THE GROUNDWATER HYDROLOGY OF AN ABANDONED COAL MINED AQUIFER :

A CASE STUDY FROM THE FOREST OF DEAN COALFIELD.

By

Philip J. Aldous BSc

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ABSTRACT

The hydrogeology of the Forest of Dean has been extensively affected by coal mining, with both abandoned deep workings and free-drainage levels still transmitting large quantities of water and extensively affecting the groundwater regime in the Coal Measure Aquifers. An examination of the significance of the mining activity for present day management of the groundwater resources of the area has been made.

This study demonstrated that careful planning prior to abandonment of collieries can reduce the number of poor quality discharges, and so substantially limit surface water pollution by ferruginous and acidic mine waters. Furthermore an historical analysis of coalfield development and mining methods employed is necessary to understand mining concessions and the basis of drainage and documentation of coal mine abandonment plans. The validity of using these plans for catchment area determinations is assessed by comparison with traditional water budget techniques. These results indicated that small scale mining continuing after the closure of the major collieries involves the removal of in situ coal from coal barriers which were designed to promote free-drainage. The hydrological integrity of the coal barriers and the effects of coal barrier removal on surface water resources and deep basin recharge is determined from the water budgets, direct exploration of workings and tracer tests. The hydrogeological characteristics (transmissivity, storativity, storage volumes and groundwater flow velocities) are determined for both mined voids and the major aquifers present, by using tracer tests, recession curves and pumping test analysis. Further direct exploration of workings and tracer tests have determined the integrity and network geometry of the mine voids present together with the role of major roadways in controlling groundwater movement.

While hydrochemical facies are used to determine flow proportions in inaccessible free-drainage levels and historical chemical data is analysed to indicate hydrogeological changes in the deep basin between mine abandonment in 1965 and present day.

Where possible conceptual models of groundwater flow and the controls on flow are developed, these will assist future groundwater resource management in similar situations. However, the prediction of the hydrogeological behaviour of abandoned coal mined aquifers is difficult because of the possibility of unrecorded workings, random collapse and associated ponding, and uncertainty over the hydrological behaviour of the coal barriers, direct investigation of the groundwater flow regime using boreholes and water tracing techniques is recommended for detailed site specific resource management investigations.

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CHAPTER 1

A REVIEW OF THE HYDROLOGY AND HYDROGEOLOGY OF ABANDONED COAL MINED AQUIFERS AND LEGISLATION CONTROLLING COAL MINE ABANDONMENT IN THE UNITED KINGDOM.

1.1 INTRODUCTION.

In 1972, 13 % (870 x 10^6 litres/day) of the total groundwater abstraction by pumping in England and Wales was from Coal Measure Aquifers, of which 42 % (365 x 10^6 litres/day) was from abandoned coal mines (pumping from some abandoned coal workings continues in many coalfields to permit safe extraction of coal in adjacent collieries). Most of this water is of poor quality and only 3.5 % (12.7 x 10^6 litres/day) of the total abstracted is used for potable supply, the remainder being disposed of to surface water courses (Rae 1978). More recently with increasing abandonment of coal mines and complete coalfield closures (ie the termination of all coal extraction activities including pumping from abandoned workings) Coal Measure Aquifers have become a management burden to Regional Water Authorities (RWA), due to problems associated with surface water and groundwater pollution, waste disposal, open cast mining operations and the maintenance of recreational resources (Aldous et al 1986 and Henton 1974, 1979, 1981, and 1983). Furthermore, these problems are likely to continue into the forseable future and combined with the current contraction of the coal mining industry may become more problematic.

This chapter reviews both the previously reported work on Coal Measure hydrogeology and hydrology and the present day United Kingdom (UK) legislation controlling coal mine abandonment. Although this thesis is primaril y concerned with groundwater hydrogeology and hydrology, the latter is important because this legislation determines the documentation of groundwater and hydrogeological conditions on coal mine closure. The chapter concludes with a guide to this thesis, outlining its importance, originality and structure.

1.2 PREVIOUS WORK.

The production of acidic, ferruginous and ochreous mine drainage discharges (AMD) by the oxidation of iron sulphides (marcasite and pyrite) (Plate 1.1) in abandoned coal mine workings has been widely reported, especially in the United States of America (US) (Ahmad 1974, Barnes and Clarke 1964, Cairney and Frost 1975, Emrich and Merritt 1969, Hawley and Shikaze 1971, Hollyday and McKenzie 1973, Porges et al 1966, Shumate and Brant 1971, Stumm and Morgan 1970, Trexler et al 1975, Wentz 1974 and Wirres and McDonnell 1983). These studies have

PLATE 1.1 A : Mine drainage spring (Old Bobs Colliery Spring) which drains to the Cannop Brook.

PLATE 1.1 B : Ferric hydroxide deposits on the trapezoidal flume at the Independent Level.

concentrated on assessing the mechanisms controlling the production of such waters, their chemical composition and origin. Other studies have examined the chemical kinetics of pyrite oxidation including those associated with microbial activity (Atkins and Pooley 1982, Atkins and Singh 1982, Carrucio et al 1976, Rawat and Singh 1982, and Singer and Stumm 1968 and 1970). While more recent work has analysed the isotopic geochemistry of acid mine drainages (Taylor et al 1984a, 1984b) to determine the origin of dissolved constituents. Other work has determined neutralisation procedures for AMD waters (Bhatt and Baker 1976) and predictive chemical water quality models (Chadderton 1979, Caruccio et al 1981 and Henton 1976) which determine the effect of AMD from both underground and open cast coal mining activities on receiving waters. Other work has determined the detrimental environmental effects of mine discharges on aquatic fauna and flora of receiving waters (Grenfield and Ireland 1978, Herricks and Cairns 1976, Letterman and Mitsch 1978 and Parsons 1977). Therefore in conclusion the hydrochemistry of post abandonment mine drainage waters (AMD's) has received considerable attention particularly in the US together with the detrimental effect of AMD waters on water quality and aqu atic fauna and flora. However, fewer studies have been reported in the U.K. (Cairney and Frost 1975, Downing et al 1970, Edmunds 1975, Gray et al 1969, Glover 1983, Ineson 1967 and Rae 1978). In comparison to the US literature these studies have not solely concentrated on the water quality effects from AMD waters but also include a geological interpretation to the hydrochemical data. The geological interpretation principally outlines the effects and locations of aquifers and aquitards on groundwater movement. This work also considers the hydrochemical conditions present prior to or during coal extraction (on a macro scale ie Coalfield) but does not interpret conditions present after abandonment or the effects of mining methods on groundwater regimes after abandonment.

The majority of hydrological studies reported which relate to coal mining have analysed the effects of open cast coal mining on surface runoff and groundwater conditions of 'open cast backfill materials' (Wood 1981, Sternberg and Agnew 1968, Norton 1983, Turback et al 1979 and Addis et al 1984). None have discussed groundwater movement in active or abandoned underground coal mines. Although Packard (1981) and Cairney (1973) do consider 'water availability' and groundwater storage volumes held within abandoned underground coal mines, as possible resources for river flow augmentation and irrigation in emergencies. Unfortunately both of these surveys were based upon desk studies and no field data was collected for actual quantification of resources. This work relies heavily upon assumptions of the behaviour of mined voids (their openess, integrity, capability of transmitting groundwater flow and storage volumes) and does not attempt to determine their actual behaviour. It therefore falls short of providing quantitative data useful for the management of groundwater resources.

There has been some awarness of the hydrogeological changes in aquifer behaviour due to coal mine abandonment, but this has either been associated with the explanation of pyrite oxidation behaviour, abandoned mine water discharge quality and future possible coal reserve exploitation or the phenomenon of water table 'rebound' or 'recovery' after the cessation of mine pumping and the establishment of new groundwater discharge outlets for Coal Measure Aquifers (Cairney and Frost 1975, Henton 1981, Hollowell 1975 and Schubert 1978). The later case is of particular interest because when new discharge outlets are formed, new groundwater flow paths and catchment areas are established. Unfortunately the reported work is qualitative and only describes the problems associated with the location and water quality of such discharges, and does not analyse the 'new' hydrogeological conditions present or attempt to assess the conditions with a view for the future management of groundwater resources. However, the necessity to demonstrate and determine groundwater flow paths and catchment areas in abandoned coal mined aquifers is demonstrated by the case study reports of groundwater tracing exercises conducted in the South Wales Coalfield by Parsons and Hunter (1972) and Mather et al (1969).

Problems associated with mining subsidence and surface stability in abandoned coal mined areas have been reported in ground engineering literature (Littlejohn 1979a and 1979b, Shadbolt et al 1973, Stewart 1973). This does not consider the effects of mining subsidence on groundwater flow paths, but is helpfull in determining the effects of subsidence on enhanced fracturing and mined void integrity. More specific mining engineering literature has concentrated on mine support methods and extraction techniques (Brady and Brown 1985 and Wilson, A. 1983). These too are useful in understanding coal mine void integrity and behaviour, although interpolation is required for post abandonment times. This information is identical to that used by Packard (1981) and Cairney (1973) in their desk studies mentioned above.

There are three further sources of information which relate directly to predicting the behaviour of groundwater in abandoned coal mines, these are the geological properties of the Coal Measure rocks, the method and extent of mining, and the effect of historic mining methods on the surrounding host rock. Although these sources do not provide direct answers to problems associated with the management of groundwater resources in abandoned coal mined aquifers, they do provide useful information which collectively is valuable (see later).

Detailed and extensive geological information is often collected to determine reserve sizes and efficient extraction techniques during mining, but this does not contain substantial detailed hydrogeological analysis. In some cases permeability data is available because it was required to predict pumping requirements for dewatering operations (Schubert 1978 and Rehm et al 1980). Furthermore, only limited hydrogeological data exists for the Coal Measure Series of rocks because they provide little water for public supply (Stark and McDonald 1980).

Detailed and often extensive information is available which describes the mode or method of coal extraction (Stewart 1973 and Joynes 1889). This is of particular use, for predicting whether the mined area was abandoned with extensive voids present through which post abandonment groundwaters may flow or whether during mining the void produced was allowed to collapse. This later case has been investigated and reported for the more recent longwall mining method by Neate (1980) and Aston (1982). One particular aspect associated with the analysis of mining methods is the role played by areas of intact coal which were left during mining to exclude groundwater from certain areas of mines still operating or from adjacent abandonded mines (Ashley 1930 and Forrest 1920). These areas of unmined coal are refered to as coal barriers and older documents often report the catastrophic effects of inrushes when these barriers were either breached or collapsed. However, the role of the coal barriers in controlling groundwater flow in abandoned coal mines is presently not understood, although more recently Miller and Thompson (1974) have investigated the efficiency of coal barriers in preventing groundwater flow into active coal mines.

In conclusion, the majority of previous research has concentrated on assessing the hydrochemistry and pollution effects of AMD waters and no comprehensive hydrological or hydrogeological study has examined the groundwater conditions in abandoned coal mined aquifers. However, there are certain aspects of the previously reported literature which are useful in the interpretation and development of further work. The most important is that which relates to the role and behaviour of intact coal barriers in controlling groundwater movement in mined voids.

1.3 CURRENT LEGISLATION CONTROLLING GROUNDWATER RESOURCES AND COAL MINE ABANDONMENT IN THE U.K.

Although this thesis is primaril y concerned with groundwater hydrogeology and hydrology, the legislation controlling groundwater resources and coal mine abandonment is considered important because it determines the extent of documentation of groundwater conditions and extent of mining on coal mine abandonment.

The statutory abandonment procedure prescribed by the Quarries and Mines Act section 20 and the Coal and Other Mines (abandonment plans) Rules 1956 states that the following groundwater conditions require recording at the time of mine closure:

SECTION 20. The abandonment plan, in addition to showing the extent of all underground workings, variation in levels, gradient of the seams, faults, the position and level of all the shafts and external dangers must also show:-

1. the position of any pump in use underground immediately before abandonment, together with the quantity of water being pumped.
2. any variation in level on the boundaries of the workings.
3. the position and extent of any known waterlogged areas.
4. the position, dimensions and method of construction of any water dam and the pressure of water being retained by it immediately prior to abandonment.

There are two complications which relate to the data collected in section 20 of the Quarries amd Mine Act. Firstly, this information relates directly to the state of hydrogeological and underground conditions on the last survey before abandonment, and significant changes in conditions (eg groundwater levels) are known to occur subsequent to this survey, and secondly it is known that in some cases this information was not recorded (see this thesis). However, in most cases this is the only source of available data (assuming that it is archived in a retreivable manner) to ascertain hydrogeological conditions after abandonment has taken place (mined and unmined areas, major roadways, drainage levels and coal barriers). This information is ess ential for the management of groundwater resources in such areas.

Even if groundwater problems are expected on abandonment, British Coal (BC formerly the National Coal Board (NCB)) has no obligation to take remedial action or discuss such matters with the local Water Authority. The control of Pollution Act Part II 1974 allows Water Authorities to enforce quality limits for pumped groundwater discharges from active coal mines but does not refer to abandoned coal mines execpt in stating :

INVESTIGATION OF WATER POLLUTION PROBLEMS ARISING FROM CLOSURE OF COAL MINES.

Each Water Authority shall have the power to carry out studies for the purposes of ascertaining :-

(a) What problems relating to the pollution of relevant waters may arise or have arisen in consequence of the abandonment of any mine in its area or might arise if any such mine were abandoned.

(b) What steps are likely to be appropriate for the purpose of dealing with the problems and what the cost of taking those steps would be.

Thus the Water Authorities have only the power to ascertain what future water resource management problems are likely to occur, and have no direct legal power to stop such problems, if possible, from occurring.

In 1979, following the growing awareness of the inadequacies of the two acts, the following two recommendations were made on the control of water pollution from abandoned coalmines: (Royal Town Planning Institute 1979).

Firstly, "gravitational discharges through the process of water table rebound resulting from the earlier cessation of pumping can create much more serious problems. This is often the case since the location of such discharges cannot be predicted and can occur through the former drainage adits, along geological lines of weakness etc. Furthermore, the NCB appear not to have a statutory responsibility for taking preventative or remedial action. The Control of Pollution Act 1974 whilst empowering regional Water Authorities to investigate the problem and ascertain the steps and cost of remedial action, defines no responsibility for the carrying out of these measures."

And secondly, "The Royal Planning Institute wishes to express its concern at this situation and recommends that the NCB be required to take appropriate measures to remedy the problems arising from the cessation of pumping operations at abandoned collieries."

However, since this recommendation no further action to alleviate this situation has been taken, although liason between Water Authorities and BC is now encouraged. However, both parties concerned seem to have only current interests under control, for instance, chemical quality and disposal of pumped water (Dangerfield 1979 and NCB 1985). Furthermore, control policies adopted by Water Authorities are dependent upon the legislative control measures available.

Therefore in conclusion, abandoned coal mined aquifers have become groundwater management problem areas because of :

I. The inadequacies of current legislation controlling coalmine abandonment procedures, namely the Quarries and Mines Act (HMSO 1954) and the Water Pollution Control Act 1974 (HMSO 1983).

and II. The lack of understanding of the hydrological and hydrogeological behaviour of abandoned coalmines due to previous research concentrating on the hydrochemical aspects of water quality deterioration and pollution caused by acid mine drainage (AMD).

1.4 THE STRUCTURE OF THIS THESIS.

The above sections have indicated that there has been a lack of research on the hydrogeological conditions and behaviour of coal mined aquifer systems. It is the aim of this study to produce an understanding of the hydrogeological and hydrological behaviour of abandoned coal mined aquifers by the formulation of a conceptual model, for use as a groundwater management tool. This requires identification of the processes that control the flow of groundwater in abandoned coal mined aquifers, because then and only then can more sophisticated modelling techniques be used to aid resource management.

Two general approaches are adopted, firstly, the use of previously published data (previous research or historic documentation (eg coal mine abandonment plans, historic pumping records or mining methods)) to predict or determine aquifer behaviour and secondly, a field survey of an abandoned coalfield for which historic records are readily available to validate the predictions, and to clarify and quantify the aquifer properties and behaviour. This approach mirrors that of a groundwater resource management investigation, which would in its initial stages draw heavily on the historic data, but would not undertake such extensive field studies.

