Burn confluence and New Bridge at 43m	1000	NT307984	0.896	0.092
Furnace Shaft at Lochty Farm at 45m	1000	NT296983	0.832	0.100
River Ore near Tullybreck at 45m	1000	NT313986	0.832	0.100
Julian Shaft at 48m	1000	NT306987	0.728	0.113
Lochty Side Shaft at 50m	1000	NT298986	0.650	0.127
Discharge between Ore Bridge and Railway Viaduct at 48m	1000	NT294973	0.728	0.113
Total			21.627	

Stochastic Analysis using No Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Volume of Discharge of No.	Upper Quartile of Volume of Discharge of No.
Wellesley				
Wellesley Shafts at 6.7m	0	NT366986	-	-
Old Shaft at 20m	1000	NT348999	1.398	1.541
Old Shaft at 25m	1000	NO354002	1.299	1.452
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	1.397	1.540
Bowhouse Outcrops at 20m	1000	NO360008	1.397	1.540
Chemiss Outcrops at 20m	1000	NO364006	1.397	1.540
Kirkland Shafts at 20m	1000	NO367004	1.397	1.540
Leven Shafts at 25m	1000	NO374002	1.298	1.451
Drainage Level in Leven Harbour at 5m	0	NO383003	-	-
Michael				
Victoria Shaft at 7.3m	0	NT322947	-	-
Lady Shaft at 15m	0	NT324947	-	-
Reservoir Shaft at 15m	0	NT326947	-	-
Coxtool Shaft at 15m	0	NT326947	-	-
Windmill Shaft at 20m	0	NT329951	-	-
Michael Shafts at 11.6m	0	NT336962	-	-
Wemyss Den Burn at 45m:	1000	NT338977	0.982	1.130
Frances				
North Foreshore at Dysart at 10m	0	NT307933	-	-
Foreshore below Frances Colliery at 10m	0	NT310937	-	-
Frances Shaft at 45m	1000	NT309938	1.040	1.166
Blair Den shafts at 5m	0	NT314943	-	-
Blair Den shafts at 15m	0	NT314943	-	-
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	1000	NT294973	0.906	1.041
River Ore, north-east of Balbeggie Cottage at 50m:	1000	NT286966	0.844	0.988
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	1000	NO308004	0.943	1.028
Old Shaft at 40m	1000	NO307009	0.943	1.027
Discharge to Lochty Burn at 45m	1000	NT301982	0.485	0.885
River Ore between Lochty Burn confluence and New Bridge at 43m	1000	NT307984	0.852	0.943
Furnace Shaft at Lochty Farm at 45m	1000	NT296983	0.784	0.884
River Ore near Tullybreck at 45m	1000	NT313986	0.784	0.884
Julian Shaft at 48m	1000	NT306987	0.674	0.786
Lochty Side Shaft at 50m	1000	NT298986	0.587	0.714
Discharge between Ore Bridge and Railway Viaduct at 48m	1000	NT294973	0.673	0.786

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Median Time of Discharge (Years)	Quartile Range
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	22.17	3.79
Old Shaft at 20m	1000	NT348999	24.06	4.01
Old Shaft at 25m	1000	NO354002	24.93	4.03
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	24.06	3.73
Bowhouse Outcrops at 20m	1000	NO360008	24.06	4.01
Chemiss Outcrops at 20m	1000	NO364006	24.06	4.01
Kirkland Shafts at 20m	1000	NO367004	24.06	4.01
Leven Shafts at 25m	1000	NO374002	24.93	3.73
Drainage Level in Leven Harbour at 5m	1000	NO383003	21.97	3.80
Michael				
Victoria Shaft at 7.3m	1000	NT322947	21.07	3.23
Lady Shaft at 15m	1000	NT324947	22.67	3.25
Reservoir Shaft at 15m	1000	NT326947	22.67	3.25
Coxtool Shaft at 15m	1000	NT326947	22.67	3.25
Windmill Shaft at 20m	1000	NT329951	23.86	3.31
Michael Shafts at 11.6m	1000	NT336962	21.90	3.29
Wemyss Den Burn at 45m:	24	NT338977	41.39	11.21
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	20.89	2.80
Foreshore below Frances Colliery at 10m	1000	NT310937	20.89	2.80
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	19.55	2.89
Blair Den shafts at 15m	1000	NT314943	22.03	2.95
Blair Den shafts at 25m	1000	NT314943	25.36	2.90
Blair Den shafts at 35m	684	NT314943	35.73	4.78
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	103	NT294973	35.74	11.01
River Ore, north-east of Balbeggie Cottage at 50m:	8	NT286966	35.76	11.00
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	997	NO308004	29.16	6.37
Old Shaft at 40m	997	NO307009	29.16	6.37
Discharge to Lochty Burn at 45m	797	NT301982	35.68	2.71
River Ore between Lochty Burn confluence and New Bridge at 43m	954	NT307984	33.03	6.51
Furnace Shaft at Lochty Farm at 45m	797	NT296983	33.03	2.71
River Ore near Tullybreck at 45m	797	NT313986	32.06	2.71
Julian Shaft at 48m	255	NT306987	35.73	11.00
Lochty Side Shaft at 50m	34	NT298986	35.74	11.00
Discharge between Ore Bridge and Railway Viaduct at 48m	255	NT294973	35.73	11.00

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Time of Discharge of No.	Upper Quartile of Time of Discharge of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	20.61	24.41
Old Shaft at 20m	1000	NT348999	22.23	26.24
Old Shaft at 25m	1000	NO354002	23.81	27.55
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	22.23	26.24
Bowhouse Outcrops at 20m	1000	NO360008	22.23	26.24
Chemiss Outcrops at 20m	1000	NO364006	22.23	26.24
Kirkland Shafts at 20m	1000	NO367004	22.23	26.24
Leven Shafts at 25m	1000	NO374002	23.81	27.55
Drainage Level in Leven Harbour at 5m	1000	NO383003	20.30	24.10
Michael				
Victoria Shaft at 7.3m	1000	NT322947	19.54	22.77
Lady Shaft at 15m	1000	NT324947	21.03	24.28
Reservoir Shaft at 15m	1000	NT326947	21.03	24.28
Coxtool Shaft at 15m	1000	NT326947	21.03	24.28
Windmill Shaft at 20m	1000	NT329951	22.00	25.31
Michael Shafts at 11.6m	1000	NT336962	20.53	23.82
Wemyss Den Burn at 45m:	24	NT338977	35.74	46.95
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	19.37	22.17
Foreshore below Frances Colliery at 10m	1000	NT310937	19.37	22.17
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	18.18	21.07
Blair Den shafts at 15m	1000	NT314943	20.91	23.85
Blair Den shafts at 25m	1000	NT314943	24.41	27.30
Blair Den shafts at 35m	684	NT314943	33.03	37.81
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	103	NT294973	35.73	46.74
River Ore, north-east of Balbeggie Cottage at 50m:	8	NT286966	35.74	46.74
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	997	NO308004	26.01	32.38
Old Shaft at 40m	997	NO307009	26.01	32.38
Discharge to Lochty Burn at 45m	797	NT301982	33.03	35.74
River Ore between Lochty Burn confluence and New Bridge at 43m	954	NT307984	29.17	35.68
Furnace Shaft at Lochty Farm at 45m	797	NT296983	33.03	35.74
River Ore near Tullybreck at 45m	797	NT313986	33.03	35.74
Julian Shaft at 48m	255	NT306987	35.73	46.74
Lochty Side Shaft at 50m	34	NT298986	35.74	46.74
Discharge between Ore Bridge and Railway Viaduct at 48m	255	NT294973	35.73	46.74

Stochastic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Median Time of Discharge (Years) of No.	Quartile Range of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	22.22	3.83
Old Shaft at 20m	196	NT348999	35.64	11.00
Old Shaft at 25m	0	NO354002	-	-
Duniface Adit to Kennoway Burn at 20m	196	NO352005	35.64	11.00
Bowhouse Outcrops at 20m	196	NO360008	35.64	11.00
Chemiss Outcrops at 20m	196	NO364006	35.64	11.00
Kirkland Shafts at 20m	196	NO367004	35.64	11.00
Leven Shafts at 25m	0	NO374002	-	-
Drainage Level in Leven Harbour at 5m	1000	NO383003	21.98	3.82
Michael				
Victoria Shaft at 7.3m	1000	NT322947	21.08	3.23
Lady Shaft at 15m	1000	NT324947	23.10	3.30
Reservoir Shaft at 15m	1000	NT326947	23.10	3.30
Coxtool Shaft at 15m	1000	NT326947	23.10	3.30
Windmill Shaft at 20m	404	NT329951	35.69	11.00
Michael Shafts at 11.6m	1000	NT336962	22.00	3.19
Wemyss Den Burn at 45m:	0	NT338977	-	-
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	21.03	2.85
Foreshore below Frances Colliery at 10m	1000	NT310937	21.03	2.85
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	19.55	2.89
Blair Den shafts at 15m	1000	NT314943	23.25	2.88
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	0	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	0	NT286966	-	-
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	34	NO308004	35.73	0.08
Old Shaft at 40m	34	NO307009	35.73	0.08
Discharge to Lochty Burn at 45m	0	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	7	NT307984	35.74	0.02
Furnace Shaft at Lochty Farm at 45m	0	NT296983	-	-
River Ore near Tullybreck at 45m	0	NT313986	-	-
Julian Shaft at 48m	0	NT306987	-	-
Lochty Side Shaft at 50m	0	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	0	NT294973	-	-

Stochastic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Time of Discharge of No.	Upper Quartile of Time of Discharge of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	20.62	24.45
Old Shaft at 20m	196	NT348999	24.73	35.74
Old Shaft at 25m	0	NO354002	-	-
Duniface Adit to Kennoway Burn at 20m	196	NO352005	24.73	35.74
Bowhouse Outcrops at 20m	196	NO360008	24.73	35.74
Chemiss Outcrops at 20m	196	NO364006	24.73	35.74
Kirkland Shafts at 20m	196	NO367004	24.73	35.74
Leven Shafts at 25m	0	NO374002	-	-
Drainage Level in Leven Harbour at 5m	1000	NO383003	20.31	24.13
Michael				
Victoria Shaft at 7.3m	1000	NT322947	19.55	22.77
Lady Shaft at 15m	1000	NT324947	21.38	24.67
Reservoir Shaft at 15m	1000	NT326947	21.38	24.67
Coxtool Shaft at 15m	1000	NT326947	21.38	24.67
Windmill Shaft at 20m	404	NT329951	24.73	35.74
Michael Shafts at 11.6m	1000	NT336962	20.67	23.86
Wemyss Den Burn at 45m:	0	NT338977	-	-
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	19.49	22.34
Foreshore below Frances Colliery at 10m	1000	NT310937	19.49	22.34
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	18.18	21.07
Blair Den shafts at 15m	1000	NT314943	21.77	24.65
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	0	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	0	NT286966	-	-
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	34	NO308004	35.67	35.74
Old Shaft at 40m	34	NO307009	35.67	35.74
Discharge to Lochty Burn at 45m	0	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	7	NT307984	35.74	35.76
Furnace Shaft at Lochty Farm at 45m	0	NT296983	-	-
River Ore near Tullybreck at 45m	0	NT313986	-	-
Julian Shaft at 48m	0	NT306987	-	-
Lochty Side Shaft at 50m	0	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	0	NT294973	-	-

Stochastic Analysis using No Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Median Time of Discharge (Years)	Quartile Range
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	0	NT366986	-	-
Old Shaft at 20m	1000	NT348999	23.86	3.98
Old Shaft at 25m	1000	NO354002	24.58	3.87
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	23.86	3.98
Bowhouse Outcrops at 20m	1000	NO360008	23.86	3.98
Chemiss Outcrops at 20m	1000	NO364006	23.86	3.98
Kirkland Shafts at 20m	1000	NO367004	23.86	3.98
Leven Shafts at 25m	1000	NO374002	24.58	3.87
Drainage Level in Leven Harbour at 5m	0	NO383003	-	-
Michael				
Victoria Shaft at 7.3m	0	NT322947	-	-
Lady Shaft at 15m	0	NT324947	-	-
Reservoir Shaft at 15m	0	NT326947	-	-
Coxtool Shaft at 15m	0	NT326947	-	-
Windmill Shaft at 20m	0	NT329951	-	-
Michael Shafts at 11.6m	0	NT336962	-	-
Wemyss Den Burn at 45m:	1000	NT338977	27.09	4.40
Frances				
North Foreshore at Dysart at 10m	0	NT307933	-	-
Foreshore below Frances Colliery at 10m	0	NT310937	-	-
Frances Shaft at 45m	1000	NT309938	26.68	3.65
Blair Den shafts at 5m	0	NT314943	-	-
Blair Den shafts at 15m	0	NT314943	-	-
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	1000	NT294973	27.18	3.77
River Ore, north-east of Balbeggie Cottage at 50m:	1000	NT286966	27.64	3.99
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	1000	NO308004	25.31	3.23
Old Shaft at 40m	1000	NO307009	25.31	3.23
Discharge to Lochty Burn at 45m	1000	NT301982	26.44	4.15
River Ore between Lochty Burn confluence and New Bridge at 43m	1000	NT307984	26.01	3.19
Furnace Shaft at Lochty Farm at 45m	1000	NT296983	26.44	4.15
River Ore near Tullybreck at 45m	1000	NT313986	26.44	4.15
Julian Shaft at 48m	1000	NT306987	27.34	3.58
Lochty Side Shaft at 50m	1000	NT298986	29.08	4.82
Discharge between Ore Bridge and Railway Viaduct at 48m	1000	NT294973	27.34	3.58

Stochastic Analysis using No Flow to the Sea Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Time of Discharge of No.	Upper Quartile of Time of Discharge of No.
Wellesley				
Wellesley Shafts at 6.7m	0	NT366986	-	-
Old Shaft at 20m	1000	NT348999	21.96	25.94
Old Shaft at 25m	1000	NO354002	22.77	26.63
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	21.96	25.94
Bowhouse Outcrops at 20m	1000	NO360008	21.96	25.94
Chemiss Outcrops at 20m	1000	NO364006	21.96	25.94
Kirkland Shafts at 20m	1000	NO367004	21.96	25.94
Leven Shafts at 25m	1000	NO374002	22.77	26.63
Drainage Level in Leven Harbour at 5m	0	NO383003	-	-
Michael				
Victoria Shaft at 7.3m	0	NT322947	-	-
Lady Shaft at 15m	0	NT324947	-	-
Reservoir Shaft at 15m	0	NT326947	-	-
Coxtool Shaft at 15m	0	NT326947	-	-
Windmill Shaft at 20m	0	NT329951	-	-
Michael Shafts at 11.6m	0	NT336962	-	-
Wemyss Den Burn at 45m:	1000	NT338977	25.10	29.50
Frances				
North Foreshore at Dysart at 10m	0	NT307933	-	-
Foreshore below Frances Colliery at 10m	0	NT310937	-	-
Frances Shaft at 45m	1000	NT309938	25.03	28.68
Blair Den shafts at 5m	0	NT314943	-	-
Blair Den shafts at 15m	0	NT314943	-	-
Blair Den shafts at 25m	0	NT314943	-	-
Blair Den shafts at 35m	0	NT314943	-	-
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	1000	NT294973	25.40	29.16
River Ore, north-east of Balbeggie Cottage at 50m:	1000	NT286966	26.01	30.00
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	1000	NO308004	23.90	27.13
Old Shaft at 40m	1000	NO307009	23.90	27.13
Discharge to Lochty Burn at 45m	1000	NT301982	24.68	28.84
River Ore between Lochty Burn confluence and New Bridge at 43m	1000	NT307984	24.58	27.77
Furnace Shaft at Lochty Farm at 45m	1000	NT296983	24.68	28.84
River Ore near Tullybreck at 45m	1000	NT313986	24.68	28.84
Julian Shaft at 48m	1000	NT306987	25.93	29.51
Lochty Side Shaft at 50m	1000	NT298986	26.44	31.26
Discharge between Ore Bridge and Railway Viaduct at 48m	1000	NT294973	25.93	29.51

APPENDIX 3

RESULTS USING THE SENSITIVITY ANALYSIS SCENARIOS

Deterministic Analysis using Scenario 1

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	1.163	28.83
Old Shaft at 20m	NT348999	0.800	31.76
Old Shaft at 25m	NO354002	0.610	34.07
Duniface Adit to Kennoway Burn at 20m	NO352005	0.800	31.76
Bowhouse Outcrops at 20m	NO360008	0.800	31.76
Chemiss Outcrops at 20m	NO364006	0.800	31.76
Kirkland Shafts at 20m	NO367004	0.800	31.76
Leven Shafts at 25m	NO374002	0.611	34.07
Drainage Level in Leven Harbour at 5m	NO383003	1.199	28.46
Michael			
Victoria Shaft at 7.3m	NT322947	1.148	27.64
Lady Shaft at 15m	NT324947	0.962	29.91
Reservoir Shaft at 15m	NT326947	0.962	29.91
Coxtool Shaft at 15m	NT326947	0.961	29.91
Windmill Shaft at 20m	NT329951	0.817	31.85
Michael Shafts at 11.6m	NT336962	1.051	29.05
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.022	27.55
Foreshore below Frances Colliery at 10m	NT310937	1.022	27.55
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.141	26.08
Blair Den shafts at 15m	NT314943	0.892	29.83
Blair Den shafts at 25m	NT314943	0.531	32.63
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.033	46.74
Old Shaft at 40m	NO307009	0.033	46.74
Discharge to Lochty Burn at 45m	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	-	-
Furnace Shaft at Lochty Farm at 45m	NT296983	-	-
River Ore near Tullybreck at 45m	NT313986	-	-
Julian Shaft at 48m	NT306987	-	-
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	-	-
Total		18.156	

Deterministic Analysis using Scenario 2

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	1.376	17.22
Old Shaft at 20m	NT348999	1.081	18.77
Old Shaft at 25m	NO354002	0.944	19.50
Duniface Adit to Kennoway Burn at 20m	NO352005	1.081	18.77
Bowhouse Outcrops at 20m	NO360008	1.081	18.77
Chemiss Outcrops at 20m	NO364006	1.081	18.77
Kirkland Shafts at 20m	NO367004	1.081	18.77
Leven Shafts at 25m	NO374002	0.944	19.53
Drainage Level in Leven Harbour at 5m	NO383003	1.409	17.08
Michael			
Victoria Shaft at 7.3m	NT322947	1.362	16.23
Lady Shaft at 15m	NT324947	1.198	17.24
Reservoir Shaft at 15m	NT326947	1.198	17.24
Coxtool Shaft at 15m	NT326947	1.198	17.24
Windmill Shaft at 20m	NT329951	1.085	18.51
Michael Shafts at 11.6m	NT336962	1.273	16 74
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.204	15.46
Foreshore below Frances Colliery at 10m	NT310937	1.204	15.46
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.307	14 45
Blair Den shafts at 15m	NT314943	1.088	16.54
Blair Den shafts at 25m	NT314943	0.810	19 74
Blair Den shafts at 35m	NT314943	0.332	24 62
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	0.005	35.73
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.565	21 38
Old Shaft at 40m	NO307009	0.565	21 38
Discharge to Lochty Burn at 45m	NT301982	0.193	23 89
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.389	23.06
Furnace Shaft at Lochty Farm at 45m	NT296983	0.192	23.89
River Ore near Tullybreck at 45m	NT313986	0.192	23 89
Julian Shaft at 48m	NT306987	0.079	24.74
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	0.079	24 74
Total		25.593	

Deterministic Analysis using Scenario 3

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	1.039	36.64
Old Shaft at 20m	NT348999	0.617	41.20
Old Shaft at 25m	NO354002	0.353	46.58
Duniface Adit to Kennoway Burn at 20m	NO352005	0.617	41.20
Bowhouse Outcrops at 20m	NO360008	0.617	41.20
Chemiss Outcrops at 20m	NO364006	0.617	41.20
Kirkland Shafts at 20m	NO367004	0.617	41.20
Leven Shafts at 25m	NO374002	0.352	46.58
Drainage Level in Leven Harbour at 5m	NO383003	1.081	36.30
Michael			
Victoria Shaft at 7.3m	NT322947	1.020	36.04
Lady Shaft at 15m	NT324947	0.803	38.69
Reservoir Shaft at 15m	NT326947	0.803	38.69
Coxtool Shaft at 15m	NT326947	0.803	38.69
Windmill Shaft at 20m	NT329951	0.623	41.46
Michael Shafts at 11.6m	NT336962	0.907	37.45
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	0.896	36.59
Foreshore below Frances Colliery at 10m	NT310937	0.896	36.59
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.029	34.90
Blair Den shafts at 15m	NT314943	0.741	39.15
Blair Den shafts at 25m	NT314943	0.193	49.63
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	-	-
Old Shaft at 40m	NO307009	-	-
Discharge to Lochty Burn at 45m	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	-	-
Furnace Shaft at Lochty Farm at 45m	NT296983	-	-
River Ore near Tullybreck at 45m	NT313986	-	-
Julian Shaft at 48m	NT306987	-	-
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	-	-
Total		14.623	

Deterministic Analysis using Scenario 4

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	1.468	13.07
Old Shaft at 20m	NT348999	1.190	13.88
Old Shaft at 25m	NO354002	1.066	14.35
Duniface Adit to Kennoway Burn at 20m	NO352005	1.190	13.88
Bowhouse Outcrops at 20m	NO360008	1.189	13.88
Chemiss Outcrops at 20m	NO364006	1.189	13.88
Kirkland Shafts at 20m	NO367004	1.189	13.88
Leven Shafts at 25m	NO374002	1.066	14.35
Drainage Level in Leven Harbour at 5m	NO383003	1.499	12.96
Michael			
Victoria Shaft at 7.3m	NT322947	1.453	12.41
Lady Shaft at 15m	NT324947	1.299	12.98
Reservoir Shaft at 15m	NT326947	1.299	12.98
Coxtool Shaft at 15m	NT326947	1.298	12.98
Windmill Shaft at 20m	NT329951	1.190	13.58
Michael Shafts at 11.6m	NT336962	1.371	12.85
Wemyss Den Burn at 45m:	NT338977	0.204	22.03
Frances			
North Foreshore at Dysart at 10m	NT307933	1.277	11.76
Foreshore below Frances Colliery at 10m	NT310937	1.277	11.76
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.377	10.95
Blair Den shafts at 15m	NT314943	1.169	12.74
Blair Den shafts at 25m	NT314943	0.899	13.77
Blair Den shafts at 35m	NT314943	0.505	16.55
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	0.132	21.05
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	0.020	23.89
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.674	14.94
Old Shaft at 40m	NO307009	0.673	14.94
Discharge to Lochty Burn at 45m	NT301982	0.401	15.81
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.529	15.44
Furnace Shaft at Lochty Farm at 45m	NT296983	0.400	15.81
River Ore near Tullybreck at 45m	NT313986	0.400	15.81
Julian Shaft at 48m	NT306987	0.173	19.03
Lochty Side Shaft at 50m	NT298986	0.090	23.89
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	0.172	19.03
Total		29.328	