The Forest of Dean Coalfield abandoned in 1965, was chosen as a field area, because it is of limited extent, lies within an enclosed basinal structure and has both a history of groundwater management problems and a particularly well documented history of coal exploitation. The Forest of Dean forms a dissected plateau surface covering some 85 km^2 (Figure 1.1), rising to 120 m AOD in the south and 220 m AOD in the north. The area is drained by only three major streams the Cannop Brook (the major stream draining south), Cinderford Brook and Blackpool Brook, all of which flow in deeply incised valleys. Much of the area is covered by mature deciduous and mixed deciduous/coniferous woodland. The soils are well drained over the arenaceous rocks but tend towards gleys over the argillaceous rocks (see chapter 2). The long term average precipitation is 860 mm p.a. with a winter maximum. Evapotranspiration

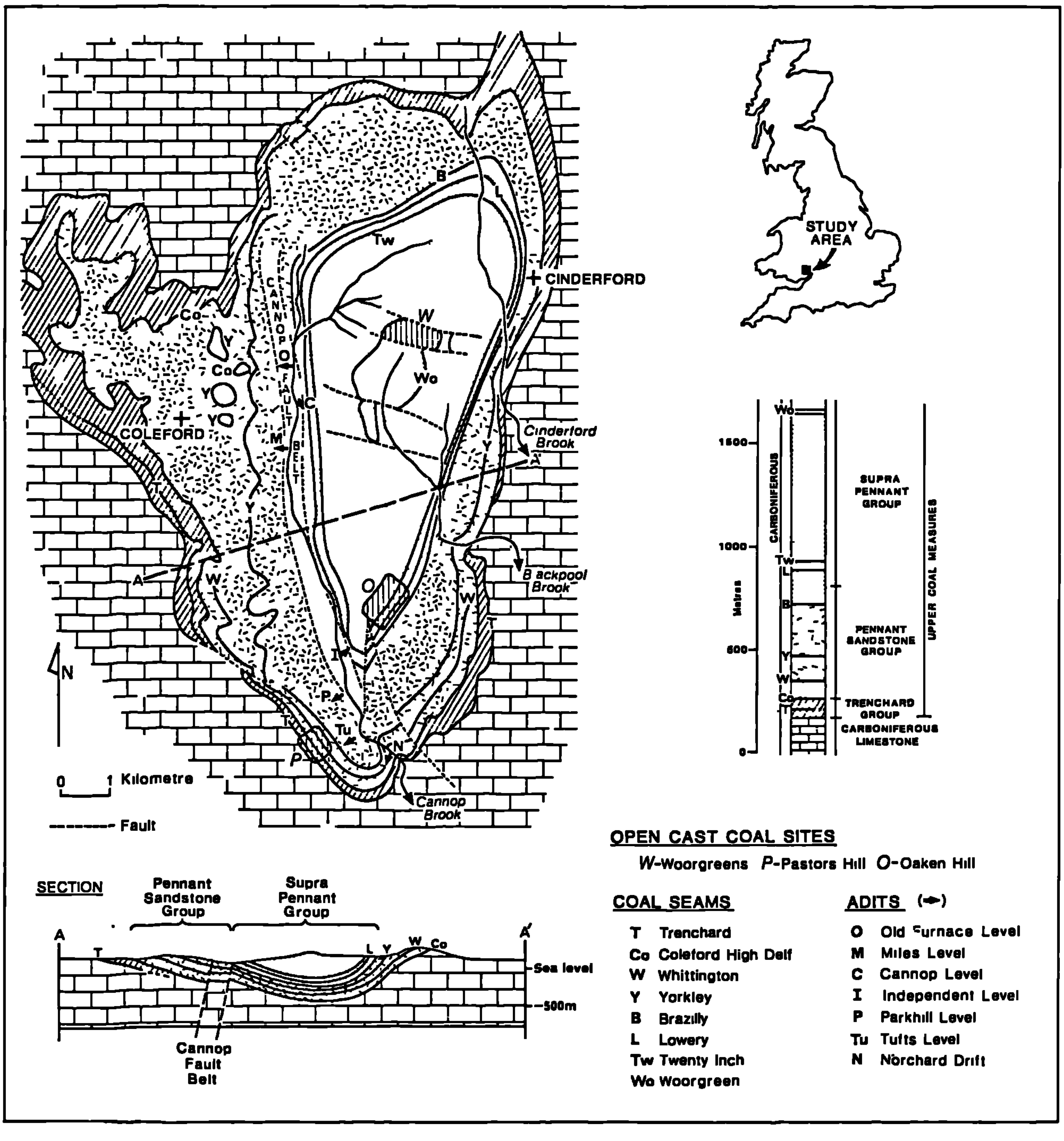


FIGURE 1.1 : Geology of the Forest of Dean Coalfield, including locations of opencast sites, major groundwater discharges from adits and surface streams.

estimated for the River Severn catchment south of Bewdley (NGR SO 78607535) is 470 mm p.a. The area is extensively used for recreation, including camping, walking, natural history, coarse and game fishing and boating. The hydrology and hydrogeology of the area has also been extensively affected by coal mining which commenced in the seventeenth century and still continues, to a limited extent today. Abandoned deep workings and free-drainage levels, still transmit water in large quantities, and extensively affects the groundwater regime in the Coal Measure Aquifers.

The structure of the thesis primarily consists of four sections (Figure 1.2) : The first section (chapters 2 and 3) uses previously published data. Chapter 2 reviews the geological information available for the Coal Measure Series of rocks identifying and predicting the main aquifer, aquiclude and aquitard units. This is then examined in detail for the Forest of Dean and the major aquifer units present are predicted. Chapter 3, reviews the available historic data sources (e.g. coal mine abandonment plans) and analyses the effects of coal mine and coalfield development and mining methods on the control of groundwater flow paths and patterns present, together with the forms of artificial drainage (free-drainage levels) which are still present today.

The second section is the major component of this study and is based upon the Forest of Dean Coalfield. Chapter 4 describes the field work undertaken together with the techniques used in data collection, interpretation and analysis. Chapter 5 uses the field data to determine and clarify the presence of the aquifer units previously identified in chapter 2. Chapter 6 uses the field data and direct exploration of the abandoned workings to identify the role of the free-drainage levels and coal barriers in controlling groundwater flow, developing the ideas in chapter 3. In addition water budgeting techniques are used to validate, catchment areas determined from coal mine abandonment plans and groundwater recharge mechanisms. The results from these chapters are used to form a conceptual model of aquifer behaviour. In chapter 7 the aquifer characteristics (transmissivity, permeability and storage volumes) are quan tified using recession curve and pumping test analysis techniques. In addition results from artificial tracer tests are presented, these are used to determined groundwater flow velocities, storage volumes, catchment boundaries and network geometries for the mined voids.

The third section comprises chapters 8 and 9. Chapter 8 presents historical chemical data that demonstrates the temporal changes that occur in deep mine outflow waters before during and after abandonment. These changes are related

FIGURE 1.2 A GUIDE TO THE STRUCTURE AND CHAPTERS OF THIS THESIS.

CHAPTER 1.
Introduction, review of previous work and current legislation controlling coal mine abandonment.

CHAPTER 2.
A review of the geology and hydrogeological behaviour of Coal Measure Rocks and the prediction of aquifer units, with reference to the Forest of Dean Coalfield.

CHAPTER 3.
The determination of the effects of mine development, mining methods and mine abandonment on the hydrogeology of Coal Measure Aquifers : A case study from the Forest of Dean Coalfield.

CHAPTER 4.
Research design and methodology.

CHAPTER 5.
The establishment of groundwater flow paths and patterns in abandoned coal mined aquifers.
1 :The Pennant and Supra Pennant Aquifers.

CHAPTER 6.
The establishment of groundwater flow paths and patterns in abandoned coal mined aquifers.
2 : The role of coal barriers and free-drainage levels.

CHAPTER 7.
The quantification of the hydrogeological characteristics of abandoned coal mined aquifers.

CHAPTER 8.
A review of the temporal hydrochemical changes associated with coal mine abandonment.

CHAPTER 9.
Hydrochemical facies separation of groundwater flow components and volumes.

CHAPTER 10.
Groundwater management problems in abandoned coal mined aquifers :
A case study from the Forest of Dean.

CHAPTER 11.
Conclusions, discussion and recommendations for further work.

to the closure of deep mined voids during the first 20 years after abandonment. Chapter 9 uses hydrochmemical separation techniques to determine groundwater flow volumes and drainage source areas by classifying surface and groundwater types by their chemical composition.

The fourth and final section, consisting of chapters 10 and 11, reviews previous groundwater management problems from the Forest of Dean Coalfield and demonstrates the importance of a clear conceptual model of abandoned coal mined aquifer systems for future groundwater resource management. In the final chapter areas for further work are discussed.

The attention of the reader is brought to the utility of Figures 1.1 and 1.2 (and Figure 4.1 refered to later) in reading this thesis. These provide a guide to the many specific localities such as mine shafts, and gauging stations, in relation to the geology which are referred to in the text. Additional copies are available loose in the back flap.

CHAPTER 2.

A REVIEW OF THE GEOLOGY AND HYDROGEOLOGY OF COAL MEASURE ROCKS WITH REFERENCE TO THE FOREST OF DEAN COALFIELD.

2.1 INTRODUCTION.

The aim of this chapter is twofold, firstly to provide a general review of the hydrogeological behaviour of Coal Measure rocks, and secondly, to review the available geological information and produce a primary interpretation of the hydrogeological conditions that are present in the Forest of Dean Coalfield.

The mining of coal has been a major industry for many years and there is extensive geological information relating to Coal Measure rocks. Unfortunately this information was generally collected to determine reserve sizes and efficient extraction techniques and did not include detailed hydrogeological analysis. Furthermore, the Coal Measure Series of rocks provides little direct water for supply and they have not been considered in detailed water resource studies, therefore little detailed hydrogeological information exists. Although extensive engineering literature is available on coalmine stability, this only considers the physical properties of Coal Measure rocks, such as tensile strength for roof support calculations (Brady and Brown 1985 and Wilson, A. 1983). The majority of hydrogeological information that is available has been associated with open cast mine exploration (Banaszak 1980), mine dewatering (Schubert 1980) and ground engineering applications in Coal Measure locations (Mather et al 1969).

2.2 THE HYDROGEOLOGICAL PROPERTIES OF COAL MEASURE ROCKS.

The geological term 'Coal Measure' refers to the sandstones, clays, coals and shales of Upper Carboniferous age in Great Britain, which lie above the Millstone Grit.

Coal Measure rocks are sedimentary in origin and form sequences known as cyclothems. A cyclothem is defined as a multiple repetition of beds of different lithology which are recognisably similar in internal sequence, but showing variations in thickness and the precise sequence of components. In the United Kingdom the Coal Measures cyclothem would be :-

Coal
Seat earth or shale
Sandstone
Shale
Coal
Seat earth or shale

But before the hydrogeological behaviour of the Coal Measures cyclothem can be interpreted the inter-relationships between hydrogeological parameters of permeability (hydraulic conductivity) and porosity, of each rock requires quantification. These parameters are also dependent upon the physical structure of the rocks present and this will also be discussed.

2.2.1 COAL SEAMS.

Coal seams can vary greatly in thickness, ranging from a few centimetres to many metres, while this is important for machinery extraction today, the predominant factors determining early mining were depth and roof stability, even seams just 0.5 m thick were extensively mined in many parts of this country (see chapter 3). Most coal seams have a common structure, the bottom of the seam is soft (and easily shovelled from the coal face at times) and called the 'bottoms' (or the 'butts' in the Forest of Dean), while the centre of the seam is hard, bright and breaks in angular lumps, the top is often dull and powdery. Furthermore, the top of the seam against the roof can be either clear-cut (normally where the roof is a sandstone) or discontinous where 'dirt' partings split the coal and roof rock (normally associated with a mudstone or shale roof). Most coals when mined, break into blocks, the breakages predominantly follow the cleat direction. (Cleat is a coal mining term used for jointing). This influenced the direction of mining and underground working because it was easier to cut across the cleat than along it. The cleat is best developed in the bright coals. Cleat partings are often infilled with mineral matter, either calcite, ankerite or pyrite (Plate 2.1).

Most coal seams are laterally continuous, although they may thin and eventually die out over distances of several kilometres. Occasionally during the deposition of Coal Measure rocks, erosion by meandering rivers flowing across the area causes the local removal of coals or peats (prior to coalification). These areas became infilled with other sedimentary deposits such as sandstones and are known as washouts.

Plate 2.1 : Block of Coleford High Delf coal showing unoxidised (bright gold) pyrite which covers the joints and fractures.

Plate 2.2 : Further vertical movement of groundwater is impeded by a coal seam, this acts as an aquitard, and a spring is located in the upper layer of the coal and sandstone above. (Photographed in an open cast coal site in the South Staffordshire Coalfield). This plate also shows the anisotropic jointing typical of coal seams.

The only previous studies that have investigated coal seams as possible aquifers for water supply are those of Banaszak (1980) and Stark and McDonald (1980), but many more workers have reported aquifer parameters from mine dewatering studies (Tables 2.1 and 2.2). This work demonstrates that the coal seams are highly anisotropic, fracture flow aquifers (Plate 2.2), with low specific storage values (1.2×10^{-3} to 3.0×10^{-6} m^{-1}), and permeabilities (0.15-0.65 m/d). Thus the low borehole yields reported by Banaszak (1980) of 82 l/min would be expected. Given the data presented above the development of such resources would be exclusively limited to single domestic supply requirements.

2.2.2 SEAT EARTH CLAYS

The seat earth clay (or 'fireclay' as it is often termed in the Forest of Dean) lies directly below the coal seam. These clay deposits are regarded as fossil soils and are occasionally characterised by the presence of numerous fossilised rootlets (Wilson M. 1965). Seat earths are the major lithological control on groundwater movement and aquifer continuity in the Coal Measure sequence of rocks, because they have very low permeabilities (Table 2.1 and 2.2) ($0.17\text{-}1.7 \times 10^{-3}$ m/d) and therefore form and act as the major aquicludes present.

The seat earth clays have not been extensively investigated with respect to their hydrogeological behaviour. Previous work has concentrated on the lithological and petrological characteristics (Wilson M. 1965, Huddle and Patterson 1961) and physical behaviour of the clays after coal extraction (White 1956, Pearson and Wade 1966). This latter case is important in the interpretation of the behavioural role which seat earth clays play in controlling water movement after coal mine abandonment. When coal is extracted from above the seat earth clay, the release of the loading pressure in the mined areas and associated increased loading around roof support structures produces a phenomenon known as seat earth squeeze, seat earth bulge or seat earth puff. The originally flat clay floor surface bulges upwards under the changing floor loading pressures enclosing the mined void. Total closure may occur in some instances (Plate 2.3), while in areas where groundwater flow or mine drainage systems are present the impermeable seat earth floor allows groundwater flow to occur down dip, often following the previous haulage roadways. Where the flow has sufficient competance, erosion of the floor occurs, this maintains an open void space and free flowing drainage (Plate

TABLE 2.1 HYDROGEOLOGICAL PROPERTIES OF THE UPPER CARBONIFEROUS COAL MEASURE ROCKS. (I).

Rock type	Porosity %	Permeability m/d	Reference
COAL	Very low	Fracture	Barnaszak 1980
		0.15-0.27	Stone and Snoeberger 1978
		0.26-0.65	Stoner 1981
		0.17	Rehm et al 1980
SEAT EARTH CLAY	High	Very low	Barnaszak 1980
		$0.17\text{-}1.7 \times 10^{-3}$	Rehm et al 1980
SANDSTONES	16	2.0×10^{-2}	Harrison 1981
	5.9	$0.78\text{-}5.2 \times 10^{-5}$	(1) Schubert 1980
		$2.0\text{-}0.08 \times 10^{-4}$	(2) Schubert 1980
		$0.78\text{-}1.2 \times 10^{-5}$	(3) Huntoon and Lundy 1979
		$9.2\text{-}0.35 \times 10^{-6}$	(4) Huntoon and Lundy 1979
		$1.0\text{-}0.1 \times 10^{-4}$	Cartwright and Hunt 1978
	12 - 26	$2.4\text{-}0.01 \times 10^{-4}$	Thurman et al 1978
		8.6×10^{-2}	Rehm et al 1980
		$1.7\text{-}5.0 \times 10^{-2}$	Cartwright et al 1983
		$0.4\text{-}1.3 \times 10^{-1}$	Daly 1976
	2.0		Kendal 1921
	36	4.1×10^{-3}	Morris and Johnson 1966.
SHALE	3.2	$0.78\text{-}6.6 \times 10^{-5}$	(1) Schubert 1980
		$0.15\text{-}1.5 \times 10^{-4}$	(2) Schubert 1980
		3.9×10^{-6}	USEPA 1980
		1.8×10^{-5}	(5) Brown and Parizek 1971
		4.0×10^{-2}	(6) Brown and Parizek 1971
		$0.03\text{-}1.5 \times 10^{-3}$	Schubert 1980
	6.4		Morris and Johnson 1966

Legend : (1) Air permeability (vertical). (2) Air permeability (horizontal). (3) Determined from pump test. (4) Determined from block. (5) Horizontal. (6) Vertical.

TABLE 2.2 HYDROGEOLOGICAL PROPERTIES OF THE UPPER CARBONIFEROUS COAL MEASURE ROCKS. (II).

Rock Type	Specific Yield	Specific Storage m^{-1}	Transmissivity m^2/d	Reference.
COAL				
		1.2×10^{-3}		Stone and Snoeberger 1978
		3.4×10^{-4}		Stoner 1981
(1)		3.0×10^{-6}		Van Voast and Hedges 1975
	0.07	5.0×10^{-5}		Moran et al 1978
		2.0×10^{-4}		Rehm et al 1980
		2.0×10^{-5}		Vogwill 1979
		5.0×10^{-6}		Rehm et al 1980
(2)		3.0×10^{-6}		Van Voast and Hedges 1975
(3)	0.07	1.0×10^{-5}		USEPA 1986
	0.01	$2.0\text{-}5.0 \times 10^{-4}$		Moran et al 1978
		1.4×10^{-4}	1.0×10^{-2}	Stark and McDonald 1980
		1.2×10^{-3}		Stone and Snoeberger 1978
(4)				Barnasak 1980
SEAT EARTH		$1.0\text{-}5.0 \times 10^{-4}$		Bara 1953
		$0.2\text{-}2.0 \times 10^{-8}$		Rehm et al 1980
		$1.0\text{-}5.0 \times 10^{-4}$		Rehm et al 1980
		$2.0\text{-}3.0 \times 10^{-4}$		Bara 1953
		3.3×10^{-6}	4.1	Stark and McDonald 1980
SANDSTONES		3.0×10^{-6}	$3.0\text{-}5.0 \times 10^{-5}$	Cartwright et al 1983
		$1.0\text{-}0.5 \times 10^{-6}$		Moran et al 1978
			5.4	Daly 1976
(5)			35-40	Harrison 1981
	0.0001	3.3×10^{-6}	28-36	Stark and McDonald 1980
			$2.6\text{-}6.9 \times 10^{-4}$	Cartwright et al 1983
SHALES		$2.5\text{-}8.0 \times 10^{-6}$	0.7-0.031	Stark and McDonald 1980
		2.5×10^{-4}		Vecchioli 1967

Legend : (1) Storage coefficient $2.0\text{-}1.0 \times 10^{-5}$ (2) Storativity $2.0\text{-}1.0 \times 10^{-5}$ (3) Storage coefficient 2.0×10^{-4} (4) Yield 82 l/min (5) Storativity 1.0×10^{-4} - 1.0×10^{-5}

Plate 2.3 : A : Abandoned workings showing haulage roadway totally infilled by seat earth clay which has 'squeezed' or 'puffed' from beneath the coal seam (South Staffordshire Coalfield).