APPENDIX 4

RESULTS USING THE COLEBROOK-WHITE EQUATION

Deterministic Analysis using Intermediate Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	1.280	23.09
Old Shaft at 20m	NT348999	0.956	24.73
Old Shaft at 25m	NO354002	0.801	25.94
Duniface Adit to Kennoway Burn at 20m	NO352005	0.956	24.73
Bowhouse Outcrops at 20m	NO360008	0.956	24.73
Chemiss Outcrops at 20m	NO364006	0.956	24.73
Kirkland Shafts at 20m	NO367004	0.956	24.73
Leven Shafts at 25m	NO374002	0.801	25.94
Drainage Level in Leven Harbour at 5m	NO383003	1.316	22.98
Michael			
Victoria Shaft at 7.3m	NT322947	1.270	21.85
Lady Shaft at 15m	NT324947	1.100	23.41
Reservoir Shaft at 15m	NT326947	1.099	23.41
Coxtool Shaft at 15m	NT326947	1.099	23.41
Windmill Shaft at 20m	NT329951	0.972	24.57
Michael Shafts at 11.6m	NT336962	1.179	22.71
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.187	20.88
Foreshore below Frances Colliery at 10m	NT310937	1.187	20.88
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.284	19.29
Blair Den shafts at 15m	NT314943	1.070	22.00
Blair Den shafts at 25m	NT314943	0.786	25.02
Blair Den shafts at 35m	NT314943	0.292	33.02
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.460	28.24
Old Shaft at 40m	NO307009	0.460	28.24
Discharge to Lochty Burn at 45m	NT301982	0.025	35.66
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.218	32.07
Furnace Shaft at Lochty Farm at 45m	NT296983	0.024	35.66
River Ore near Tullybreck at 45m	NT313986	0.024	35.66
Julian Shaft at 48m	NT306987	-	-
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	-	-
Total		22.714	

Deterministic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	4.689	23.10
Old Shaft at 20m	NT348999	-	
Old Shaft at 25m	NO354002	-	
Duniface Adit to Kennoway Burn at 20m	NO352005	-	
Bowhouse Outcrops at 20m	NO360008	-	
Chemiss Outcrops at 20m	NO364006	-	
Kirkland Shafts at 20m	NO367004	-	
Leven Shafts at 25m	NO374002	-	
Drainage Level in Leven Harbour at 5m	NO383003	5.108	22.98
Michael			
Victoria Shaft at 7.3m	NT322947	2.242	21.86
Lady Shaft at 15m	NT324947	1.177	23.87
Reservoir Shaft at 15m	NT326947	1.177	23.87
Coxtool Shaft at 15m	NT326947	1.176	23.87
Windmill Shaft at 20m	NT329951	-	-
Michael Shafts at 11.6m	NT336962	1.733	22.81
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.497	20.95
Foreshore below Frances Colliery at 10m	NT310937	1.496	20.95
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.833	19.29
Blair Den shafts at 15m	NT314943	1.037	23.04
Blair Den shafts at 25m	NT314943	-	-
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	-	-
Old Shaft at 40m	NO307009	-	-
Discharge to Lochty Burn at 45m	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	-	-
Furnace Shaft at Lochty Farm at 45m	NT296983	-	-
River Ore near Tullybreck at 45m	NT313986	-	-
Julian Shaft at 48m	NT306987	-	-
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	-	-
Total		23.166	

Deterministic Analysis using No Flow to the Sea Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	-	-
Old Shaft at 20m	NT348999	1.494	24.59
Old Shaft at 25m	NO354002	1.399	25.07
Duniface Adit to Kennoway Burn at 20m	NO352005	1.493	24.59
Bowhouse Outcrops at 20m	NO360008	1.493	24.59
Chemiss Outcrops at 20m	NO364006	1.493	24.59
Kirkland Shafts at 20m	NO367004	1.493	24.59
Leven Shafts at 25m	NO374002	1.398	25.07
Drainage Level in Leven Harbour at 5m	NO383003	-	-
Michael			
Victoria Shaft at 7.3m	NT322947	-	-
Lady Shaft at 15m	NT324947	-	-
Reservoir Shaft at 15m	NT326947	-	-
Coxtool Shaft at 15m	NT326947	-	-
Windmill Shaft at 20m	NT329951	-	-
Michael Shafts at 11.6m	NT336962	-	-
Wemyss Den Burn at 45m:	NT338977	1.108	27.57
Frances			
North Foreshore at Dysart at 10m	NT307933	-	-
Foreshore below Frances Colliery at 10m	NT310937	-	-
Frances Shaft at 45m	NT309938	1.211	26.66
Blair Den shafts at 5m	NT314943	-	-
Blair Den shafts at 15m	NT314943	-	-
Blair Den shafts at 25m	NT314943	-	-
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	1.045	27.31
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	0.990	27.69
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.985	25.69
Old Shaft at 40m	NO307009	0.984	25.69
Discharge to Lochty Burn at 45m	NT301982	0.834	26.71
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.897	26.28
Furnace Shaft at Lochty Farm at 45m	NT296983	0.833	26.71
River Ore near Tullybreck at 45m	NT313986	0.833	26.71
Julian Shaft at 48m	NT306987	0.727	27.64
Lochty Side Shaft at 50m	NT298986	0.654	29.11
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	0.726	27.64
Total		22.090	

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Mean Volume of Discharge (Ml/day)		Standard Deviation of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.283		0.067	
Old Shaft at 20m	1000	NT348999	0.958		0.092	
Old Shaft at 25m	1000	NO354002	0.801		0.112	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.958		0.092	
Bowhouse Outcrops at 20m	1000	NO360008	0.958		0.092	
Chemiss Outcrops at 20m	1000	NO364006	0.958		0.092	
Kirkland Shafts at 20m	1000	NO367004	0.958		0.092	
Leven Shafts at 25m	1000	NO374002	0.801		0.112	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.318		0.066	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.280		0.058	
Lady Shaft at 15m	1000	NT324947	1.109		0.067	
Reservoir Shaft at 15m	1000	NT326947	1.109		0.067	
Coxtool Shaft at 15m	1000	NT326947	1.109		0.067	
Windmill Shaft at 20m	1000	NT329951	0.980		0.076	
Michael Shafts at 11.6m	1000	NT336962	1.188		0.062	
Wemyss Den Burn at 45m:	35	NT338977	0.083	0.003	0.443	0.016
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.098		0.043	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.098		0.043	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.199		0.038	
Blair Den shafts at 15m	1000	NT314943	0.977		0.052	
Blair Den shafts at 25m	1000	NT314943	0.652		0.082	
Blair Den shafts at 35m	430	NT314943	0.126	0.054	0.161	0.077
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	75	NT294973	0.002	0.0002	0.009	0.001
River Ore, north-east of Balbeggie Cottage at 50m:	3	NT286966	0.0006	2e-6	0.013	4e-5
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	999	NO308004	0.432	0.432	0.114	0.114
Old Shaft at 40m	999	NO307009	0.432	0.432	0.114	0.114
Discharge to Lochty Burn at 45m	857	NT301982	0.064	0.055	0.074	0.068
River Ore between Lochty Burn confluence and New Bridge at 43m	968	NT307984	0.204	0.198	0.129	0.127
Furnace Shaft at Lochty Farm at 45m	857	NT296983	0.063	0.054	0.074	0.068
River Ore near Tullybreck at 45m	857	NT313986	0.063	0.054	0.074	0.068
Julian Shaft at 48m	328	NT306987	0.072	0.024	0.105	0.036
Lochty Side Shaft at 50m	36	NT298986	0.069	0.002	0.361	0.014
Discharge between Ore Bridge and Railway Viaduct at 48m	328	NT294973	0.072	0.105	0.105	0.036
Total			22.475	22.205		

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Mean Time of Discharge (Years)	Standard Deviation of Time
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	23.05	1.96
Old Shaft at 20m	1000	NT348999	24.91	2.15
Old Shaft at 25m	1000	NO354002	26.10	2.50
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	24.91	2.15
Bowhouse Outcrops at 20m	1000	NO360008	24.91	2.15
Chemiss Outcrops at 20m	1000	NO364006	24.91	2.15
Kirkland Shafts at 20m	1000	NO367004	24.91	2.15
Leven Shafts at 25m	1000	NO374002	26.11	2.50
Drainage Level in Leven Harbour at 5m	1000	NO383003	22.85	1.94
Michael				
Victoria Shaft at 7.3m	1000	NT322947	22.07	1.70
Lady Shaft at 15m	1000	NT324947	23.41	1.80
Reservoir Shaft at 15m	1000	NT326947	23.41	1.80
Coxtool Shaft at 15m	1000	NT326947	23.41	1.80
Windmill Shaft at 20m	1000	NT329951	24.52	1.93
Michael Shafts at 11.6m	1000	NT336962	22.81	1.75
Wemyss Den Burn at 45m:	35	NT338977	40.93	218.15
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	19.96	2.06
Foreshore below Frances Colliery at 10m	1000	NT310937	19.96	2.06
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	17.60	2.28
Blair Den shafts at 15m	1000	NT314943	21.97	1.74
Blair Den shafts at 25m	1000	NT314943	26.08	2.29
Blair Den shafts at 35m	430	NT314943	38.05	44.36
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	75	NT294973	41.75	147.76
River Ore, north-east of Balbeggie Cottage at 50m:	3	NT286966	39.42	880.15
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	999	NO308004	29.16	4.07
Old Shaft at 40m	999	NO307009	29.16	4.07
Discharge to Lochty Burn at 45m	857	NT301982	35.32	15.50
River Ore between Lochty Burn confluence and New Bridge at 43m	968	NT307984	32.35	7.75
Furnace Shaft at Lochty Farm at 45m	857	NT296983	35.34	15.52
River Ore near Tullybreck at 45m	857	NT313986	35.34	15.52
Julian Shaft at 48m	328	NT306987	39.07	56.36
Lochty Side Shaft at 50m	36	NT298986	40.02	210.13
Discharge between Ore Bridge and Railway Viaduct at 48m	328	NT294973	39.07	56.36