Plate 2.3 : B : Areal view from opencast site highwall showing the complex of coal workings infilled by seat earth clay (South Staffordshire Coalfield).

2.4). (This later, important situation will be discussed in more detail in subsequent chapters).

2.2.3 COAL MEASURE SANDSTONES.

Sandstones are the most inconsistent member of the Coal Measures rock group, varying widely in texture, size and colour. However, the sandstones of the Coal Measures sequence provide the most reliable source of water for abstraction. This is indicated by the more extensive hydrogeological information available for these aquifers (Table 2.1 and 2.2). However, care hould be taken in the interpretation of this data because both primary and secondary permeability values differ considerably. Values reported range between 0.4 x 10^{-1} and 0.35 x 10^{-6} m/d). Reported porosity values ranged between 2 and 26 %. Transmissivities for the sandstones are the highest of any f the Coal Measure rocks.

2.2.4 SHALES.

Generally where mudstones are present these grade slowly into shales, permeability values are extremely low (Freeze and Cherry 1979), typically between 8.64 x 10^{-5} and 8.64 x 10^{-7} m/d. Some values reported, in coalmining literature are slightly higher, probably due to increased fracturing. The primary porosity of shale is generally less than 7 %. These hydrogeological parameters vary considerably, in outcrop areas, shales can be brittle, fractured, and often quite permeable, while at depth under pressure, they are softer, less fractured and generally less permeable. However, because of these low permeabilities shales retard downward percolation of groundwater and act as aquitards.

2.2.5 THE HYDROGEOLOGICAL BEHAVIOUR OF THE UNITED KINGDOM CYCLOTHEM.

The major aquifers of the cyclothem unit are the sandstones, these are extensive, highly transmissive, fracture flow aquifers. Similarly the unmined coal seams are fracture flow aquifers, but the fracture pattern is highly anisotropic and yields for the aquifers low. The major control on groundwater movement in the cyclothem unit is the presence of the highly impermeable seat earth clays which retard vertical water movement. The seat earth clays can therefore be expected to form the aquicludes of the Coal Measure Series. Similarly, the shales also with low permeabilities are the aquitards (Plate 2.2).

Plate 2.4 : Free-drainage level in coal workings abandoned in 1956 (Miles Level, Forest of Dean). Closure of the adjacent mined void galleries by swelling of the seat earth has occurred, but the competance of the small stream keeps the roadway open.

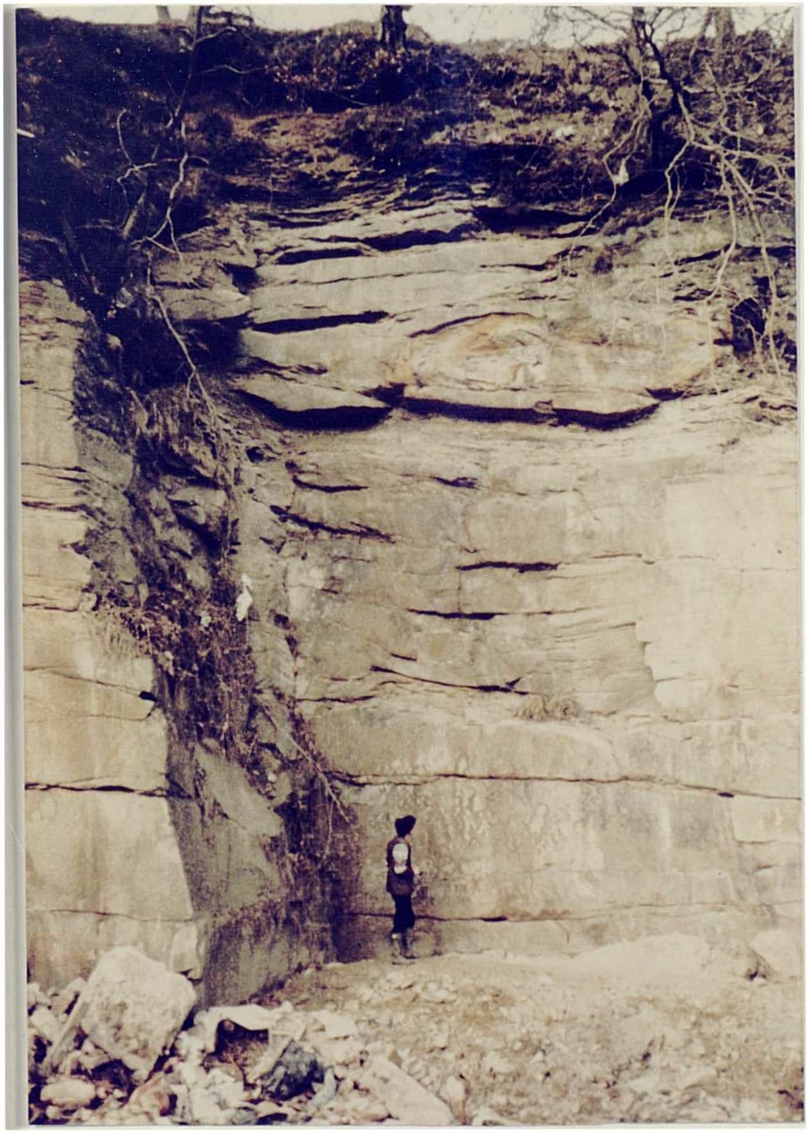


Plate 2.5 : Pennant Sandstone wall in Oak Quarry, Coleford, Forest of Dean, showing the massive blockular structure. Also a sand lens is exposed in the upper half of the quarry wall.

2.3 THE GEOLOGY OF THE FOREST OF DEAN.

This section uses the geological information for the Forest of Dean Coalfield and the hydrogeological interpretation of the role of the cyclotherm unit to define the principal aquifers present in the Forest of Dean Coalfield.

The geological information for the Forest of Dean has been collated from published literature (Crookall (1930), HMSO (1946), Mushet (1824), Sibley (1912), Sibley and Reynolds (1937), Sopwith (1841) and Trotter (1942)), and supplemented from the archives held at British Coal (Llanishen, South Wales) and the Deputy Gaveller (Surveyor of Minerals and Ores for the Forest of Dean, Forestry Commission, Coleford, Gloucestershire).

The Coal Measure rocks are of Upper Carboniferous age and are underlain by rocks of the Carboniferous Limestone sequence. Although this study is primarily concerned with the hydrogeological conditions present within the Coal Measure rocks, it is important to include at this stage a brief resume of the Carboniferous Limestones surrounding the Coalfield, because in many locations mine workings (iron ore and coal) exist in both sequences and these workings are often interconnected.

2.3.1 THE CARBONIFEROUS LIMESTONE SEQUENCE.

The Carboniferous Limestone sequence is shown in Figure 2.2 and is subdivided into two groups; the Drybrook Sandstones and the Main Limestones (Whitehead, Crease, and Lower Dolomite).

The Drybrook Sandstones were incorrectly termed 'Millstone Grit' in many of the early mining documents. However, they are 210 m thick, and consist of medium coarse grained poorly fractured sandstones. The Drybrook Sandstones are subdivided into two beds by the Drybrook Limestone which varies in thickness between 50 and 120 m. Within the limestone there are two iron ores both of which have been mined.

Below the Drybrook Sandstones lies the Whitehead, Crease and Lower Dolomite Limestones. All three contain iron ochre, but the Whitehead and Lower Dolomite have only been mined to a limited extent. The Crease Limestone is the most extensively mined. The ore bodies being variable in size and irregular shaped, and extending to depths of -125 m A.O.D. The iron ore workings where located

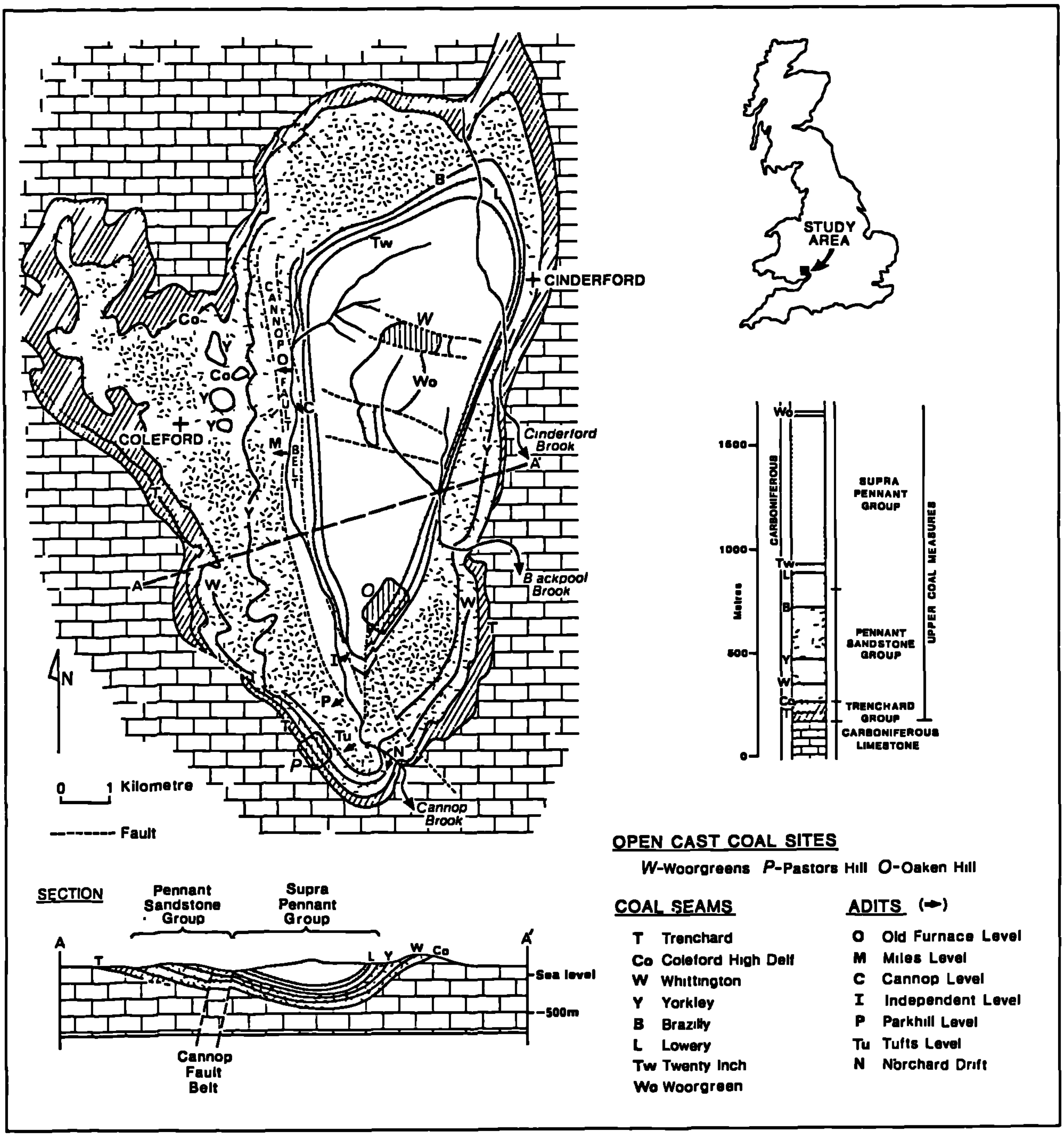
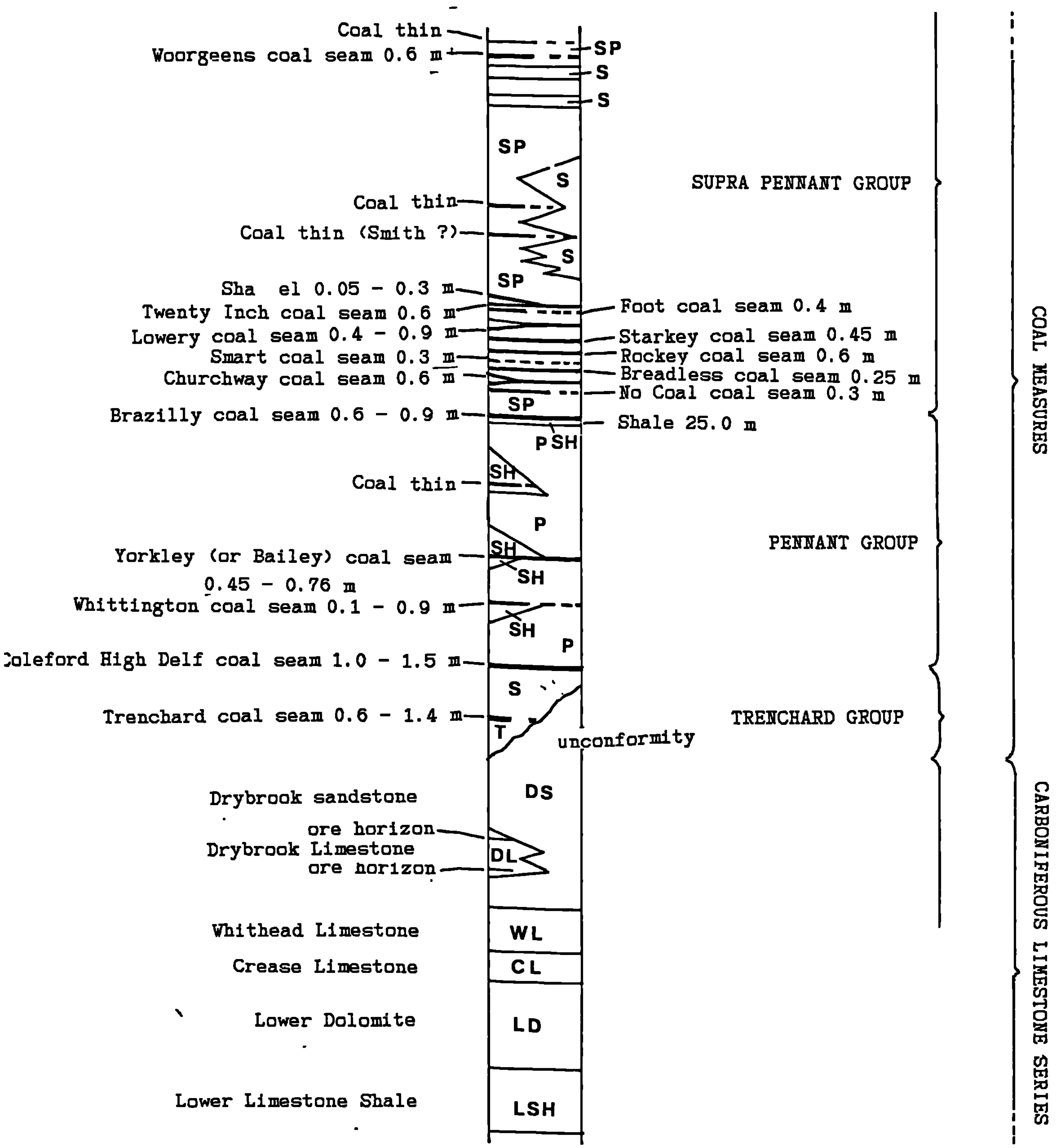


FIGURE 2.1 : Geology of the Forest of Dean Coalfield, including the locations of open cast coal mining sites, major groundwater discharges from adits and surface streams.

Figure 2.2 : Geological Series for the Forest of Dean Coalfield (not to scale).



Legend : T - Trenchard
P - Pennant (mainly sandstone)
SP - Supra Pennant
S - Sandstone
Sh - Shale
Coal seam thicknesses shown in metres.
Seat earth clays omitted for clarity (see text for description).

along the western and north eastern outcrop of the Carboniferous Limestone, close to edge of the Coalfield. All the workings are now abandoned.

2.3.2 THE COAL MEASURE GROUP OF ROCKS.

The Coal Measures are subdivided into three major stratigraphic divisions : The Trenchard Group, The Pennant Group and The Supra Pennant Group (Figure 2.2). The Trenchard Group lies conformably over the Carboniferous Limestone, and forms the base of coalfield (Figure 2.1). The Pennant Group, forms the highest land which fringes the outer edges of the coalfield, with steeper dips on the eastern flanks (15°) than the the west (3°). The Supra Pennant Group overlies the Pennant Group and outcrops in the centre of the basin.

2.3.2.1 THE TRENCHARD GROUP.

The Trenchard Group (Figure 2.2) is only 50 m in thickness and forms the base of the Coal Measures, lying directly over the Carboniferous Limestone. It comprises of shales, sandstones, grits and conglomerates. Only one coal seam is present the Trenchard coal seam (1.4 m), which is split by an intermediate sandstone into the Upper and Lower Trenchard coal seams, each about 0.6 m in thickness. The coal seam is underlain by 1.9 m of impermeable seat earth which acts as an aquiclude, and forms the base of the Trenchard Aquifer (Table 2.3). The Trenchard Aquifer includes the Trenchard coal seam and 26 m of sandstone which lies between the coal seam and below the Coleford High Delf coal seam seat earth clay above. The Upper Trenchard coal seam was extracted extensively by both shallow and deep mining methods in the southern part of the coalfield, while the Lower was marred by shale partings and was not mined. The Trenchard coal seam does not continue throughout the whole Trenchard Group, but thins to the north and is absent north of a line between Coleford and the point where the Blackpool Brook leaves the Coal Measure strata (Figure 2.1).