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Median Volume of Discharge (Ml/day)		Quartile Range	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.284		0.094	
Old Shaft at 20m	1000	NT348999	0.962		0.131	
Old Shaft at 25m	1000	NO354002	0.808		0.155	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.962		0.131	
Bowhouse Outcrops at 20m	1000	NO360008	0.962		0.131	
Chemiss Outcrops at 20m	1000	NO364006	0.962		0.131	
Kirkland Shafts at 20m	1000	NO367004	0.962		0.131	
Leven Shafts at 25m	1000	NO374002	0.808		0.155	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.320		0.092	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.281		0.078	
Lady Shaft at 15m	1000	NT324947	1.112		0.089	
Reservoir Shaft at 15m	1000	NT326947	1.112		0.089	
Coxtool Shaft at 15m	1000	NT326947	1.112		0.089	
Windmill Shaft at 20m	1000	NT329951	0.984		0.106	
Michael Shafts at 11.6m	1000	NT336962	1.189		0.083	
Wemyss Den Burn at 45m:	35	NT338977	0.081	0	0.016	0
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.104		0.059	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.103		0.059	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.202		0.054	
Blair Den shafts at 15m	1000	NT314943	0.984		0.075	
Blair Den shafts at 25m	1000	NT314943	0.663		0.116	
Blair Den shafts at 35m	430	NT314943	0.106	0	0.077	0.096
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	75	NT294973	0.0009	0	0.003	0
River Ore, north-east of Balbeggie Cottage at 50m:	3	NT286966	0.0007	0	0.0008	0
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	999	NO308004	0.456	0.456	0.125	0.126
Old Shaft at 40m	999	NO307009	0.456	0.456	0.125	0.126
Discharge to Lochty Burn at 45m	857	NT301982	0.035	0.024	0.094	0.085
River Ore between Lochty Burn confluence and New Bridge at 43m	968	NT307984	0.214	0.209	0.215	0.222
Furnace Shaft at Lochty Farm at 45m	857	NT296983	0.035	0.023	0.094	0.085
River Ore near Tullybreck at 45m	857	NT313986	0.035	0.023	0.094	0.085
Julian Shaft at 48m	328	NT306987	0.076	0	0.007	0.073
Lochty Side Shaft at 50m	36	NT298986	0.077	0	0.009	0
Discharge between Ore Bridge and Railway Viaduct at 48m	328	NT294973	0.076	0	0.007	0.073
Total			22.525	22.067		

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Volume of Discharge		Upper Quartile of Volume of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.236		1.329	
Old Shaft at 20m	1000	NT348999	0.894		1.025	
Old Shaft at 25m	1000	NO354002	0.725		0.881	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.894		1.025	
Bowhouse Outcrops at 20m	1000	NO360008	0.894		1.025	
Chemiss Outcrops at 20m	1000	NO364006	0.894		1.025	
Kirkland Shafts at 20m	1000	NO367004	0.894		1.024	
Leven Shafts at 25m	1000	NO374002	0.725		0.881	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.271		1.363	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.244		1.322	
Lady Shaft at 15m	1000	NT324947	1.068		1.157	
Reservoir Shaft at 15m	1000	NT326947	1.068		1.157	
Coxtool Shaft at 15m	1000	NT326947	1.068		1.157	
Windmill Shaft at 20m	1000	NT329951	0.932		1.038	
Michael Shafts at 11.6m	1000	NT336962	1.150		1.233	
Wemyss Den Burn at 45m:	35	NT338977	0.072	0	0.088	0
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.069		1.128	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.069		1.128	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.173		1.227	
Blair Den shafts at 15m	1000	NT314943	0.941		1.017	
Blair Den shafts at 25m	1000	NT314943	0.598		0.714	
Blair Den shafts at 35m	430	NT314943	0.079	0	0.156	0.096
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	75	NT294973	0.0003	0	0.003	0
River Ore, north-east of Balbeggie Cottage at 50m:	3	NT286966	0.0001	0	0.0009	0
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	999	NO308004	0.387	0.386	0.512	0.512
Old Shaft at 40m	999	NO307009	0.387	0.386	0.512	0.512
Discharge to Lochty Burn at 45m	857	NT301982	0.007	0.003	0.101	0.088
River Ore between Lochty Burn confluence and New Bridge at 43m	968	NT307984	0.093	0.083	0.308	0.305
Furnace Shaft at Lochty Farm at 45m	857	NT296983	0.007	0.003	0.100	0.088
River Ore near Tullybreck at 45m	857	NT313986	0.007	0.003	0.100	0.088
Julian Shaft at 48m	328	NT306987	0.073	0	0.080	0.073
Lochty Side Shaft at 50m	36	NT298986	0.073	0	0.082	0
Discharge between Ore Bridge and Railway Viaduct at 48m	328	NT294973	0.073	0	0.080	0.073

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Median Time of Discharge (Years)	Quartile Range
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	23.01	2.51
Old Shaft at 20m	1000	NT348999	24.68	2.41
Old Shaft at 25m	1000	NO354002	25.93	2.95
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	24.68	2.41
Bowhouse Outcrops at 20m	1000	NO360008	24.68	2.41
Chemiss Outcrops at 20m	1000	NO364006	24.68	2.41
Kirkland Shafts at 20m	1000	NO367004	24.68	2.41
Leven Shafts at 25m	1000	NO374002	25.93	2.95
Drainage Level in Leven Harbour at 5m	1000	NO383003	22.78	2.49
Michael				
Victoria Shaft at 7.3m	1000	NT322947	21.95	2.07
Lady Shaft at 15m	1000	NT324947	23.59	2.50
Reservoir Shaft at 15m	1000	NT326947	23.59	2.50
Coxtool Shaft at 15m	1000	NT326947	23.59	2.50
Windmill Shaft at 20m	1000	NT329951	24.57	2.02
Michael Shafts at 11.6m	1000	NT336962	22.78	2.31
Wemyss Den Burn at 45m:	35	NT338977	36.04	11.03
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	20.26	2.51
Foreshore below Frances Colliery at 10m	1000	NT310937	20.26	2.51
Frances Shaft at 45m	0	NT309938		
Blair Den shafts at 5m	1000	NT314943	17.87	3.42
Blair Den shafts at 15m	1000	NT314943	21.78	2.02
Blair Den shafts at 25m	1000	NT314943	25.60	2.41
Blair Den shafts at 35m	430	NT314943	35.74	3.89
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	75	NT294973	35.76	11.00
River Ore, north-east of Balbeggie Cottage at 50m:	3	NT286966	35.76	11.03
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	999	NO308004	28.23	5.80
Old Shaft at 40m	999	NO307009	28.23	5.80
Discharge to Lochty Burn at 45m	857	NT301982	35.65	3.66
River Ore between Lochty Burn confluence and New Bridge at 43m	968	NT307984	32.07	5.40
Furnace Shaft at Lochty Farm at 45m	857	NT296983	35.65	3.66
River Ore near Tullybreck at 45m	857	NT313986	35.65	3.66
Julian Shaft at 48m	328	NT306987	35.74	11.01
Lochty Side Shaft at 50m	36	NT298986	35.74	11.00
Discharge between Ore Bridge and Railway Viaduct at 48m	328	NT294973	35.74	11.01

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Time of Discharge of No.	Upper Quartile of Time of Discharge of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	21.77	24.28
Old Shaft at 20m	1000	NT348999	23.76	26.17
Old Shaft at 25m	1000	NO354002	24.58	27.52
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	23.76	26.17
Bowhouse Outcrops at 20m	1000	NO360008	23.76	26.17
Chemiss Outcrops at 20m	1000	NO364006	23.76	26.17
Kirkland Shafts at 20m	1000	NO367004	23.76	26.17
Leven Shafts at 25m	1000	NO374002	24.58	27.52
Drainage Level in Leven Harbour at 5m	1000	NO383003	21.56	24.05
Michael				
Victoria Shaft at 7.3m	1000	NT322947	21.02	23.09
Lady Shaft at 15m	1000	NT324947	22.08	24.58
Reservoir Shaft at 15m	1000	NT326947	22.08	24.58
Coxtool Shaft at 15m	1000	NT326947	22.08	24.58
Windmill Shaft at 20m	1000	NT329951	23.43	25.45
Michael Shafts at 11.6m	1000	NT336962	21.60	23.90
Wemyss Den Burn at 45m:	35	NT338977	35.74	46.77
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	18.78	21.28
Foreshore below Frances Colliery at 10m	1000	NT310937	18.78	21.28
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	15.73	19.16
Blair Den shafts at 15m	1000	NT314943	21.02	23.05
Blair Den shafts at 25m	1000	NT314943	24.67	27.07
Blair Den shafts at 35m	430	NT314943	34.92	38.81
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	75	NT294973	35.74	46.74
River Ore, north-east of Balbeggie Cottage at 50m:	3	NT286966	35.74	46.76
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	999	NO308004	26.25	32.04
Old Shaft at 40m	999	NO307009	26.25	32.04
Discharge to Lochty Burn at 45m	857	NT301982	32.07	35.73
River Ore between Lochty Burn confluence and New Bridge at 43m	968	NT307984	29.52	34.92
Furnace Shaft at Lochty Farm at 45m	857	NT296983	32.07	35.73
River Ore near Tullybreck at 45m	857	NT313986	32.07	35.73
Julian Shaft at 48m	328	NT306987	35.73	46.74
Lochty Side Shaft at 50m	36	NT298986	35.74	46.74
Discharge between Ore Bridge and Railway Viaduct at 48m	328	NT294973	35.73	46.74

APPENDIX 5

RESULTS USING STORATIVITY VARIABILITY

Deterministic Analysis using Intermediate Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	1.270	26.44
Old Shaft at 20m	NT348999	0.946	28.64
Old Shaft at 25m	NO354002	0.791	30.00
Duniface Adit to Kennoway Burn at 20m	NO352005	0.946	28.64
Bowhouse Outcrops at 20m	NO360008	0.946	28.64
Chemiss Outcrops at 20m	NO364006	0.946	28.64
Kirkland Shafts at 20m	NO367004	0.946	28.64
Leven Shafts at 25m	NO374002	0.790	30.00
Drainage Level in Leven Harbour at 5m	NO383003	1.305	26.25
Michael			
Victoria Shaft at 7.3m	NT322947	1.262	25.99
Lady Shaft at 15m	NT324947	1.087	27.24
Reservoir Shaft at 15m	NT326947	1.086	27.24
Coxtool Shaft at 15m	NT326947	1.086	27.24
Windmill Shaft at 20m	NT329951	0.959	28.66
Michael Shafts at 11.6m	NT336962	1.168	26.63
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.111	25.95
Foreshore below Frances Colliery at 10m	NT310937	1.111	25.95
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.224	24.94
Blair Den shafts at 15m	NT314943	0.982	27.13
Blair Den shafts at 25m	NT314943	0.686	34.81
Blair Den shafts at 35m	NT314943	0.079	46.70
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.398	34.91
Old Shaft at 40m	NO307009	0.398	34.91
Discharge to Lochty Burn at 45m	NT301982	0.007	46.73
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.104	35.74
Furnace Shaft at Lochty Farm at 45m	NT296983	0.007	46.73
River Ore near Tullybreck at 45m	NT313986	0.007	46.73
Julian Shaft at 48m	NT306987	-	-
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	-	-
Total		21.645	