2.3.2.2 THE PENNANT GROUP.

The Pennant Group consists of massive sandstones (Plate 2.5) with subordinate shales, and includes three coal seams of workable thickness, the Coleford High Delf, Whittington and Yorkley coal seams. The group increases in thickness from 180 m in the north to 240 m in the south. The Coleford High Delf coal seam is 1.0-1.5 m thick, and was the most extensively worked coal in the coalfield (Figure 2.3), with workings extending to depths of -400 m in the centre of the basin (Figure 2.4). The Coleford High Delf coal seam is a bright bitumous coal, normally lying in three leats, separated by two dirt partings,

TABLE 2.3

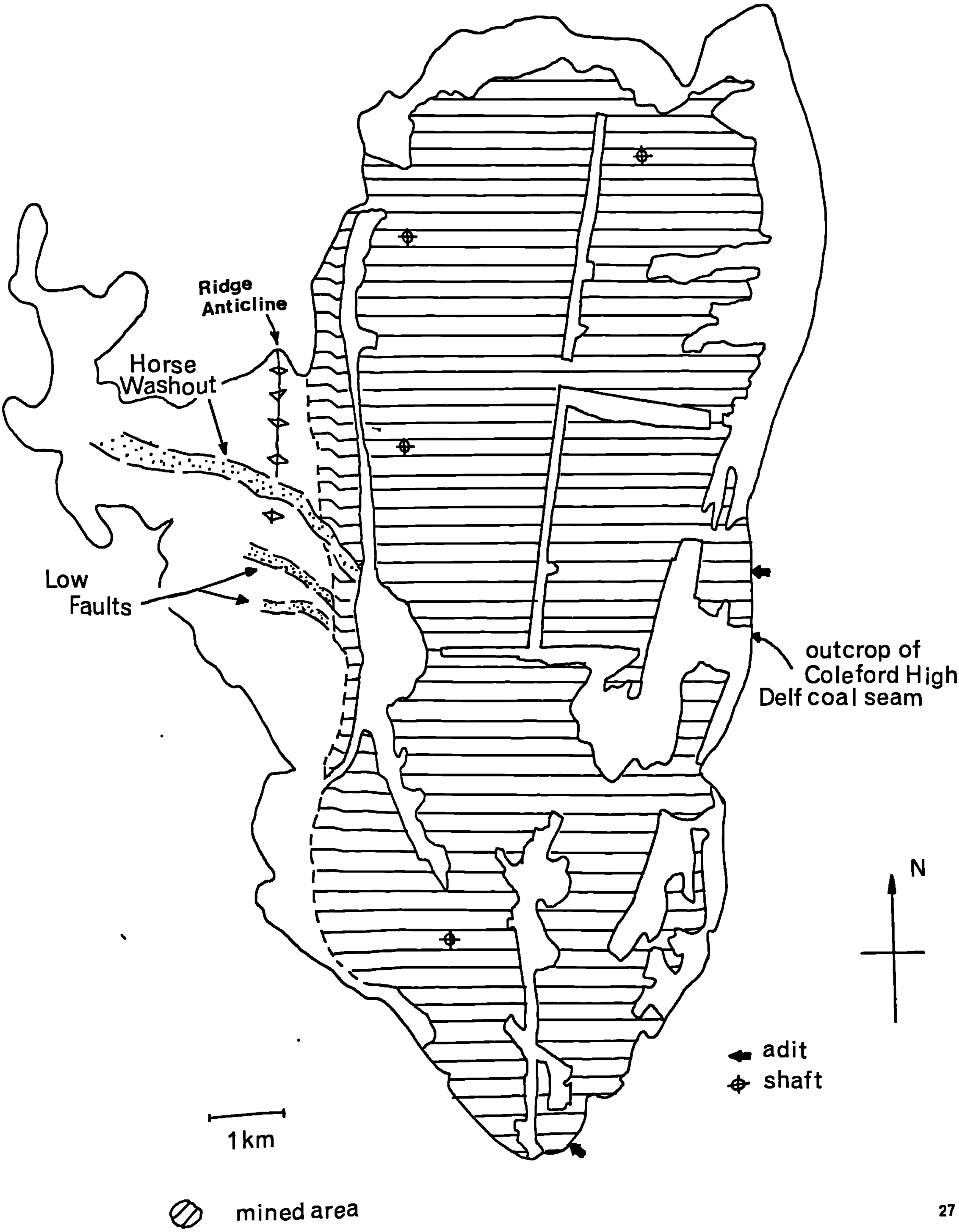
SUMMARY TABLE SHOWING THE PENNANT GROUP AQUIFERS, INCLUDING THE STRATA THICKNESS AND EXTENT OF MINING OF COAL SEAMS.

AQUIFER	STRATA	THICKNESS (m)	MINED
YORKLEY AQUIFER	Sandstone	100-140	-
	Yorkley coal seam	0.45-0.76	Outcrop area only
	Seat earth clay	1.0	-
COLEFORD HIGH DELF	Sandstone	21.0	-
	Whittington coal seam	0.1-0.9	Very little
	Seat earth clay	0.6	-
	Sandstone	52.0	-
	Coleford High Delf coal seam	1.0-1.5	Extensive
	Seat earth clay	1.2-2.4	-
TRENCHARD AQUIFER	Sandstone	26.0	-
	Trenchard coal seam	0.6-1.4	Extensive
	Seat earth clay	1.9	-

TABLE 2.5 STRATA ASSOCIATED WITH THE CLASSIFICATION OF THE SERRIDGE AQUIFER (NOTE THE INTERVENING SHALE LAYER WHICH SUBDIVIDES THE SERRIDGE AND CRABTREEHILL SANDSTONES).

SERRIDGE AQUIFER		
STRATA	THICKNESS (m)	MINED
Sandstone and shale	9.0	-
Woorgreen coal seam	0.6	Previously little, now extensively by open cast mining.
Crabtreehill Sandstone	8.0	-
Argillaceous clays and shales	9.0	-
Crabtreehill Sandstone	8.0	-
Shales	75.0-100	-
Serridge Sandstone	100	-
Shale	6.6	-

Figure 2.3 : 1965 National Coal Board abandonment plan showing extent of deep coal extraction in the Coleford High Delf coal seam. Workings in the outcrop areas are not shown on this abandonment plan as they are workings conducted by the 'free miners' (see chapter 3) and plans are only held by the Deputy Gaveller (Coleford). However most outcrop areas in this seam have been extensively worked, and for a detailed hydrogeological survey a combination of both data sources is required. The washouts in the Coleford High Delf coal seam known as the Horse and Low Faults are also shown.



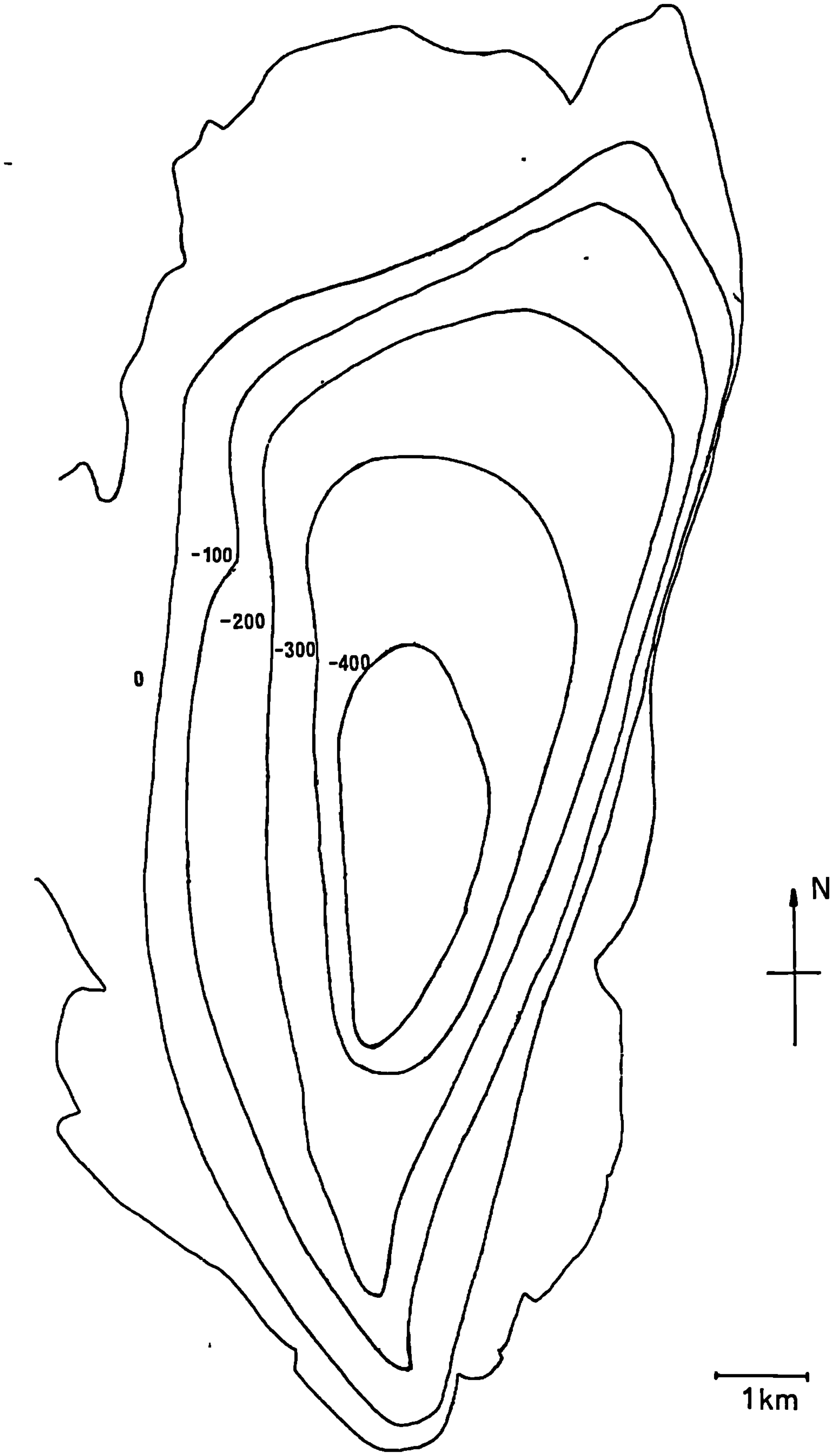


Figure 2.4 : Depth contours of Coleford High Delf coal seam for the central basin, in m A.O.D.

but one or both of these may be absent in some locations. The cleat (jointing) is normally poorly developed or absent. Around the outcrop and at shallow depth the seam has a sandstone roof, but in the central basin at depth shales intervene between the sandstone and the coal. Two important washouts occur in the Coleford High Delf coal seam, the Horse Washout (or Horse Fault) and Low Fault (Figure 2.3) (Buddle 1842). The term 'fault' is used in the local mining phraseology, to describe any interruption in the regular deposition of the seam or vein of coal. However, unlike normal geological nomenclature, there is no dislocation in the strata. (The hydrogeological implications of washout areas will be discussed in chapter 6).

There are 73 m of sandstone between the Coleford High Delf and Yorkley coal seams in the north and central areas. These are massive well cemented sandstones with a calcite matrix, and a well developed jointing and bedding planes (cross bedding is also present). They have a low intergranular porosity (~2 %), but form the largest aquifer unit in the area, with groundwater flow dominated by the presence of numerous large fractures. In the southern area the sandstones divide into upper and lower divisions separated by 21 m of shales in which is included the Whittington coal seam. The Whittington coal seam was not an important coal because it was sulphury, only attained a thickness of 0.9 m, and was frequently interrupted by clod and dirt partings. The seam becomes unworkable and finally disappears north of an east-west line through Oakenhill (NGR 6270 0725). Therefore the Whittington coal seam was not extensively extracted (Figure 2.5), with most workings being confined to outcrop areas only.

The Yorkley coal seam lies 70-100 m above the Coleford High Delf coal seam, and attains a maximum thickness in the south, where three separate bands are separated by partings of neglible thickness. The seam is underlain by a seat earth clay upto 3.0 m in thickness but averaging 1.0 m. Close to the outcrop in the south and west the seam averages 0.6 m in thickness, and it is here where most extraction has taken place (and continues today). At depth the seam remains entirely intact (Figure 2.6). The seam thins to the north-east and finally disappears north of Cannop Ponds (NGR 60901050) and Cannop Colliery (NGR 60751245). Above the Yorkley coal seam lie a further 100-140 m of massive sandstones which have been extensively quarried for building and memorial stone because of their dark blue colour (Trotter 1942). The only deposits of

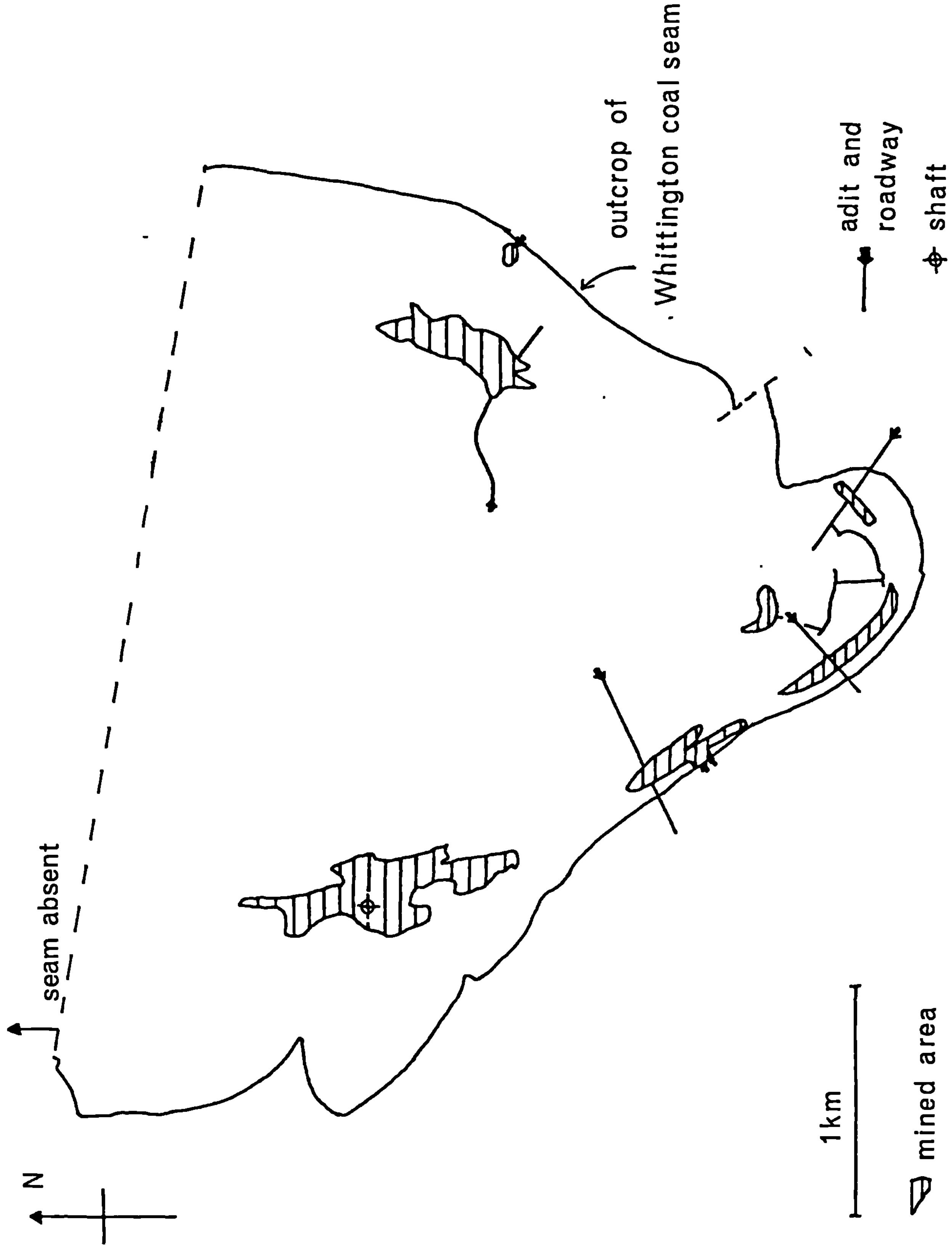
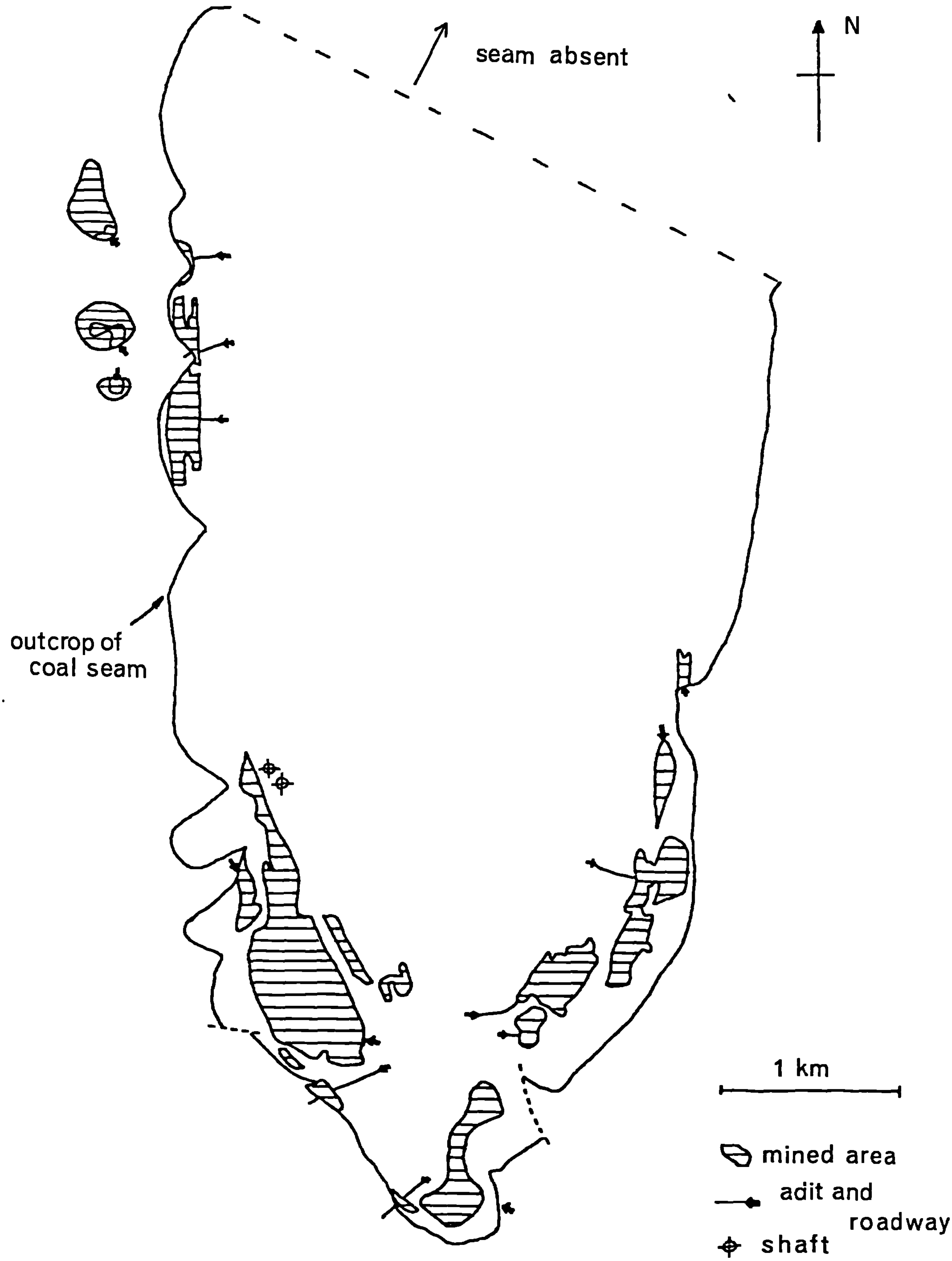


Figure 2.5 : 1965 National Coal Board abandonment plan showing the extent of workings in the Whittington coal seam.

Figure 2.6 : 1965 National Coal Board abandonm nt mine plan showing the extent and location of workings in the Yorkley coal seam.



iron ore within the Coal Measure rocks occurs within the sandstones above the Yorkley coal seam. Trotter states :

" It would appear that the solutions came down from above, were trapped by the argillaceous measures immediately below the Yorkley Coal (presumably the seat earth clay), and were prevented by them from descending to lower horizons" (Trotter 1942 p75). The ore occurs in shallow pockets or as veins along fracture and joint walls.

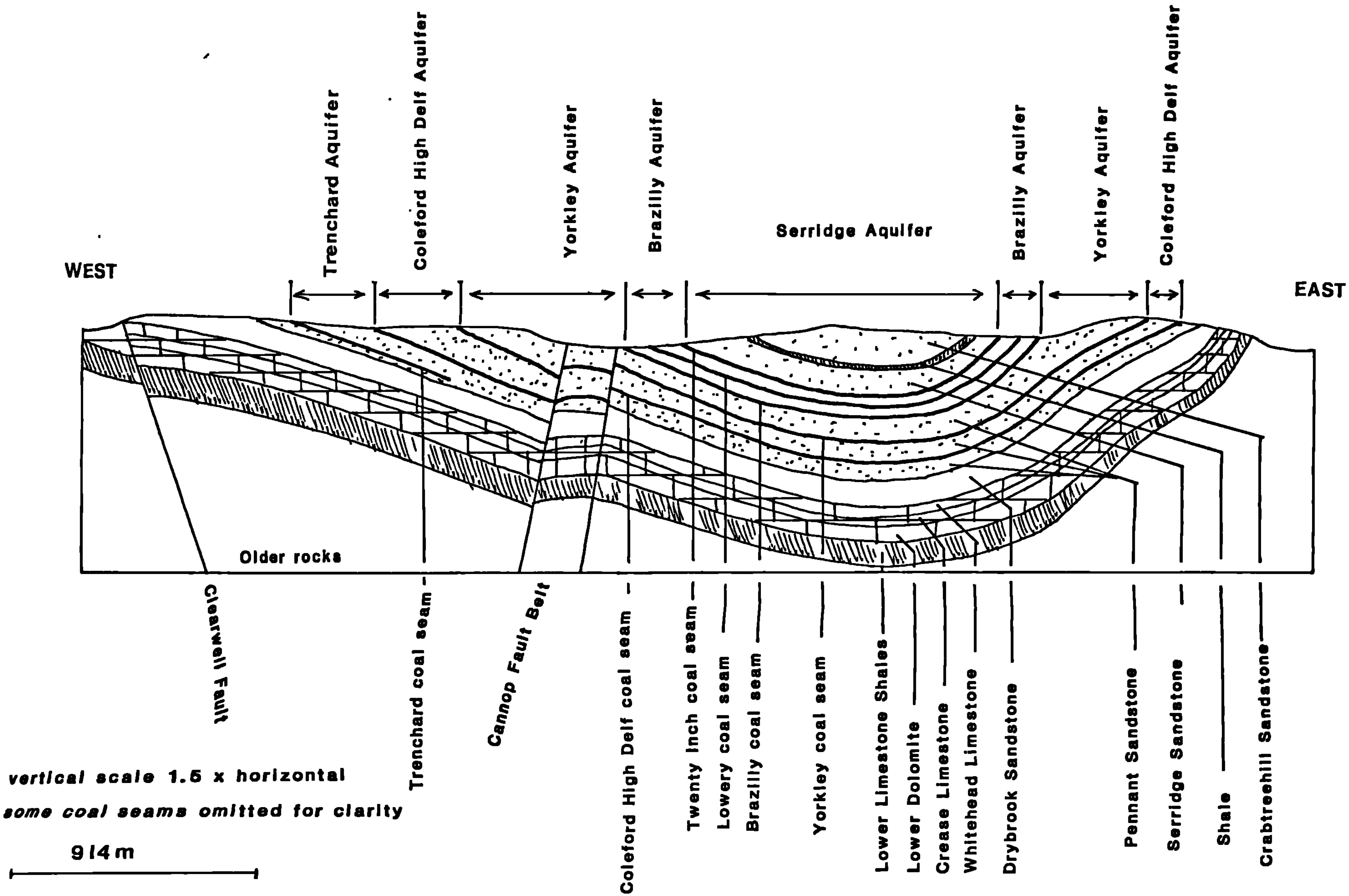
All the coal seams present in the Pennant Group are underlain by thick impermeable seat earth clays. These vary in thickness, from 1.2 to 2.4 m below the Coleford High Delf coal seam, with an average of 1.0 m for the Yorkley, to only 0.6 m beneath the Whittington coal seam. The seat earth clays impede vertical drainage and acts as aquicludes. The presence of the aquicludes divides the Pennant Group into two aquifers. The Coleford High Delf Aquifer and Yorkley Aquifer (Table 2.3). The Coleford High Delf Aquifer includes the Coleford High Delf coal seam and the 73 m of Pennant Sandstone above, which lies below the Yorkley coal seam seat earth. The Yorkley Aquifer similarly consists of the Yorkley coal seam and the 100-140 m of Pennant Sandstone above. The Coleford High Delf Aquifer is unconfined in outcrop areas but in the central basin is confined by the Yorkley Aquifer (Figure 2.7). Similarly the Yorkley Aquifer is unconfined in outcrop areas but confined by the overlying Supra Pennant Group in the central basin. The Whittington coal seam does not form a separate aquifer because the seam is not laterally continuous as in the case of the Coleford High Delf or Yorkley.

Within the Pennant Group lies the Cannop Fault Belt an 8 km long zone of fracturing embracing upto 25 faults which trends west of north along the Cannop Valley (Figure 2.1). To the west, and also affecting the Pennant rocks, is the Ridge Anticline, a shallow north-south asymmetrical plunging fold with greater dips on its eastern flank (Figure 2.3).

2.3.2.3 THE SUPRA PENNANT GROUP.

The Supra Pennant Group overlies the Pennant Group and outcrops in the centre of the basin. It consists of shales, sandstones and coal seams divided into two stratigraphic units, a Lower Division 91 m thick in which there are twelve coal seams (known as the Brazilly Aquifer), and an Upper Division 240 m thick which contains sandstones, shales and only subordinate coal seams (known as the Serridge Aquifer)(Figure 2.7).

FIGURE 2.7 : Geological cross-section of the Forest of Dean Coalfie d, showing the identified aquifer units.



The Brazilly Aquifer includes the twelve coal seams from the Brazilly to the Crow (Figure 2.2). Although there are extensive shale layers between the separate coals and intermediate sandstones this aquifer classification of the major aquifer units has combined them together. The shales act as aquicludes which although retard vertical groundwater movement do not completely impede it. Separate confined aquifers will occur between the coal seams within the intermediate sandstones. This combined classification and concept of multiple confined aquifers will be discussed in detail in chapter 5.

The Brazilly coal seam is divided from the Pennant Group by a layer of shales 25.0 m thick, this acts as an aquiclude and provides the base of the Brazilly Aquifer. The thickness, roof and floor materials, and extent of mining of the twelve coal seams is shown in Table 2.4. Only the Twenty Inch, Lowery, Starkey and Churchway High Delf coal seams where mined extensively. The coals which w ere not extensively mined are either thin, banded (broken into layers and separated by either shale or sandstone layers), or laterally discontinuous. A layer of 6.6 m of shale lies between the Crow Delf coal seam of the Brazilly Aquifer and the lower most strata of the Serridge Aquifer or upper division of the Supra Pennant Group above.

In contrast to the Pennant Group, the Supra Pennant Group does not contain thick extensive seat earth clays beneath the numerous coals. Geological records show that the Brazilly, No Coal, Breadless, Shaftnel, Crow Delf, Foot, Starkey and Rockey coal seams all have shale layers beneath the coal and seat earth clays are absent. The Churchway, Lowery and Twenty Inch coal seams have floors which vary between seat earth clays and shales. The argillaceous floors (the seat earth clays) tended to be present nearer the western outcrop and were not laterally continuous as is the case in the Pennant Group.

The Serridge Aquifer is dominated by the presence of the Serridge and Crabtreehill Sandstones. The Serridge Sandstones are 100 m in thickness and are divided into two equal parts by a thin coal of 0.1 m thickness. The lower of the sandstones is separated into two layers by shales. Unfortunately there is little information concerning the 75-100 m of strata which lies between the Serridge and Crabtreehill sandstones, and outcrop exposures are poor. However, the presence of numerous springs at the base of the Crabtreehill Sandstone would indicate that the strata consists mainly of shales. The Crabtreehill Sandstones are also separated into two layers, while the sandstones average a

TABLE 2.4 SUPRA PENNANT GROUP (BRAZILLY AQUIFER) COAL SEAMS PRESENT, THICKNESS, INTERVENING STRATA AND EXTENT OF MINING

Coal Seam	Thickness (m)	Floor material and thickness (m)	Roof and Intermediate strata (m)	Extent of Mining
Crow Delf	0.05-0.3	Shale 6.0	Shale 6.6	Northern outcrop only
Shaftnel or Twenty Tops	0.05-0.3	Shale 1.3	Shale 6.0	Limited extent where thickness permitted
Twenty Inch	0.5-0.6	Shale and Seat earth 1.0-1.2	Shale 1.3	Extensive
Foot or Little Delf	0.3-0.45	Shale 1.2	Shale 1.0-1.2	Outcrop only
Lowery or Parkend High Delf	0.9	Seat earth 1.0	Shale 1.7	Extensive
Starkey	0.45	Shale 1.7	Shale 3.25	Extensive
Rockey	0.6	Shale 3.0-3.5	Sandstone 9.0-12.0	Outcrop only
Smart	0.3	Seat earth and Shale 1.8	Shale 3.0-5.0	Outcrop only
Breadless	0.2	Shale 9.8	Sandstone 6.0-9.0	Outcrop only
Churchway High Delf	0.6	Seat earth 0.1-0.6 and/or Shale 5.9	Shale 9.8	Extensive
No Coal	0.05-0.3	Shale 18.3	Shale 0.5, Sandstone 3.6 and Shale 5.9	Very little
Brazilly	0.6-0.9	Shale 27.0	Sandstone 15-20	Very little

TABLE 2.6. AQUIFER CLASSIFICATION FOR THE FOREST OF DEAN COALFIELD.

GEOLOGICAL GROUP	AQUIFER NAME	STRATA INCLUDED.
SUPRA PENNANT	SERRIDGE AQUIFER	Serridge and Crabtreehill Sandstones of the Upper Division of the Supra Pennant Group, including the Woorgreen coal seams. Outcrops within the central basin, aquifer is unconfined. Base of the aquifer defined by shale above Crow Delf coal seam of the Brazilly Aquifer.
SUPRA PENNANT	BRAZILLY AQUIFER	Includes all the coal seams (worked and unworked from Brazilly to Crow Delf) of the lower division of the Supra Pennant Group. Base of the aquifer is defined by shale below the Brazilly coal seam. The aquifer is confined by the Serridge Aquifer in the centre and unconfined at the outcrop.
PENNANT	YORKLEY AQUIFER	Includes the Pennant Sandstone between the Supra Pennant Group (Brazilly Aquifer) and the Yorkley coal seam. Base of aquifer (aquiclude) is the unworked Yorkley coal seam and seat earth clay in the central basin, and the seat earth at the worked outcrop area. Aquifer unconfined at outcrop, and confined by Brazilly Aquifer in central basin.
PENNANT	COLEFORD HIGH DELF AQUIFER	Includes the Pennant Sandstone between the Yorkley aquiclude and Coleford High Delf coal seam. Base of aquifer is defined by Coleford High Delf coal seam seat earth. Aquifer is confined in central basin, and unconfined at outcrop. Aquifer includes coal workings in the Coleford High Delf coal seam.
PENNANT	TRENCHARD AQUIFER	The smallest of the aquifers, which includes the sandstone between the Coleford High Delf coal seam seat earth and the Trenchard coal seam. Base of aquifer is the Trenchard coal seam seat earth. Aquifer includes abandoned coal workings in Trenchard coal seam.

thickness of 8.0 m each the intervening strata of argillaceous clays and shales are 9.0 m in thickness. Above the uppermost Crabtreehill Sandstones lies the Woorgreen coal seams. Two seams are present, termed the upper and lower and both are 0.6 m thick lying only 10.0 m below the surface.

Underground mining is still occuring in four small mines along the eastern and northern outcrop of the Yorkley and Coleford High Delf coal seams, but it is the Supra Pennant Group which is now more economically viable using open cast methods (Figure 2.1). At one site the Woorgreen coals of the Upper Division were extracted where the overburden was <10m, and two further sites are planned for the lower division, where many seams outcrop over a small surface area and the intra-seam rocks are soft and easily removed.

2.4 C NCLUSIONS.

1. The Forest of Dean geology typifies the differences that can occur in the size of cyclothem units. This is shown by the 200 m of massive sandstones, few thick coal seams and general absence of continous shales in the Pennant Group, while the Supra Pennant is characterised by thinner more variable cyclotherms; the Lower Division (or Brazilly Aquifer) contains many shales and thin coals and small sandstones, while the Upper Division (or Serridge Aquifer) contains few coal seams but thick shales and sandstones.

2. The major geological control on groundwater movement in Coal Measure rocks is determined by the presence of the seat earth clays, although intact coal seams and shales do also show many similar hydrogeological properties but are slightly more permeable. The major aquifers present are the sandstones

3. The Coal Measure Sandstones also vary greatly in size and nature this is typified by those associated with the Supra Pennant Series which are grey extend for only 5-10m in thickness, and are not massive in structure or highly faulted like those of the Pennant Sandstone of the Pennant Gro p

4. From the limited knowledge of the hydrogeological properties of Coal Measure rocks it has been possible to predict the major aquifers units present in the Forest of Dean. However, this determination does not account for the effects of mining (mine dewatering methods or historical coalfield development techiques on the hydrogeological properties of the rocks present This will be investigated in the next chapter.

5. In conclusion this chapter has predicted five main aquifer units present in the Forest of Dean Coalfield. The Pennant Group can be subdivided into three aquifer units, the Trenchard Aquifer, Coleford High Delf Aquifer and Yorkley Aquifer (Table 2.6), and the Supra Pennant Group into two aquifer units, the Brazilly Aquifer and Serridge Aquifer (Table 2.6). A summary is shown in Table 2.6 and Figure 2.7.

CHAPTER 3

THE DETERMINATION OF THE EFFECTS OF MINE DEVELOPMENT, MINING METHODS AND MINE ABANDON MENT ON THE HYDROGEOLOGY OF COAL MEASURE AQUIFERS : A CASE STUDY FROM THE FOREST OF DEAN.

3.1 INTRODUCTION

The previous chapter has reviewed the hydrogeological properties of Coal Measure rocks, and used this knowledge to predict the major aquifer units pre ent in the Forest of Dean. This interpretation did not accounted for the extent of mining present, nor did it include the effects of differing coal extraction methods and coal mine drainage techniques. This chapter discus es the hydrogeological changes that occur in Coal Measures strata during the mining of coal (pre-mining, mining and post-mining time periods are all discussed), which can be interpreted from historic data. The data used is available from archive sources and early scientific and historical publications. This is often the only information available on which to base groundwater management policies or to design more detailed site specific projects.

3.2 MINING HISTORY, COALFIELD DEVELOPMENT AND ABANDONMENT

This section reviews the historical development of mining methods and legislation, outlining the methods of mine drainage that were operated. Although this account relates specifically to the Forest of Dean, the details given also apply to other coal mining areas because the Forest of Dean was one of the earliest coalfields developed for large scale coal extraction, and the methods and techniques employed were later used in other UK coalfields.