Deterministic Analysis using Maximum Flow to the Sea Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	4.649	26.44
Old Shaft at 20m	NT348999	-	-
Old Shaft at 25m	NO354002	-	-
Duniface Adit to Kennoway Burn at 20m	NO352005	-	-
Bowhouse Outcrops at 20m	NO360008	-	-
Chemiss Outcrops at 20m	NO364006	-	-
Kirkland Shafts at 20m	NO367004	-	-
Leven Shafts at 25m	NO374002	-	-
Drainage Level in Leven Harbour at 5m	NO383003	5.067	26.25
Michael			
Victoria Shaft at 7.3m	NT322947	2.219	25.99
Lady Shaft at 15m	NT324947	1.115	27.64
Reservoir Shaft at 15m	NT326947	1.114	27.64
Coxtool Shaft at 15m	NT326947	1.113	27.64
Windmill Shaft at 20m	NT329951	-	-
Michael Shafts at 11.6m	NT336962	1.699	26.71
Wemyss Den Burn at 45m:	NT338977	-	-
Frances			
North Foreshore at Dysart at 10m	NT307933	1.341	26.01
Foreshore below Frances Colliery at 10m	NT310937	1.341	26.01
Frances Shaft at 45m	NT309938	-	-
Blair Den shafts at 5m	NT314943	1.722	24.94
Blair Den shafts at 15m	NT314943	0.797	29.14
Blair Den shafts at 25m	NT314943	-	-
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	-	-
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	-	-
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	-	-
Old Shaft at 40m	NO307009	-	-
Discharge to Lochty Burn at 45m	NT301982	-	-
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	-	-
Furnace Shaft at Lochty Farm at 45m	NT296983	-	-
River Ore near Tullybreck at 45m	NT313986	-	-
Julian Shaft at 48m	NT306987	-	-
Lochty Side Shaft at 50m	NT298986	-	-
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	-	-
Total		22.177	

Deterministic Analysis using No Flow to the Sea Scenario

Discharge Point	Grid Reference	Volume of Discharge (Ml/day)	Time of Discharge (years)
Wellesley			
Wellesley Shafts at 6.7m	NT366986	-	-
Old Shaft at 20m	NT348999	1.447	28.04
Old Shaft at 25m	NO354002	1.358	29.07
Duniface Adit to Kennoway Burn at 20m	NO352005	1.447	28.04
Bowhouse Outcrops at 20m	NO360008	1.447	28.04
Chemiss Outcrops at 20m	NO364006	1.447	28.04
Kirkland Shafts at 20m	NO367004	1.447	28.04
Leven Shafts at 25m	NO374002	1.357	29.07
Drainage Level in Leven Harbour at 5m	NO383003	-	-
Michael			
Victoria Shaft at 7.3m	NT322947	-	-
Lady Shaft at 15m	NT324947	-	-
Reservoir Shaft at 15m	NT326947	-	-
Coxtool Shaft at 15m	NT326947	-	-
Windmill Shaft at 20m	NT329951	-	-
Michael Shafts at 11.6m	NT336962	-	-
Wemyss Den Burn at 45m:	NT338977	1.033	33.03
Frances			
North Foreshore at Dysart at 10m	NT307933	-	-
Foreshore below Frances Colliery at 10m	NT310937	-	-
Frances Shaft at 45m	NT309938	1.092	33.68
Blair Den shafts at 5m	NT314943	-	-
Blair Den shafts at 15m	NT314943	-	-
Blair Den shafts at 25m	NT314943	-	-
Blair Den shafts at 35m	NT314943	-	-
Randolph			
Discharge between Ore Bridge and Railway viaduct at 48m	NT294973	0.961	34.01
River Ore, north-east of Balbeggie Cottage at 50m:	NT286966	0.907	34.81
Kingslaw Burn at 85m	NT294952	-	-
Balgonie			
Balgonie Engine Shaft at 40m	NO308004	0.974	31.69
Old Shaft at 40m	NO307009	0.973	31.69
Discharge to Lochty Burn at 45m	NT301982	0.921	32.78
River Ore between Lochty Burn confluence and New Bridge at 43m	NT307984	0.882	32.07
Furnace Shaft at Lochty Farm at 45m	NT296983	0.820	32.78
River Ore near Tullybreck at 45m	NT313986	0.820	32.78
Julian Shaft at 48m	NT306987	0.718	34.04
Lochty Side Shaft at 50m	NT298986	0.639	34.85
Discharge between Ore Bridge and Railway Viaduct at 48m	NT294973	0.717	34.04
Total		21.306	

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Mean Volume of Discharge (Ml/day)		Standard Deviation of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.273		0.065	
Old Shaft at 20m	1000	NT348999	0.946		0.087	
Old Shaft at 25m	1000	NO354002	0.789		0.106	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.946		0.087	
Bowhouse Outcrops at 20m	1000	NO360008	0.946		0.087	
Chemiss Outcrops at 20m	1000	NO364006	0.946		0.087	
Kirkland Shafts at 20m	1000	NO367004	0.946		0.087	
Leven Shafts at 25m	1000	NO374002	0.789		0.106	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.308		0.064	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.270		0.056	
Lady Shaft at 15m	1000	NT324947	1.100		0.064	
Reservoir Shaft at 15m	1000	NT326947	1.100		0.064	
Coxtool Shaft at 15m	1000	NT326947	1.100		0.064	
Windmill Shaft at 20m	1000	NT329951	0.967		0.071	
Michael Shafts at 11.6m	1000	NT336962	1.176		0.060	
Wemyss Den Burn at 45m:	26	NT338977	0.074	0.002	0.464	0.012
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.116		0.043	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.116		0.043	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.230		0.039	
Blair Den shafts at 15m	1000	NT314943	0.990		0.047	
Blair Den shafts at 25m	1000	NT314943	0.687		0.070	
Blair Den shafts at 35m	686	NT314943	0.158	0.108	0.138	0.103
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	116	NT294973	0.002	0.0002	0.007	0.001
River Ore, north-east of Balbeggie Cottage at 50m:	9	NT286966	0.0004	4e-6	0.004	5e-5
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	997	NO308004	0.397	0.395	0.127	0.127
Old Shaft at 40m	997	NO307009	0.397	0.395	0.127	0.127
Discharge to Lochty Burn at 45m	814	NT301982	0.049	0.040	0.064	0.057
River Ore between Lochty Burn confluence and New Bridge at 43m	959	NT30 984	0.169	0.163	0.125	0.122
Furnace Shaft at Lochty Farm at 45m	814	NT296983	0.049	0.040	0.064	0.057
River Ore near Tullybreck at 45m	814	NT313986	0.049	0.040	0.064	0.057
Julian Shaft at 48m	281	NT306987	0.072	0.020	0.117	0.034
Lochty Side Shaft at 50m	28	NT298986	0.070	0.002	0.422	0.012
Discharge between Ore Bridge and Railway Viaduct at 48m	281	NT294973	0.072	0.020	0.117	0.034
Total						

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Mean Time of Discharge (Years)	Standard Deviation of Time of Discharge
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	26.34	1.75
Old Shaft at 20m	1000	NT348999	28.36	2.10
Old Shaft at 25m	1000	NO354002	29.83	2.41
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	28.36	2.10
Bowhouse Outcrops at 20m	1000	NO360008	28.36	2.10
Chemiss Outcrops at 20m	1000	NO364006	28.36	2.10
Kirkland Shafts at 20m	1000	NO367004	28.36	2.10
Leven Shafts at 25m	1000	NO374002	29.83	2.41
Drainage Level in Leven Harbour at 5m	1000	NO38[illegible]003	26.14	1.72
Michael				
Victoria Shaft at 7.3m	1000	NT322947	25.79	1.47
Lady Shaft at 15m	1000	NT324947	27.08	1.74
Reservoir Shaft at 15m	1000	NT326947	27.08	1.74
Coxtool Shaft at 15m	1000	NT326947	27.08	1.74
Windmill Shaft at 20m	1000	NT329951	28.35	1.97
Michael Shafts at 11.6m	1000	NT336962	26.46	1.61
Wemyss Den Burn at 45m:	26	NT338977	47.07	293.82
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	25.80	1.39
Foreshore below Frances Colliery at 10m	1000	NT310937	25.80	1.39
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	24.91	1.26
Blair Den shafts at 15m	1000	NT314943	27.05	1.64
Blair Den shafts at 25m	1000	NT314943	34.02	2.40
Blair Den shafts at 35m	686	NT314943	44.11	30.48
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	116	NT294973	47.22	131.04
River Ore, north-east of Balbeggie Cottage at 50m:	9	NT286966	46.75	520.32
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	997	NO308004	35.13	4.98
Old Shaft at 40m	997	NO307009	35.13	4.98
Discharge to Lochty Burn at 45m	814	NT301982	41.92	21.12
River Ore between Lochty Burn confluence and New Bridge at 43m	959	NT307984	39.06	10.28
Furnace Shaft at Lochty Farm at 45m	814	NT296983	41.95	21.13
River Ore near Tullybreck at 45m	814	NT315986	41.95	21.13
Julian Shaft at 48m	281	NT306987	45.72	73.52
Lochty Side Shaft at 50m	28	NT298986	46.35	278.20
Discharge between Ore Bridge and Railway Viaduct at 48m	281	NT294973	45.72	73.52

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Median Volume of Discharge (Ml/day)		Quartile Range	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.274		0.089	
Old Shaft at 20m	1000	NT348999	0.949		0.117	
Old Shaft at 25m	1000	NO354002	0.797		0.138	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.949		0.117	
Bowhouse Outcrops at 20m	1000	NO360008	0.949		0.117	
Chemiss Outcrops at 20m	1000	NO364006	0.949		0.117	
Kirkland Shafts at 20m	1000	NO367004	0.948		0.117	
Leven Shafts at 25m	1000	NO374002	0.797		0.138	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.309		0.087	
Michael						
Victoria Shaft at 7.3m	1000	NT32[illegible]947	1.269		0.078	
Lady Shaft at 15m	1000	NT324947	1.095		0.089	
Reservoir Shaft at 15m	1000	NT326947	1.095		0.089	
Coxtool Shaft at 15m	1000	NT326947	1.095		0.089	
Windmill Shaft at 20m	1000	NT329951	0.967		0.097	
Michael Shafts at 11.6m	1000	NT336962	1.175		0.084	
Wemyss Den Burn at 45m:	26	NT338977	0.073	0	0.004	0
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.121		0.056	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.121		0.056	
Frances Shaft at 45m	0	NT[illegible]0[illegible]938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.234		0.053	
Blair Den shafts at 15m	1000	NT314943	0.994		0.061	
Blair Den shafts at 25m	1000	NT314943	0.698		0.087	
Blair Den shafts at 35m	686	NT314943	0.132	0.098	0.116	0.160
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	116	NT294973	0.0007	0	0.003	0
River Ore, north-east of Balbeggie Cottage at 50m:	9	NT286966	0.0002	0	0.0007	0
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	997	NO308004	0.431	0.430	0.159	0.160
Old Shaft at 40m	997	NO307009	0.431	0.430	0.159	0.160
Discharge to Lochty Burn at 45m	814	NT301982	0.023	0.013	0.068	0.056
River Ore between Lochty Burn confluence and New Bridge at 43m	9[illegible]9	NT30[illegible]984	0.155	0.146	0.209	0.215
Furnace Shaft at Lochty Farm at 45m	814	NT296983	0.023	0.013	0.067	0.056
River Ore near Tullybreck at 45m	814	NT31[illegible]986	0.023	0.013	0.067	0.056
Julian Shaft at 48m	281	NT306987	0.077	0	0.007	0.062
Lochty Side Shaft at 50m	28	NT298986	0.076	0	0.010	0
Discharge between Ore Bridge and Railway Viaduct at 48m	281	NT294973	0.077	0	0.007	0.062
Total						

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Volume of Discharge		Upper Quartile of Volume of Discharge	
			of No.	of 1000 Runs	of No.	of 1000 Runs
Wellesley						
Wellesley Shafts at 6.7m	1000	NT366986	1.227		1.316	
Old Shaft at 20m	1000	NT348999	0.888		1.005	
Old Shaft at 25m	1000	NO354002	0.723		0.861	
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	0.888		1.005	
Bowhouse Outcrops at 20m	1000	NO360008	0.888		1.005	
Chemiss Outcrops at 20m	1000	NO364006	0.888		1.005	
Kirkland Shafts at 20m	1000	NO367004	0.888		1.005	
Leven Shafts at 25m	1000	NO374002	0.723		0.861	
Drainage Level in Leven Harbour at 5m	1000	NO383003	1.263		1.350	
Michael						
Victoria Shaft at 7.3m	1000	NT322947	1.232		1.311	
Lady Shaft at 15m	1000	NT324947	1.052		1.142	
Reservoir Shaft at 15m	1000	NT326947	1.052		1.142	
Coxtool Shaft at 15m	1000	NT326947	1.052		1.142	
Windmill Shaft at 20m	1000	NT329951	0.922		1.019	
Michael Shafts at 11.6m	1000	NT336962	1.136		1.220	
Wemyss Den Burn at 45m:	26	NT338977	0.071	0	0.075	0
Frances						
North Foreshore at Dysart at 10m	1000	NT307933	1.089		1.145	
Foreshore below Frances Colliery at 10m	1000	NT310937	1.089		1.145	
Frances Shaft at 45m	0	NT309938	-		-	
Blair Den shafts at 5m	1000	NT314943	1.205		1.258	
Blair Den shafts at 15m	1000	NT314943	0.960		1.021	
Blair Den shafts at 25m	1000	NT314943	0.645		0.732	
Blair Den shafts at 35m	686	NT314943	0.093	0	0.209	0.160
Randolph						
Discharge between Ore Bridge and Railway viaduct at 48m	116	NT294973	0.0002	0	0.003	0
River Ore, north-east of Balbeggie Cottage at 50m:	9	NT286966	8e-5	0	0.0008	0
Kingslaw Burn at 85m	0	NT294952	-		-	
Balgonie						
Balgonie Engine Shaft at 40m	997	NO308004	0.330	0.328	0.489	0.159
Old Shaft at 40m	997	NO307009	0.330	0.328	0.489	0.159
Discharge to Lochty Burn at 45m	814	NT301982	0.006	0.0008	0.074	0.068
River Ore between Lochty Burn confluence and New Bridge at 43m	959	NT307984	0.063	0.0530	0.271	0.209
Furnace Shaft at Lochty Farm at 45m	814	NT296983	0.006	0.0008	0.073	0.067
River Ore near Tullybreck at 45m	814	NT313986	0.006	0.0008	0.073	0.067
Julian Shaft at 48m	281	NT306987	0.073	0	0.080	0.007
Lochty Side Shaft at 50m	28	NT298986	0.072	0	0.082	0.010
Discharge between Ore Bridge and Railway Viaduct at 48m	281	NT294973	0.073	0	0.080	0.007

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Median Time of Discharge (Years)	Quartile Range
			of No.	of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	26.20	2.41
Old Shaft at 20m	1000	NT348999	28.15	2.96
Old Shaft at 25m	1000	NO354002	29.77	3.62
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	28.15	2.96
Bowhouse Outcrops at 20m	1000	NO360008	28.15	2.96
Chemiss Outcrops at 20m	1000	NO364006	28.15	2.96
Kirkland Shafts at 20m	1000	NO367004	28.15	2.96
Leven Shafts at 25m	1000	NO374002	29.77	3.62
Drainage Level in Leven Harbour at 5m	1000	NO383003	26.01	2.35
Michael				
Victoria Shaft at 7.3m	1000	NT322947	25.62	1.97
Lady Shaft at 15m	1000	NT324947	26.97	2.05
Reservoir Shaft at 15m	1000	NT326947	26.97	2.05
Coxtool Shaft at 15m	1000	NT326947	26.97	2.05
Windmill Shaft at 20m	1000	NT329951	28.16	2.72
Michael Shafts at 11.6m	1000	NT336962	26.34	2.23
Wemyss Den Burn at 45m:	26	NT338977	46.76	0.30
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	25.61	1.81
Foreshore below Frances Colliery at 10m	1000	NT310937	25.61	1.81
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	24.74	1.42
Blair Den shafts at 15m	1000	NT314943	26.81	1.88
Blair Den shafts at 25m	1000	NT314943	34.03	3.23
Blair Den shafts at 35m	686	NT314943	45.91	8.15
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	116	NT294973	46.74	0.03
River Ore, north-east of Balbeggie Cottage at 50m:	9	NT286966	46.74	0.02
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	997	NO308004	34.89	3.66
Old Shaft at 40m	997	NO307009	34.89	3.66
Discharge to Lochty Burn at 45m	814	NT301982	45.91	11.00
River Ore between Lochty Burn confluence and New Bridge at 43m	959	NT307984	35.73	11.00
Furnace Shaft at Lochty Farm at 45m	814	NT296983	45.91	11.00
River Ore near Tullybreck at 45m	814	NT313986	45.91	11.00
Julian Shaft at 48m	281	NT306987	46.74	0.01
Lochty Side Shaft at 50m	28	NT298986	46.74	0.02
Discharge between Ore Bridge and Railway Viaduct at 48m	281	NT294973	46.74	0.01

Stochastic Analysis using Intermediate Scenario

Discharge Point	No.	Grid Reference	Lower Quartile of Time of Discharge of No.	Upper Quartile of Time of Discharge of No.
Wellesley				
Wellesley Shafts at 6.7m	1000	NT366986	25.01	27.42
Old Shaft at 20m	1000	NT348999	26.81	29.77
Old Shaft at 25m	1000	NO354002	28.04	31.66
Duniface Adit to Kennoway Burn at 20m	1000	NO352005	26.81	29.77
Bowhouse Outcrops at 20m	1000	NO360008	26.81	29.77
Chemiss Outcrops at 20m	1000	NO364006	26.81	29.77
Kirkland Shafts at 20m	1000	NO367004	26.81	29.77
Leven Shafts at 25m	1000	NO374002	28.04	31.66
Drainage Level in Leven Harbour at 5m	1000	NO383003	24.86	27.21
Michael				
Victoria Shaft at 7.3m	1000	NT322947	24.66	26.63
Lady Shaft at 15m	1000	NT324947	25.88	27.93
Reservoir Shaft at 15m	1000	NT326947	25.88	27.93
Coxtool Shaft at 15m	1000	NT326947	25.88	27.93
Windmill Shaft at 20m	1000	NT329951	26.81	29.52
Michael Shafts at 11.6m	1000	NT336962	25.11	27.35
Wemyss Den Burn at 45m:	26	NT338977	46.74	47.04
Frances				
North Foreshore at Dysart at 10m	1000	NT307933	24.74	26.55
Foreshore below Frances Colliery at 10m	1000	NT310937	24.74	26.55
Frances Shaft at 45m	0	NT309938	-	-
Blair Den shafts at 5m	1000	NT314943	24.06	25.48
Blair Den shafts at 15m	1000	NT314943	25.95	27.83
Blair Den shafts at 25m	1000	NT314943	32.36	35.58
Blair Den shafts at 35m	686	NT314943	38.58	46.73
Randolph				
Discharge between Ore Bridge and Railway viaduct at 48m	116	NT294973	46.74	46.76
River Ore, north-east of Balbeggie Cottage at 50m:	9	NT286966	46.74	46.76
Kingslaw Burn at 85m	0	NT294952	-	-
Balgonie				
Balgonie Engine Shaft at 40m	997	NO308004	32.07	35.73
Old Shaft at 40m	997	NO307009	32.07	35.73
Discharge to Lochty Burn at 45m	814	NT301982	35.73	46.73
River Ore between Lochty Burn confluence and New Bridge at 43m	959	NT307984	34.89	45.90
Furnace Shaft at Lochty Farm at 45m	814	NT296983	35.73	46.73
River Ore near Tullybreck at 45m	814	NT313986	35.73	46.73
Julian Shaft at 48m	281	NT306987	46.73	46.74
Lochty Side Shaft at 50m	28	NT298986	46.74	46.76
Discharge between Ore Bridge and Railway Viaduct at 48m	281	NT294973	46.73	46.74

REFERENCES

Adams, R., and Younger, P.L., 1997, Simulation of Groundwater Rebound in Abandoned Mines Using a Physically Based Modelling Approach. . *Proceedings of the 6th International Mine Water Congress,* Slovenia. *In Press*

Ahmad, M.U., 1974, Coal Mining and its Effect on Water Quality. *American Water Resources Association Proceedings.* **18**, 138 - 148.

Aldous P.J., Smart P.L., and Black, J.A., 1986, Groundwater Management Problems in Abandoned Coal-Mined Aquifers: A Case Study of the Forest of Dean, England. *Quarterly Journal of Engineering Geology.* **19**, 375 - 388.

Aldous, P.J., and Smart, P.L., 1988, Tracing Groundwater Movement in Abandoned Coal Mined Aquifers using Fluorescent Dyes. *Groundwater.* **26** (2), 172 - 178.

Aljoe, W.W., and Hawkins, J.W., 1994, Application of Aquifer Testing in Surface and Underground Coal Mines. *Proceedings of the 5th International Mine Water Congress,* Nottingham. **1**, 3 -21.

Anderson, M.P., and Woessner, W.W., 1992, *Applied Groundwater Modelling: Simulation of Flow and Advective Transport.* Academic Press, San Diego. 381 pp.

Anderton, R., Bridges, P.H., Leeder, M.R., and Sellwood, B.W., 1979, *A Dynamic Stratigraphy of the British Isles: A Study in Crustal Evolution.* George Allen and Unwin Ltd., London. 301 pp.

Aston, T.R.C., and Whittaker, B.N., 1985, Undersea Longwall Mining Subsidence with Special Reference to Geological and Water Occurrence Criteria in the North-East of England Coalfield. *Mining Science and Technology.* **2** (2), 105 - 130.

Atkins, A.S., and Singh, R.N., 1982, A Study of Acid and Ferruginous Minewater in Coal Mining Operations. *International Journal of Mine Water.* **2**, 37 - 57.

Atkinson, F., 1966, *The Great Northern Coalfield 1700 - 1900.* University Tutorial Press, London 76 pp.

Barton, P., 1978, The Acid Mine Drainage. *In* Nriagu, J.O. (Ed) *Sulfur in the Environment Part II Ecological Impacts.* Wiley, New York. 313 - 358.

Bennett, W., 1993, Anglers' Pollution Case Could Result in Huge Pit Costs. *Independent*, 15 March, p 6.

Beveridge, R., Brown, S., Gallagher, M., and Merritt, J., 1991, Economic Geology *In* Craig, G.Y. (Ed) *Geology of Scotland.* (3rd Edn.). Geological Society, Bath. 545 - 595.