The first record of mining activity in the Forest of Dean appears in the Old Justice Seat held at Gloucester in 1282 (Hart 1953). These early workings were limited to outcrop areas only, reaching depths of up to 5.0 m. By the fourteenth century these workings developed into 'bell pit mines' (Stewart 1973 and Gregory 1962). Bell pit mines comprised of a shaft sunk to a shallow depth (~10.0 m) to intersect a coal seam, the coal being extracted radially from the shaft bottom. The lateral extent of the workings depended upon the natural support of the roof material, as no artificial roof support system was used. As soon as one shaft became dangerous or roof collapse occured in the worked coal area, another would be sunk a small distance away. This method of extraction gives rise to the circular subsidence features that are common in outcrop areas

(Plate 3.1). The unsupported shaft limited the depth of extraction and workings were therefore confined to outcrop areas only and required no form of artificial drainage.

By the mid seventeenth century the system of pillar and stall working had been developed. This method of working was carried out from shallow shafts (~20.0 m in depth) and small levels or adits but extraction was still confined to the outcrop areas. Pillar and stall workings operated from a major haulage roadway, from which minor roads penetrate the coal seam. Coal was extracted in an organised manner to leave pillars of intact coal to support the roof. These pillars are typically 4 m x 4 m in cross section (measured in a free mine abandoned in 1900 during an underground survey in 1983), but the size of pillar varies widely depending on the nature and stability of the roof material and dip of the seam extracted. Where the dip of the seam is high the pillars are rectangular in cross section. In the Bixslade area of the Forest of Dean the angle of dip is 20° and pillars are typically 4 m x 25 m in cross sectional shape, the smaller side faces up dip, in order not to retard downdip drainage. In many situations, pillars were not sufficient to stop roof collapse and pit props or 'cradles' (a pillar of blocks of wood, stacked in pairs in alternating directions) were also employed. On abandonment pillar detrioration or pillar 'robbing' often caused roof collapse. Pillar deterioration is the physical breakdown of the intact coal from natural spalling (the flaking of the coal along the jointing over the exposed pillar surface) which slowly lessens the load bearing strength of the pillar resulting in roof failure. Pillar robbing is the removal of the intact coal by mining from the pillar which also subsequently lessens the load bearing strength of the remaining pillar. This practice was frequent when mines were abandoned. Pillar and stall workings were the first organised extraction methods employed in the Forest of Dean.

It was not until the late eighteenth century that the organised pillar and stall mining was combined with the first artificial drainage methods. Drainage was facilitated by what are termed 'free-drainage levels' (or soughs or suffs . These were low gradient levels (1 in 295) driven across the strata (and referred to as cross-measure levels or cross-measure drivages) from a low point in the valley floor into the hillside until the coal seam was intersected (Figure 3.1), from this point two further low gradient levels would be driven along the coal seam in each direction. These later levels are known as long-measure levels or long-measure drivages, because they were driven at length within the same strata. Groundwater drained by gravity to the surface, where it discharged into the nearest water course. The free-drainage levels allowed

Plate 3.1 : Circular subsidence features typical of outcrop areas where coal has been mined from shallow depths by unsupported bell pit methods. (Photograph from South Wales Coalfield, Blaenavon, Gwent).

lowering of groundwater levels permitting the extraction of coal from deeper areas. The effects of this development on abstraction must have been dramatic. In 1676 it is recorded that miners other than those who had directly paid for the drainage level were 'forcibly' restricted from within 90.0 m of the level mouth. This was amended to 275 m in 1697, 460 m in 1728 and 910 m in 1755.

The drainage barriers also subdivided the Pennant Sandstone Aquifer into two separate units, a unit above river level, and a second unit below river level. This is important for present day management of water resources because many of these free-drainage levels still function today as major groundwater discharges. The former of these two units drains groundwater (Pennant Sandstone outcrop recharge) via the long-measure levels to the surface river or stream. This is called the 'shallow groundwater circulation' (Figure 3.1). Below this recharge to the deep basin below river level occurred via leakage from the drainage barriers.

When the free-drainage levels were developed, the organisation of coal extraction and coalfield development was initiated. This was neccessary to protect the considerable investment of time and money in driving the drainage levels. The area of coal to be mined from one adit and in one seam was specified, the area being termed a gale (Hart 1953). Barriers of intact coal where left around the boundaries of each gale to prevent the ingress of groundwater (Figure 3.1). Where these barriers ran along the dip of the coal they were known as boundary barriers, and where they formed the base of the long measure levels they were known as drainage barriers (Figure 3.1). Generally the barriers were 18.0 m wide, although this varied from 9.0 to 55.0 m, with the thinnest in the outcrop area and the widest at depth. The system of gales therefore defines mining concessions, and is also the basis for drainage and documentation in this and other coalfields (Ashley 1930, Forrest 1920). In the Forest of Dean this was and still is controlled by the Deputy Gaveller (see below). The gales were operated by 'Free Miners', being people who had been born in the Hundred of St. Briavels (a district covering much of the Forest of Dean), and on proof of being twenty-one years of age and having worked in a colliery for a year could obtain their own gale for coal mining. This historical situation still exists, and is exercised by the few remaining Free Miners in four such mines. However, gales and boundaries were only defined for the coal seams to be worked within the area of new mines. Thus previously working mines remained unrecorded, and coalfield development continued in only a semi-organised manner. By 1841 disputes concerning the ownership of mines and gales and drainage problems had become numerous (Hart 1952), and this required

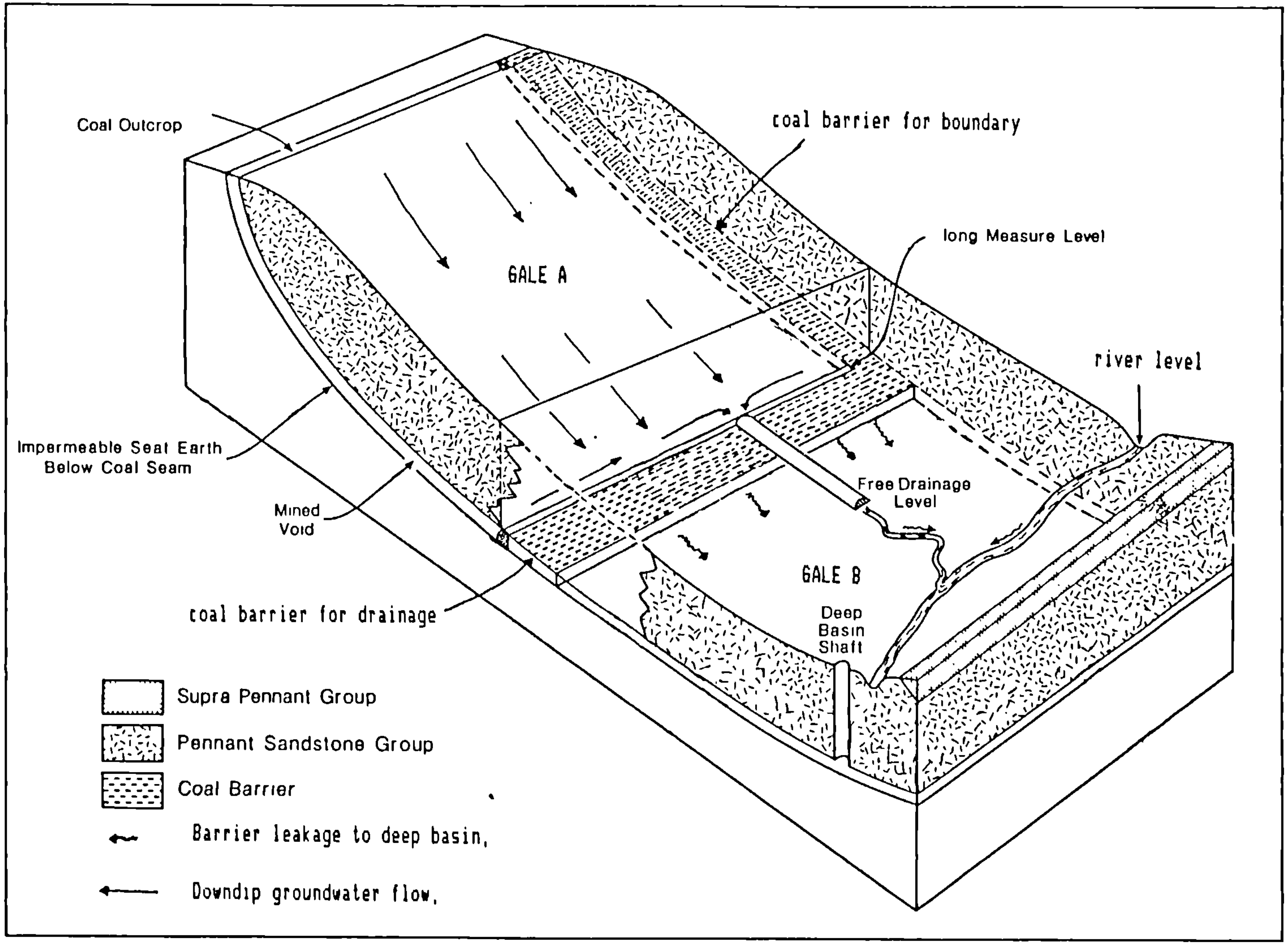


Figure 3.1

Schematic block diagram illustrating the hydrological function of intact coal barriers in coal mine drainage, and gale boundary determination.

an Act of Parliament to clarify the situation. The Act established the Forest of Dean Mining Commissioners who subsequently delineated all possible gales for all the coal seams (it is important to note that gales in different coal seams were often mined from one adit or shaft, and although the gales had different names the adit, shaft or colliery could have a totally different name which reflected the miners personality or cognomen (for instance, Strip And Get At It Colliery or Young Colliers Colliery)). The Commissioners also published plans covering coal extraction for all the gales, which had not previously been attempted, and produced a report defining Free Mining rights which was published in 1841 (Sopwith 1841). Sopwith's account covers the rules and regulations of working both iron and coal mines in the Forest of Dean, together with preliminary observations about the working of the gales and a set of sixteen plans of the gales. Although old this is a vital document to locate the correct gale name for a particular area. The gale plans are held in the Deputy Gavellers Office (Coleford). The Forest of Dean at this time was the most organised coalfield in the UK, and was soon copied in the Cannock Coalfield (Forrest 1920).

However, it was not until 1872 that it became a legal requirement that plans showing the boundaries and extent of mining activity had to be produced and deposited with the Gaveller (Gregory 1982). These plans are particularly important in the study of abandoned coal mine hydrogeology, as they provide the only documented evidence of the extent of mining activity available for inspection. Despite this organisation, disputes about gale boundaries and coal 'robbing' (mining coal from your neighbours gale) continued (Hart 1952). Therefore in 1904, the Forest of Dean coal resources were reviewed, and in 1909 the Forest of Dean Commissioners published a set of plans for the most important coal seams indicating the extent of workings and the defined gale boundaries and gale names. It was also at this time that the boundary and drainage barriers were classified under three categories;

(i) Barriers licensed to be worked
(ii) Barriers which may be licensed to be worked
and (iii) Barriers to be reserved.

All of the categories were marked on the original plans, which are also held at the Deputy Gavellers Office (Coleford). The barriers which were licensed to be worked or could be worked were exclusively boundary barriers. This allowed adjacent gales to be joined, a practice for which there are few records. In fact, there is documentary evidence that on publication, this classification and set of maps were wrong because a memorandum dated 1909 to the Deputy Gaveller from a Mr. Forester Brown states that 'some of the coal supposed to be in barriers has already been mined prior to the maps being drawn'. It is therefore impossible to predict the status of these barriers with any certainty today. The barriers which were classified as 'reserved' formed a ring around the coalfield at or close to river level and formed the drainage barriers of the free-drainage levels, which intercepted all the recharge from the outcrop and up dip drainage.

The final act of the 1904 report was to amalgamate fourty four gales which had been defined in the central basin in the Coleford High Delf and Yorkley coal seams (Figure 3.2) into five large economically viable gales (Figure 3.3). These deep mines were drained by pumping, and during the eighteenth century the technique of longwall mining was developed and used to mine these gales. This mining method as the name suggests consists of working coal along a wall cut into the face of the seam. The long face was developed between two main roadways which were parallel, and the coal was extracted between the roadways. Areas of coal could be left to support the roof, but generally this was not necessary providing the major interconnecting roadways were supported to allow access to the working area and provide ventilation. The roof adjacent to the longwall coal face was thus allowed to collapse naturall y into the mined void (Aston 1982 and Neate 1980). Longwall mining combined with Pillar and Stall was used for the extraction of the Coleford High Delf coal seam in the deep basin, and was favoured because of its high extraction percentage compared with other methods (~ 65%).

In 1947 the National Coal Board (NCB) (now British Coal) took over the five deep basin mines, but the outcrop areas continued to be mined by the 'Free Miners'. The five collieries which mined coal from the Coleford High Delf coal seam reached a depth of -400 m AOD in the central basin, but despite the retention of the coal barriers at or near to river level to direct groundwater flow into the free-drainage levels, pumping requirements were high. The mines were forced to close between 1959 and 1965 when the ratio of volume of water raised per ton of coal was about 40 to 1. The sequence of abandonment was Norchard Drift Colliery 1957, Eastern United and Arthur and Edward Collieries 1959, Cannop Colliery 1960, Princess Royal Colliery 1962, and Northern United Colliery 1965 (Figure 3.3).

When pumping ceases on abandonment of the coalfield the mined void and associated dewatered aquifers gradually fill with recharge water, and a saturated groundwater body is established, a process known as 'water table rebound' (Henton 1981) or 'water table recovery'. Post mining groundwater

Figure 3.2 : Plan of the Coleford High Delf coal seam showing the gales defined
Although 137 gales existed some numbers are excluded on the 190

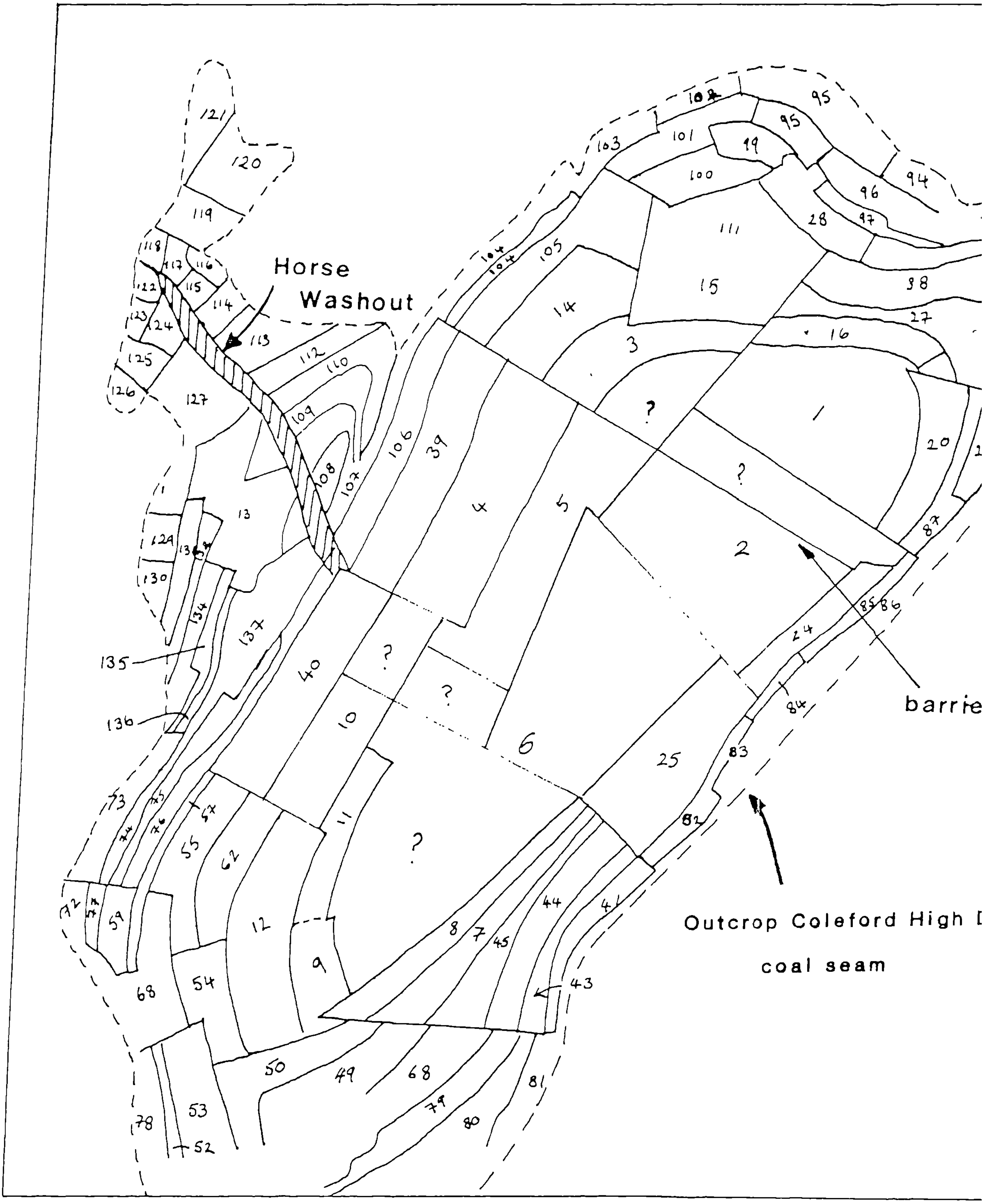
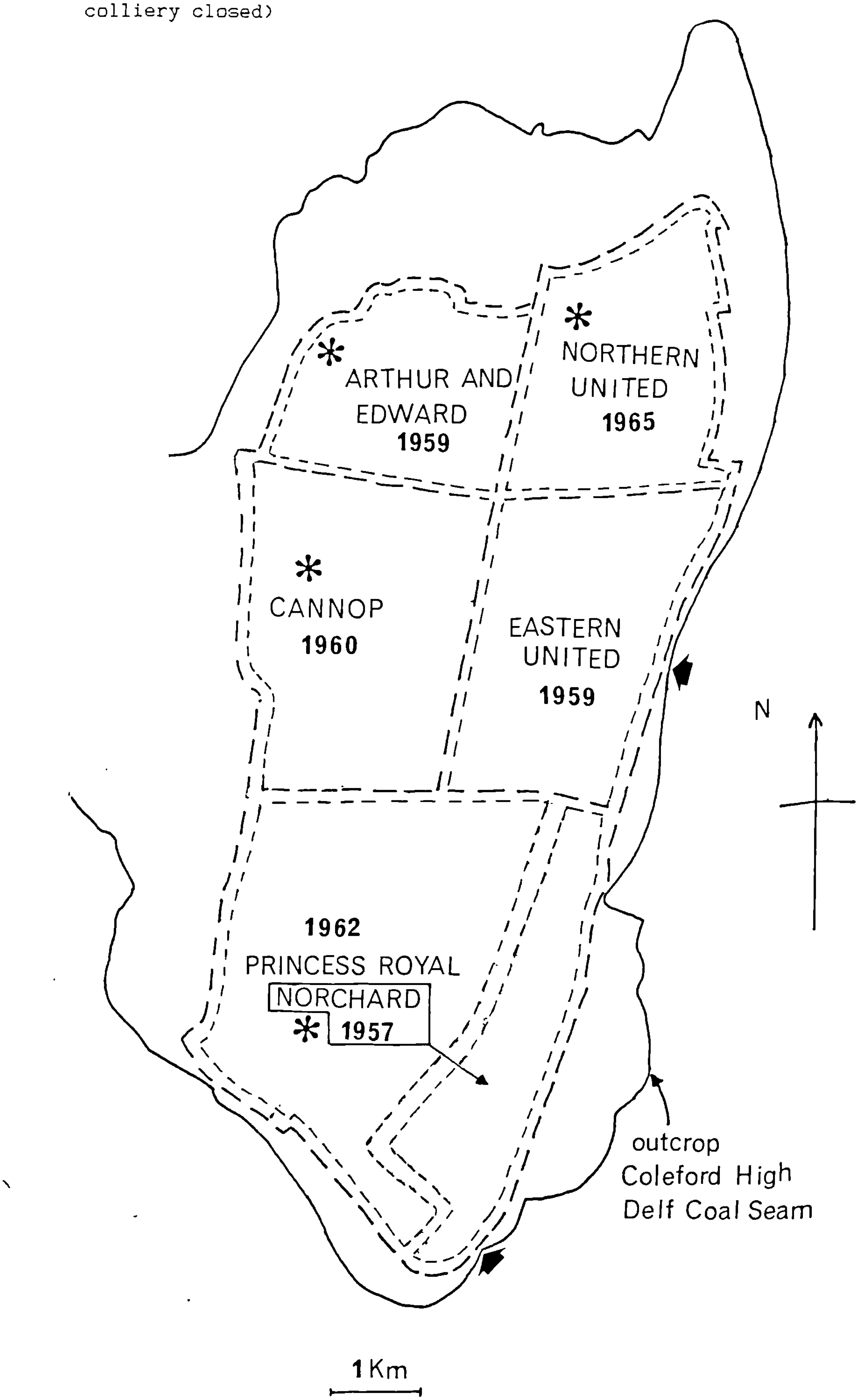