Bryner, L.C., Walker, R.B., and Palmer, R., 1967, Some Factors Influencing the Biological and Non-Biological Oxidation of Sulphide Minerals. *Trans. AIME.* **238,** 56 - 62.

Building Research Establishment, 1977, *Building Defects and Maintenance.* Construction Press, New York. 239 pp.

Bullen Consultants, 1994, *Report on the Effect of Ceasing Pumping from the Frances and Michael Collieries.* Final Report to Forth River Purification Board. Bullen Consultants, Glasgow. 70 pp.

Cairney, T., and Frost, R.C., 1975, A Case Study of Mine Water Quality Deterioration, Mainsforth Colliery, County Durham. *Journal of Hydrology.* **25,** 275 - 293.

Calver A., 1997, Recharge Response Functions. *Hydrology and Earth System Sciences.* **1,** 47 - 53.

Caruccio, F.T., and Ferm, J.C., 1974, Paleoenvironment - Predictor of Acid Mine Drainage Problems. *5th Symposium - Coal Mine Drainage Research.* Kentucky National Associate. 5 - 9.

Caruccio, T.F., 1970, The Quantification of Reactive Pyrite by Grain Size. *3rd Symposium on Coal Mine Drainage.* Res. Mellen Inst. Pittsburgh, Pennsylvania. 123 - 131.

Casagrande, D.J., 1987, Sulphur in Peat and Coal. *In* Scott, A.C. (Ed) *Coal and Coal-Bearing Strata: Recent Advances.* Geological Society Special Publication **32,** 87 - 105.

Chadwick, A., and Morfett, J., 1994, *Hydraulics in Civil and Environmental Engineering.* E and F.N. Spon, London. 557 pp.

Chiang, W.H., and Kinzelbach, W., 1992, *Processing MODFLOW: Pre- and Postprocessors for Simulation of Flow and Contaminants Transport in Groundwater Systems with MODFLOW, MODPATH and MT3D. Version 3.0.* Heidelberg, Hamburg. 97 pp.

Creedy, D.P., 1991, An Introduction to Geological Aspects of Methane Occurrence and Control in British Deep Mines. *Quarterly Journal of Engineering Geology.* **24,** 209 - 220.

Curl, S.J., 1978, *Methane Prediction in Coal Mines.* I.E.A. Coal Research Report No. ICTIS/TR04.

Denby B., Hasssani F.P. and Scoble M.J. 1982, The influence of water on the shear strength of coal measures rocks and discontinuities in surface mining. *Proceedings of the 1st International Mine Water Congress of the International Mine Water Association.* Budapest, Hungary. 334 - 345.

Department of the Environment, 1992, *This Common Inheritance: The Second Year Report: Britain's Environmental Strategy / Presented to Parliament by the Secretaries of state for the Environment.* HMSO, London. 192 pp.

Dron, R.W., 1902, *The Coalfields of Scotland.* Blackie and Son Ltd., London. 368 pp.

Dumpleton, S. 1995, The Dangerous Legacy of Dead Collieries. *Surveyor.* **24**, August 22-23.

Edwards, M.G., 1988, *Mathematical Modelling of Groundwater Inflows to Shafts and Drifts Under Construction.* Unpublished Ph.D. Thesis, University of Birmingham.

Emrich, G.H., and Merritt, G.L., 1969, Effects of Mine Drainage on Groundwater. *Groundwater.* **7** (3) 27 - 32.

Environmental Law and Management, 1993, **5** (3/4), July/August, p 94.

Environmental Simulations Inc., 1996, *Guide to Using Groundwater Vistas: Advanced Model Design and Analysis.* WexTech Systems Inc. 209 pp.

Fawcett, R.J., Hibberd, S., and Singh, R.N., 1984, An Appraisal of Mathematical Models to Predict Inflows into Underground Coal Workings. *International Journal of Mine Water.* Granada, Spain. **3** (2), 33 - 54.

Featherstone R.E., and Nalluri, C., 1982, *Civil Engineering Hydraulics.* (2nd Edn.) BSP Professional Books, London. 373 pp.

Fetter C.W., 1992, *Contaminant Hydrogeology.* Macmillan, New York. 458 pp.

Foreman, J.W., 1974, A Progress Report Evaluation of Mine Drainage Abatement Projects in Western Pennsylvania. *5th Symposium - Coal Mine Drainage Research.* Kentucky National Associate. 128 - 132

Forth River Purification Board 1981, *Water Research News.* **10,** p 8.

Freeze, R.A., and Cherry, J.A., 1979, *Groundwater.* Prentice-Hall Inc., New Jersey. 604 pp.

Frost, R.C., 1979, Evaluation of the Rate of Decrease in the Iron Content of Water Pumped from a Flooded Shaft Mine in County Durham, England. *Journal of Hydrology.* **40,** 101 - 111.

Gale, J.E., 1982, Assessing the Permeability Characteristics of Fractured Rock. *Geological Society of America.* Special Paper **189** Ed. Narasimhan T.N. p 163 - 181.

Geikie, A., 1902, *The Geology of Eastern Fife.* Hedderwick and Sons, Glasgow. 421 pp.

Glover, H.G., 1973, Acidic and Ferruginous Mine Drainages *In* Chadwick, M.J., and Goodman, G.T., (Eds.) *The Ecology of Resource Degradation and Renewal: 15th Symposium of the British Ecological Society.* Blackwell Scientific Publication. Oxford. 173 - 196.

Glover, H.G., 1983, Mine Water Pollution - An Overview of Problems and Control Strategies in the United Kingdom. *In* Odennaal, P.E.(Ed.) *Mine Water Pollution.* Water Science and Technology, **15** (2), 59 - 70.

Guérin, F.P.M., and Billaux, D.M., 1994 On the Relationship Between Connectivity and the Continuum Approximation in Fracture-Flow and Transport Modelling. *Applied Hydrogeology.* **2,** 24-31.

Hall, T., 1981, *King Coal: Miners, Coal and Britain's Industrial Future.* Penguin. 278 pp.

Hansard 1993, House of Commons Official Report. *Parliamentary Debates.* **229,** (221) Wednesday 21 July.

Hansard 1994, House of Commons Official Report. *Coal Industry Bill.* March 22.

Harbourne, K.J., 1994, *An Economic Evaluation of the Alternative Options for the Future of the Coalfield Dewatering Scheme in County Durham.* Unpublished M.Sc. Thesis, University of Newcastle upon Tyne.

Harper, D., and Olyphant, G.A., 1993, Statistical Evaluation of Hydrologic Conditions in the Vicinity of Abandoned Underground Coal Mines around Cannelburg, Indiana. *Journal of Hydrology.* **146,** 49 - 71

Harrison, R., and Scott, W., 1987, *Availability and Temperatures of Minewaters in the Northumberland and Durham Coalfields.* Unpublished report. 45 pp.

Hedin, R.S., Nairn, R.W. and Heinmann, R.L.P., 1994, *The Passive Treatment of Coal Mine Drainage.* Information Circular **9389,** U.S. Bureau of Mines. 35 pp.

Henton, M.P., 1974, Hydrogeological Problems Associated with Waste Disposal into Abandoned Coal Workings. *Water Services.* October. 349 - 352.

Henton, M.P., 1979, Abandoned Coalfields: Problems of Pollution. *Surveyor.* **153,** 31 May, 9 - 11

Henton, M.P., 1981, The Problem of Water Table Rebound After Mining Activity and its Effects on Ground and Surface Water Quality. *Proceedings of an International Symposium on Quality of Groundwater.* Noordwijkerhaut, Netherlands, 111 - 116.

Hill, A., 1991, *Coal Mining: A technological report 1700 - 1950.* A British Mining Supplement. Northern Mine Research Society, Sheffield, England. 56 pp.

Hill, M., 1990a, *Preconditioned Conjugate-Gradient 2 (PCG2), A computer Program for Solving Ground-Water Flow Equations.* U.S. Geological Survey.

Hill, M., 1990b, Solving Groundwater Flow Problems by Conjugate-Gradient methods and the Strongly Implicit Procedure. *Water Resources Research.* **26** (9), 1961 - 1969.

Howarth, W., 1988, *Water Pollution Law.* Shaw, London. 608 pp.

Jackson, K.B., 1993, *The Environmental Impact of the Cessation in Mine Dewatering upon the Waste Disposal Sites within County Durham.* Unpublished M.Sc. Thesis University of Newcastle upon Tyne.

Jarvis, A., 1994, *Impacts of Acid Mine Drainage on the Ecology of the Newhouse Burn (Stony Heap) in County Durham.* Unpublished M.Sc. Thesis. University of Newcastle upon Tyne

Kleinmann, R.L.P., 1980, Bacteriological Control of Acid Problems in Surface Mines and Coal Refuse. *Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation.* Kentucky U.S.A. 333 - 337.

Kleinmann, R.L.P., 1981, Field Evaluation of a bactericidal treatment to control acid mine drainage. *Symposium on Surface Mining Hydrology, Sedimentology and Reclamation.* University of Kentucky, 325 - 329.

Knox, J., 1954, *The Economic Geology of the Fife Coalfield, Area III, Markinch, Dysart and Leven.* Memoirs of the Geological Society, Scotland, HMSO. 134 pp.

Kuiper, L.K., 1981, A Comparison of the Incomplete Cholesky-Conjugate Gradient method With the Strongly Implicit Method as Applied to the Solution of Two-Dimensional Groundwater Flow Equations. *Water Resources Research.* **17** (4), 1082 - 1086.

Ladwig, K.J., 1985, *Hydrologic aspects of acid mine drainage.* Control Information Circulation U.S. Bureau of mines. **9027,** 12 - 18.

Lancaster, D., 1995, *Delineating the Catchment Area and Flow System of a Major Polluted Spring in County Durham.* Unpublished M.Sc. Thesis, University of Newcastle upon Tyne.

Lemon, R., 1991, Pumping and disposal of deep strata mine water. *Mining Technology.* **73,** 69 - 76.

Lloyd, J.W., Jeffery, R.I., and Neill, N.H., 1991, Hydrogeological assessments for underground mines. *In* Downing, R.A., and Wilkinson, W.B., (Eds.) *Applied Groundwater Hydrology.* Claredon Press, Oxford. 302 - 313.

Lloyd, J.W., Rushton, K.R., and Jones, P.A., 1983, An Assessment of Groundwater Inflow into a Proposed Shaft and Drift in the Warwickshire Coalfield Using Packer Test Data in an Electrical Analogue Model. *International Journal of Mine Water.* **2** (4), 1 - 18.

Manners, G., 1981, *Coal in Britain: An Uncertain Future.* The Resources Management Series, **4** Allen and Unwin, London. 108 pp.

Marsh, T.J., and Littlewood, I.G., 1978, An Estimate of Annual Runoff from England and Wales, 1728-1976. *Hydrological Sciences Bulletin* **23,** 131 - 142.

McDonald, M.G., and Harbaugh, A.W., 1988, *A Modular Three-Dimensional Finite-Difference Groundwater Flow Model.* Techniques of Water-Resources Investigation, Book. 6, Chapter A1. U.S. Geological Survey. 576 pp.

McDonald, M.G., Harbaugh, A.W., Brennon, R.O., and Ackerman, D.J., 1991, *A method of Converting No-Flow Cells to Variable-head Cells for the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model.* U.S. Geological Survey Open File Report **91-536.**

Meijerink, J.A, and van der Vorst, H.A., 1977, An Iterative Solution Method for Linear Systems of which the Coefficient Matrix is a Symmetric M-Matrix. *Mathematics of Computation.* **31** (137), 148 - 162.

Meyer, P.D., Valocchi A.J., Ashby S.F., and Saylor P.E. 1989, A Numerical Investigation of the Conjugate Gradient Method as Applied to Three-Dimensional Groundwater Flow Problems in Randomly Heterogeneous Porous Media. *Water Resources Research.* **25** (6), 1440 -1446.

Miller, J.T., and Thompson, D.R., 1974, Seepage and mine barrier width. *5th Symposium - Coal Mine Drainage Research.* Kentucky National Associate. 103 - 127.

Minett, S.T., 1987, *The Hydrogeology of Parts of the Northumberland and Durham Coalfield Related to Opencast Mining Operation.* Unpublished Ph.D. Thesis, University of Newcastle upon Tyne.

Minett, S.T., Blythe, D.A., Hallam, G.D., and Hughes, D.B., 1986, Analysis of an advanced dewatering scheme at an opencast coal site in Northumberland. *Groundwater in Engineering Geology.* 347 - 352.

Morrison, J.L., Scheetz, B.E., Strickler, D.W., Williams, E.G., Rose, A.W., Davis, A., and Parizek, R.R., 1990, *Predicting the Occurrence of Acid Mine Drainage in the Alleghenian Coal-Bearing Strata of Western Pennsylvania; An Assessment by Simulated Weathering (Leaching) Experiments and Overburden Characterization.* Geological Society of America Special Paper **248.** 87- 99.

Morth, A.H., Smith, E.E., and Schumate, K.S., 1972, *Pyritic Systems a Mathematical Model.* U.S. Environmental Protection Agency, Washington. 171 pp.

Muir, A., c1953, *The Fife Coal Company Limited: A Short History.* The Fife Coal Company Limited, Leven, Scotland. 133 pp.

National Coal Board, 1975, *Subsidence Engineers Handbook.* 111 pp.

National Research Council, 1996, *Rock Fractures and Fluid Flow: Contemporary Understanding and Applications.* National Academy Press, Washington. 551 pp.

Ngah, S.A., Reed, S.M., and Singh, R.N., 1984, Groundwater problems in Surface Mining in the United Kingdom. *International Journal of Mine Water.* **3** (1), 1 - 12.

Norton, P.J., 1983, Groundwater Rebound Effects on Surface Coal Mining in the U.K. *2nd Surface Mining and Quarrying Symposium.* Bristol. 254 - 263.

NRA, 1994, Abandoned Mines and the Water Environment. *Water Quality Series.* (14) 46 pp.

Owili-Eger, A.S.C., and Manula, C.B., 1976, Modelling and Simulation of Mine Water Drainage. *14th Application Of Computational Methods in the Mineral Industry.* Pennsylvania.

Pearson, J.M., 1993, *Around Kirkcaldy.* John MacMillan Pearson, Leven, Fife. 48 pp.

Perry, A.O., 1993, Hydrologic Models Used by the U.S. Bureau of Mines. *Proceedings of the Federal Interagency Workshop on Hydrologic Modelling Demands for the 90's.* U.S. Geological Society Water Resources Investigations Report **93-4018**. 1.16 - 1.23.

Peters, T.W., 1978, Mine Drainage Problems in North Derbyshire. *Mining Engineer.* **137,** 463 - 472.

Puente, C., and Atkins, J.T., 1989, Simulation of Rainfall - Runoff Response in Mined and Unmined Watersheds in Coal Areas of West Virginia U.S. *Geological Survey Water Supply.* Paper **2298.** Government Printing Office, Washington D.C. 48 pp.

Ricca, V., and Hemmerich, H., 1978, Underground Mine Drainage Quantity and Quality Generation Model. *Proceedings of the International Conference Water in Mining and Underground Works.* SIAMOS Granada, Spain.

Richardson, G., 1983, *Geological Notes and Local Details for 1:100000 Sheets NZ26NW, NE, SW, SE (Newcastle upon Tyne and Gateshead).* Geological Survey of England and Wales N.E.R.C.

Robb, G., 1992, *Modelling Dalquharran Mine as a Source of Pollution of the Water of Girvan.* Unpublished M.Sc. Thesis University of Newcastle upon Tyne.

Robins, N.S., 1990, *Hydrogeology of Scotland.* British Geological Survey HMSO 90 pp.

Rogoz, M., 1978, Water Capacity of Abandoned Workings in Underground Coal Mines. *Proceedings of the International Conference Water in Mining and Underground Works.* SIAMOS Granada, Spain.

Rogoz, M., 1994, Computer Simulation of the Process of Flooding Up a Group of Mines. *Proceedings of the 5th International Mine Water Congress,* Nottingham. **1,** 369 - 378.

Saad, Y., 1985, Practical Use of Polynomial Preconditionings for the Conjugate Gradient Method. *SIAM Journal of Scientific and Statistical Computing.* **6** (4), 865 - 881.

Scullion, J., and Edwards, R.W., 1980, The Effect of Pollutants from the Coal Industry on the Fish Fauna of a Small River in the South Wales Coalfield. *Environmental Pollution.* **21.**

Sherwood, J.M., 1993, *A Lumped Parameter Model of the Groundwater Rebound Associated with the Imminent Closure of Mines in the Durham Coalfield.* Unpublished M.Sc. Thesis, University of Newcastle upon Tyne.

Sherwood, J.M., and Younger, P.L., 1994, Modelling Groundwater Rebound after Coalfield Closure: An Example from County Durham, UK. *Proceedings of the 5th International Mine Water Congress,* Nottingham. **2,** 769 - 778.

Silverman, M.P., Rogoff, M.H., and Wender, I., 1963, Removal of Pyritic Sulphur from Coal by Bacterial Action. *Fuel.* **42,** 113 - 124.

Singer, C.P., and Stumm., 1970, Acidic Mine Drainage: The Rate Determining Step. *Science.* **167,** 1121 - 1123.

Singh, R.N., Hibberd, S., and Fawcett, R.J., 1985, Numerical Calculation of Groundwater Inflow to Longwall Coal Faces. *Proceedings of the 2nd International Mine Water Congress.* International Mine Water Association, Granada. **1,** 541 - 552.

Singh, R.N., Hibberd, S., and Fawcett, R.J., 1986, Studies in the Prediction of Water Inflows to Longwall Mine Workings. *International Journal of Mine Water.* **5** (3), 29 - 46.

Smith, J.A., and Colls, J.J., 1996, Groundwater Rebound in the Leicestershire Coalfield. *Journal of the Institution of Water and Environmental Management.* **10,** June, 280 - 289.

Strömberg, B., and Banwart, S., 1994, Kinetic Modelling of Geochemical Processes at the Aitik Mining Waste Rock Site in Northern Sweden. *Applied Geochemistry.* **9,** 583 - 595.

Stumm, W., and Morgan, J.J., 1981, *Aquatic Chemistry: An Introduction Emphasising Chemical Equilibria in Natural Waters.* (2^{nd} Edition) Wiley, New York. 780 pp.

Taylor, R.K., and Spears, D.A., 1970, The Breakdown of British Coal Measure Rocks. *International Journal of Rock Mechanics and Mining Sciences.* **7,** 481 - 501.

Tickell, O., 1993, Pouring Coal on Troubled Waters. *Times.* 11 December. Section 3, p 1.

Todd, D.K., 1980, *Groundwater Hydrology.* (2^{nd} Edn.) Wiley and Sons, New York. 535 pp.

Toran L., and Bradbury, K.R., 1988, Groundwater Flow Model of Drawdown and Recovery Near and Underground Mine. *Groundwater.* **26** (6), 724 - 733.

Turner, I., 1993, *A Geotechnical Assessment of Groundwater Rise through Mineworkings in Gateshead.* Unpublished M.Sc. Thesis, University of Newcastle upon Tyne.

Turnpenny, A.W.H., Sadler, K., Aston, R.J., Milner, A.G.P., and Lynam, S., 1987, The Fish Populations of Some Streams in Wales and Northern England in Relation to Acidity and Associated Factors. *Journal of Fish Biology.* **31,** 415 - 434.

Ward, R.C., and Robinson,, N., 1990, *Principles of Hydrology.* (3^{rd} Edn.) McGraw-Hill, London. 365 pp.

Wardell Armstrong, 1993, *A Study of the Regional Geology of the Durham Coalfield and the Potential Impact of Ceasing Mine Dewatering - Part 2 Groundwater Model.* Report to the NRA, Northumbria Region.

Warner, R.W., 1973, Acid Coal Mine Drainage effects on aquatic life. *Ecology and Reclamation of Devastated Land.* **1.**

Whitelaw, J., 1993, Pitfalls. *Water and Environmental Management.* May.

Whittaker, B.N., and Reddish, D.J., 1989, Subsidence - Occurrence, Prediction and Control. *Developments in Geotechnical Engineering.* **56.**

Wilkinson, W.B., and Brassington, F.C., 1991, Rising Groundwater Levels: An International Problem. *In* Downing R.A. and Wilkinson W.B. *Applied Groundwater Hydrology: A British Perspective.* Claredon Oxford 304 pp.

Williams, E.G., and Keith, M.L., 1963, Relationship between sulfur in coals and the occurrence of marine reaf beds. *Economic Geology.* **58,** 720 - 729.

Winston, R.B., 1996 The MODFLOW Help File. Version 1.0.0. http://scribe.geol.lsu.edu/rbwinston.html

Winterton, J., and Winterton, R., 1984, *Coal, Crisis and conflict: The 1984-85 Miners' Strike in Yorkshire.* Manchester University Press. Manchester 360 pp..

Younger, P.L. 1993, Possible Environmental Impact of the closure of two collieries in County Durham. *Journal of the Institution of Water and Environmental Management.* **7** (5), 7 October.

Younger, P.L. 1995, Polluted Groundwater in Abandoned Coalfields: Some Hydrogeological and Geochemical Idiosyncrasies. *4th Annual Conference on Groundwater Pollution.* London, 15 - 16 March.

Younger, P.L. 1997, The Longevity of Minewater Pollution: A Basis for Decision-Making. *Science of the Total Environment,* **194 / 195**, 457 - 466.

Younger, P.L. and Bradley, K.F. 1994, Application of Geochemical Mineral Exploration Techniques to the Cataloguing of Problematic Discharges from Abandoned Mines in North-East England. *5th International Mine Water Congress*, Nottingham (U.K.), September.

Younger, P.L., and Harbourne, K.J., 1995, 'To Pump or Not To Pump' Cost-Benefit Analysis of Future Environmental Management Options for the Abandoned Durham Coalfield. *Journal of the Chartered Institution of Water and Environmental Management.* **9,** 405 - 415.

Younger, P.L., and Sherwood, J.M., 1993, The Cost of Decommissioning a Coalfield: Potential Environmental Problems in County Durham. *Mineral Planning.* **57**, 26 - 29.

Younger, P.L., Barbour, M.H., and Sherwood, J.M. 1995, Predicting the Consequences of Ceasing Pumping from the Frances and Michael Collieries, Fife Scotland. *British Hydrological Society 5th National Hydrology Symposium,* Edinburgh. 2.25 - 2.33.