Figure 3.3 : Plan of the Coleford High Delf coal seam, showing the five deep basin gales, which were formed following the amalgamation of the previous fourty four gales in 1904. (Dates refer to the when the respective colliery closed)



Key : * Major Shaft, Major Adit, = = = Coal barrier.

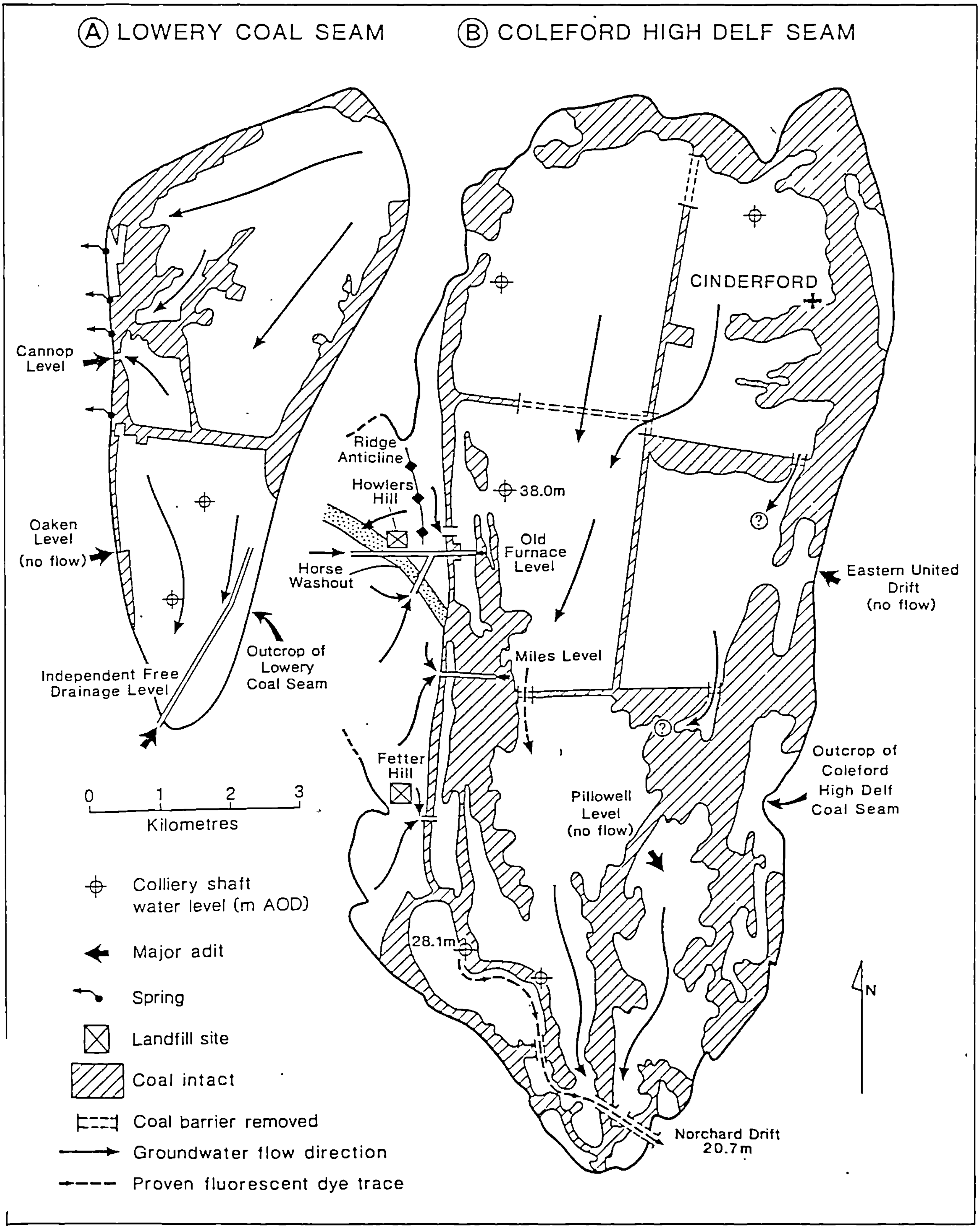
levels may not return to pre-mining levels as a new equilibrium is established due to enhanced groundwater flow in the mined voids and other aquifers affected by mining subsidence. Thus groundwater issues from previously dry adit entrances or new springs may appear. The location of these discharges and springs is partially determined by the position of coal barriers and to lesser extent mine roadways.

For example, in the case of the Lowery seam (Supra Pennant Group) (Figure 3.4 A), deep basin mining involved only one major coal barrier 20 m wide, running east-west across the centre of the main basin, which was therefore divided into two units. However, in the north-west the seam was too thin to extract, and a substantial area was left unmined down dip of the outcrop. On abandonment, the main east-west barrier remained intact, causing the ponding of water in the northern workings. These now discharge through the Cannop Level (whose workings were protected to the east by a minor barrier), and via many ferruginous springs around the outcrop zone. These springs are caused by discharge through the unmined zone in response to the pressure head generated by ponding behind the main barrier, which retards flow to the south (the lowest possible discharge point). In the southern unit coal removal was more complete and mine water discharges only from the Independent Level (mean annual flow 10 l/s).

In the Coleford High Delf coal seam (Pennant Group) (Figure 3.4 B), as the first mines closed pumping requirements in adjacent collieries, increased despite their separation by barriers of coal 55 m thick. This indicates that the barriers leaked, either directly via the jointing in the barrier coal, or after the impostion of a hydraulic head, the increased water levels allowed the ponded groundwater to move over the barrier in the more permeable sandstones (as observed by Miller and Thompson 1974). Where the floor is of an impermeable seat earth, and the roof is also of an impermeable material such as shale, the efficency of the barrier to restrict groundwater flow is enhanced. In the case of the Coleford High Delf coal seam, the floor material is a thick seat earth clay, but the roof consists of a well fractured sandstone, the Pennant Sandstone. Therefore groundwater flow could occur over the coal barrier as soon as ponding of the water to roof level had occurred. This situation occurred on closure of the deep basin mines. Therefore the efficiency of a coal barrier depends upon the roof and floor of the coal seam acting as confining strata in addition to the barrier thickness.

As the deep mines where abandoned, there were two problems with drainage in the central basin, firstly the ring of intact drainage barriers did not

Figure 3.4 : Extent of mining, coal barriers and groundwater flow in the lowery (A), and Coleford High Delf (B) coal seams, based on available coal mine plans.



satisfactorily exclude water from the deep basin and secondly, once within the deep basin the lateral barriers that were intended to separate drainage did not function efficiently. As the pumping capacity was exceeded (inflow was greater than outflow) a limited saturated groundwater zone formed in the central basin. To avoid this water ponding, the major east-west and north-south barriers were punctured at the level where the major haulage roadways circumnavigate the deep basin, at an elevation of circa -200m AOD. The removal of these barriers was licensed by the Deputy Gaveller, (as documented in his records). The final colliery to close was the Northern United in 1965 which worked coal in the north-east corner of the coalfield and was least effected by the water problems. The punctured barriers allowed the development of an integrated groundwater flow from north to south. Thus only a single mine water discharge point occurs at the lowest adit entrance, the Norchard Drift (20.7 m AOD) (Figure 3.4 B). This groundwater flow below the ring of drainage barriers at river level is termed the 'deep groundwater circulation' (in comparison to the 'shallow groundwater circulation' mentioned earlier)(Figure 3.8).

From the limited data collated from abandonment plans (which in some cases have water levels marked when abandoned areas were last surveyed) figures 3.5, A, B and C have been constructed. These diagrams show the area of flooded workings in February, April and December 1965. Unfortunately there is insufficient data (and contrary to the Quarries and Mines Act (HMSO 1954) (chapter 1)) for the determination of head differences which may have existed across the coal barriers before post abandonment drainage occured. Prior to 1965 the saturated area which began to form due to to the cessation of pumping activity was limited (Figure 3.5 A). It developed rapidly following winter and early spring recharge in 1965, and by December 1965 (Figure 3.5 B) a considerable area of flooded workings existed, but no outflow point had been established. In contrast the differences between water levels in December 1965 and June 1966 are small, and it was not until June 1966 (Figure 3.5 D) that flow commenced from the Norchard Drift. Since 1966 changes in water levels have been small (Figure 3.5 E), and a single integrated groundwater body now exists. The only available historic discharge data for the Norchard Drift is in Table 3.1. The validity of the data is dubious, on some occasions the discharge was measured by inserting a current meter propeller into the free-falling discharge from the culvert which carries the flow from the adit to the receiving stream. This method would over estimate the discharge. The values that are known to have been estimated by current metering the difference between upstream and downstream discharges of the receiving stream are marked (+). This data is the most reliable although errors could remain high (+/- 10%). The data for 1978

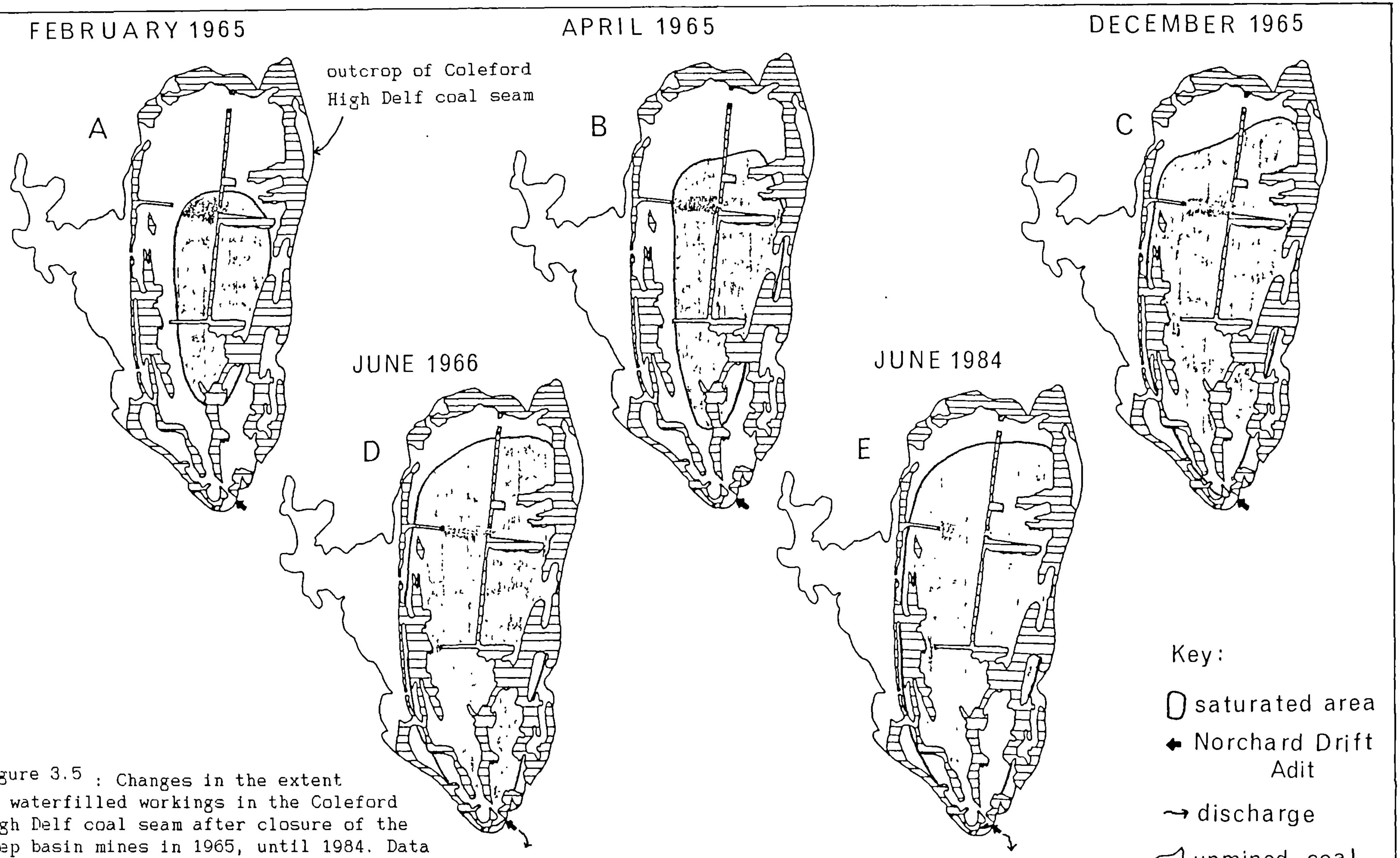


Figure 3.5 : Changes in the extent of waterfilled workings in the Coleford High Delf coal seam after closure of the deep basin mines in 1965, until 1984. Data for A. B. and C. determined from available NCB abandonment plans. Data for 1966 interpolated from the altitude of the Norchard Drift Adit and 1984 from groundwater level monitoring sites.

and 1979 shows a marked seasonal cycle, and maximum and minimum discharges (439 and 163 ls^{-1}) compare favourably with the those collected during this study (445 and 120 ls^{-1}). The data for 1971 until 1973 shows a more varied response, and no seasonal cycle. This may be due to a more rapid response through the open workings, but the data is insufficient for detailed analysis.

Table 3.1 Historic discharge data for the Norchard Drift (compiled from various sources).

Date	Discharge ls^{-1}	Date	Discharge ls^{-1}
5. 4.67	278	1. 1.73	109
7.10.71	292	9. 1.73	102
27. 3.72	575	16. 3.73	244
19. 4.72	389	1.11.73	215
17. 5.72	353	4. 8.77	297+
9. 6.72	456	18. 8.78	251+
23. 6.72	579	1. 9.78	248+
10. 7.72	340	15. 9.78	216+
14. 7.72	216	27.10.78	168+
25.7.72	222	24.11.78	164+
7. 8.72	186	8.12.78	183+
1. 9.72	179	16. 2.79	416+
24.10.72	135	2. 3.79	439+
6.11.72	166		

Today all deep basin workings are abandoned and remain flooded, the underground mining of coal continues only in the outcrop areas of the Pennant Group, where four small 'Free Mines' are located. More recently opencast mining has also been undertaken along the outcrop of both the Pennant and Supra Pennant Groups (mentioned in chapter 2 and discussed in more detail in chapter 10).

3.3 MINE DEVELOPMENT AND ABANDONMENT: ITS EFFECTS ON THE HYDROGEOLOGY OF ADJACENT AQUIFERS.

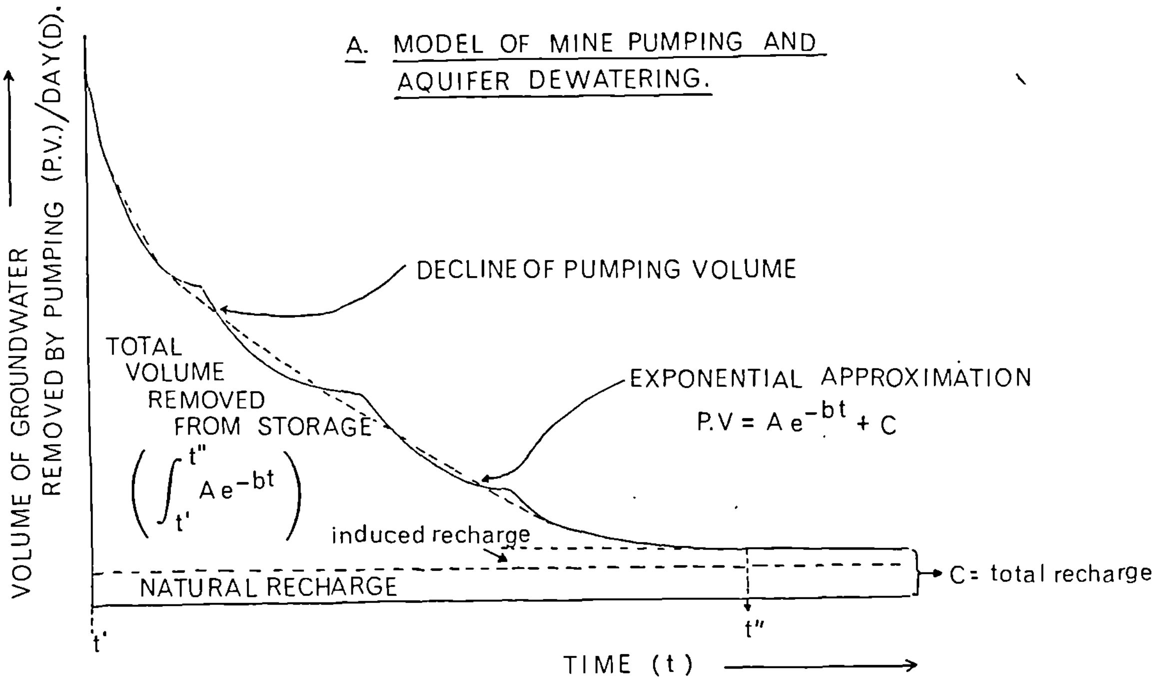
The considerable depths at which coal is often mined causes the intersection and disruption of groundwater bodies in the saturated zone, during mine development. Large volumes of water may need removing by pumping to ensure safe coal extraction and working conditions, often causing the dewatering of aquifers which lie directly above the coal seam. For example in the Forest of Dean, mining of the Coleford High Delf coal seam, necessitated the dewatering of the Pennant Sandstone Aquifer.

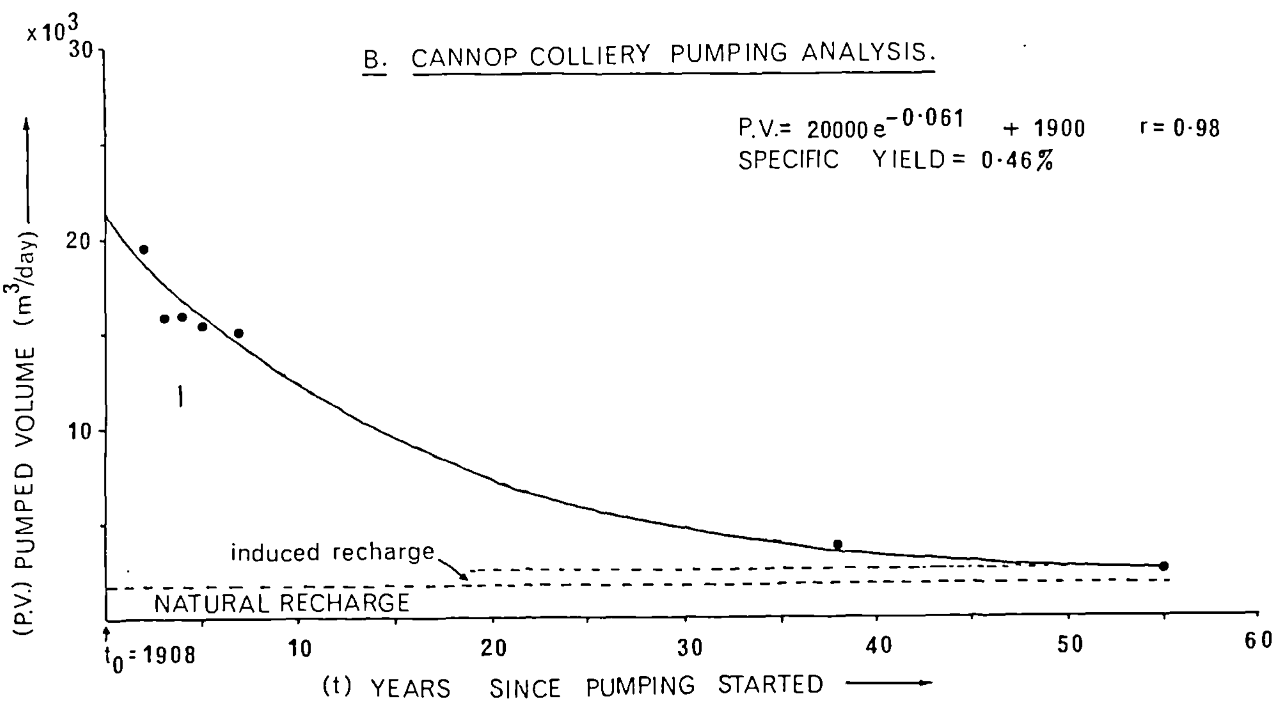
Initially, when new mineshafts were sunk, the pumping volumes were high, (often in the region of 20000 m^3d^{-1}). This water was formerly held within aquifer storage zones (predominantly fracture and fissure storage). As pumping continued the volumes removed declined as sections of the aquifer were dewatered (Figure 3.6A). When new areas (most probably deeper sections of the mine) were entered, pumping volumes were maintained at previous levels, but overall the general trend was for the pumping volumes to decline as the aquifer was totally dewatered. This decline is of an exponential form, with pumped volumes becoming asymptotic towards the amount of annual groundwater recharge occurring within the catchment area of the particular mine unit. Data for the Forest of Dean is shown in Table 3.2. This is a combination of values reported in the 1909 Coalfield Survey, and a more recent 1943 Ministry of Fuel and Power Survey. Such data should be assessed with caution because it is difficult to ascertain if the values are representative. Although those quoted here were described as yearly average pumped volumes, this is not always the case, and often only the highest values when inrushes or 'feeders' were intersected are reported. These values can be considerably larger than the normal annual average pumped volume. The values in Table 3.2 show that the Supra Pennant Aquifer had reached the equilibrium situation where pumping volumes equalled recharge. In comparison the Pennant total (free-drainage and pumped volume) is much larger than the total recharge. At this time the Pennant was not fully developed and therefore aquifer dewatering was continuing. Furthermore, the data requires careful interpretation with respect to the hydrogeological conditions present. Although the total recharge to the Pennant aquifer is 9.4 x 10^6 m^3 giving an imbalance of 4.1 x 10^6 m^3, the difference may be explained if the 6.8 x 10^6 m^3 recharge from above the Yorkley coal seam (the Yorkley Aquifer) is not attributed to the main Pennant Aquifer (the Coleford High Delf Aquifer) associated with the Coleford High Delf coal seam. Precise classification of aquifer units is required for detailed analysis but this situation accords with that suggested in chapter 2 (see below and chapter 5).

The only available long term data for a colliery during development is that for Cannop Colliery (Figure 3.6 B). The decline in pumping values follows the predicted exponential form, however there is a discrepancy between minimum pumping values and the annual direct recharge volume (the pumped volume is greater than the annual recharge volume). This could be additional recharge associated with the increased hydraulic head levels. This induced recharge is from three sources: Firstly, leakage of free-drainage level water into deep basin workings through the coal barriers left at or near to river level. Secondly, loss of river water into the underlying Pennant Sandstone Aquifer (Large sections of the tributaries and main channel of the headwaters to the Cannop Brook were canalised at large capital costs to prevent leakage into the Pennant Sandstone. A similar situation has also been reported by Ashmead (1937)

Figure 3.6 : A. Model of temporal changes in mine pumping and aquifer dewatering, showing the decline in pumping volumes with respect to time, as mining develops.

Figure 3.6 : B. Available pumping data from the Cannop Colliery over a 50 year period, from 1908.





for the north eastern Pennsylvanian Coalfield). Thirdly, leakage from the Yorkley coal seam and sandstone above the Coleford High Delf. This could occur by two different processes, natural leakage through the Yorkley coal seam aquiclude (or aquitard) or in the main shaft where it intersected the Yorkley coal seam. The later case would depend upon the grouting facilities available when the shaft was sunk. It is recorded (Joynes 1917) that when the Cannop Colliery was developed that extreme 'water difficulties' were encounted above the Yorkley coal seam where 'single inflows' of water (interpret ed as single fracture or fissure discharges) were of the order of 6500 m^3d^{-1} compared with only 273 m^3d^{-1} below. Joynes also states that the Cannop shaft was cement grouted. This evidence would suggest that the Yorkley coal seam and sandstone above are isolated from the Coleford High Delf coal seam and sandstone below, and that vertical movement of water between the two aquifer units is restricted but does occur. However, it is not possible to determine whether this movement is by a point source associated with shafts or diffuse natural leakage. Thus significant dewatering of both aquifer units occured during mine development, although there is further evidence to suggest that the Pennant Sandstone is divided into two sub-aquifers, the Yorkley and Coleford High Delf Aquifer units.

The sequence of events that occur when the coalfield is abandoned can be modelled in a similar manner (Figure 3.7). As some of the deep mines stop pumping on closure those that remain working, pump larger volumes to compensate. This rise in pumping volume is characterised by steps, each step corresponds to another colliery closure. (The schematic model in Figure 3.7 assumes that the adjacent boundary barriers are not efficient in excluding water movement between deep basin mines (as was the case in the Forest of Dean Coalfield)). The depressed water table slowly recovers since the pumped volume from the remaining mines is smaller than that removed from all the collieries when the coalfield developed (and larger pumps were not installed because this was uneconomic). Finally as the last colliery closes the rest water level attains a new equilibrium. Unfortunately little data is available to quantify this model, some rest water level data exists for the Forest of Dean, which has been discussed above and presented in Figure 3.5.

3.4 A TENTATIVE QUANTIFICATION OF THE CHANGES IN SPECIFIC YIELD FOR COAL MEASURE ROCKS DURING MINE DEVELOPMENT AND ABANDONMENT.

The specific yield of an unconfined aquifer is defined as the volume of water that is released from storage per unit surface area per unit decline in water table and can be expressed as :-

FIGURE 3.7 : Schematic model of the effects of mine development and abandonment on groundwater conditions in coalfield aquifers.

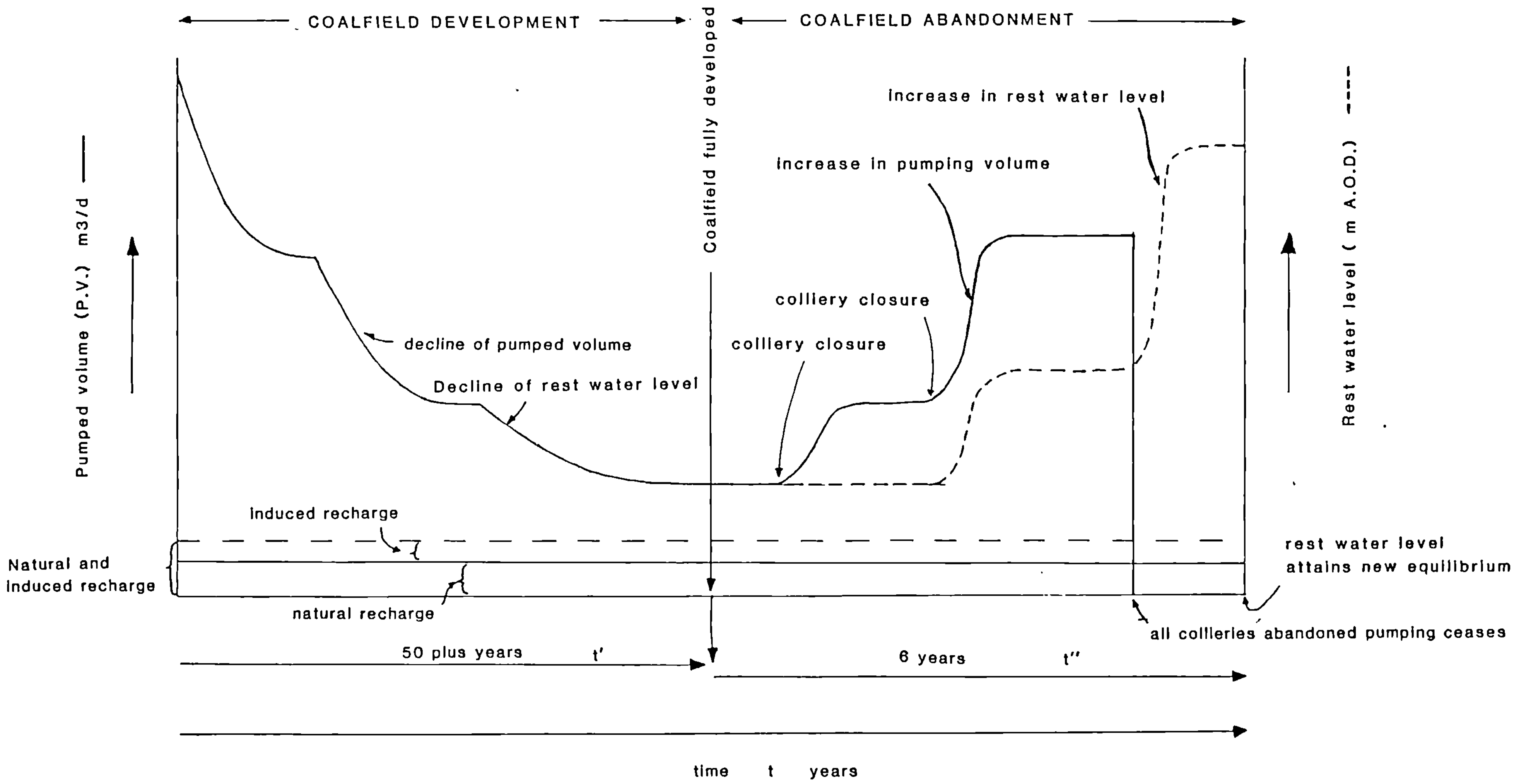


TABLE 3.2

COMPARISON OF PUMPING/DRAINAGE VOLUMES AND RECHARGE VOLUMES AFTER FULL DEVELOPMENT OF THE COALFIELD ~ 1928. (Data sources various).

PUMPING VOLUMES (m^3/year)		RECHARGE VOLUMES* (m^3/year)	
SUPRA PENNANT COLLIERIES	1.4 x 10^6	SUPRA PENNANT SERIES	2.2 x 10^6
FREE DRAINAGE LEVEL DISCHARGE.	0.8 x 10^6		
SUB TOTAL	2.2 x 10^6	SUB TOTAL	2.2 x 10^6
PENNANT COLLIERIES	9.9 x 10^6	PENNANT SERIES	9.4 x 10^6
		(Yorkley Aquifer	2.7 x 10^6)
		(Coleford High Delf Aquifer	6.7 x 10^6)
FREE DRAINAGE LEVEL DISCHARGES	3.6 x 10^6		
SUB TOTAL	13.5 x 10^6	SUB TOTAL	9.4 x 10^6
TOTAL PUMPED/DRAINED	15.7 x 10^3	TOTAL RECHARGE	11.6 x 10^6

* These calculations use a mean annual 1915-1960 rainfall of 712 mm and evapotranspiration estimated for the River Severn catchment, south of Bewdley (NGR SO 78607535) of 470 mm. Producing a net effective rainfall of 242 mm per year. The infiltration co-efficients assumed are 1.0 for the Pennant Group and 0.7 for the Supra Pennant Group.

TABLE 3.4

CLOSURE DATES AND RECHARGE VOLUME STORED WITHIN MINED VOIDS BEFORE DISCHARGE OCCURED AT THE NORCHARD DRIFT IN JUNE 1966.

COLLIERY	CLOSURE DATE	RECHARGE VOLUME UNTIL FLOW COMMENCES* (m^3)
ARTHUR AND EDWARD	1959	13.37 x 10^6
CANNOP COLLIERY	1960	3.73 x 10^6
PRINCESS ROYAL AND NORCHARD DRIFT	1962	21.60 x 10^6
NORTHERN UNITED	1965	2.19 x 10^6
	TOTAL	40.89 x 10^6

* These calculations use a mean annual 1915-1960 rainafll of 712 mm and evapotranspiration estimated for the River Severn catchment, south of Bewdley (NGR SO 78607535) of 470 mm. Producing a net effective rainfall of 242 mm per year. The infiltration co-efficient is assumed to be 1.0 for the Pennant Group. The Norchard Drift and Princess Royal Colliery recharge volume accounts for the earlier closure of the Norchard workings in 1957.

TABLE.3.3

CALCULATION OF SPECIFIC YIELD FOR THE PENNANT SANDSTONE AQUIFER AND COLEFORD HIGH DELF COAL SEAM DURING COALFIELD DEVELOPMENT AND ABANDONMENT.

CALCULATION PERIOD	MINE DEVELOPMENT	ABANDONMENT
	1905 - 1959	1959-1966
SPECIFIC YIELD CALCULATION EQUATION	$S_y = 100 \frac{\sum_{t=1}^{t=t_R} V_w}{V_R}$	$S_y = 100 \frac{\sum_{t=t_c}^{t=t_Q} R_v}{V_R}$
SPECIFIC YIELD	$S_y=0.46\%$	$S_y=1.1\%$
CALCULATION PERIOD	POST ABANDONMENT	
	1983 - 1985	
SPECIFIC YIELD CALCULATION EQUATION	$S_y = 100 \frac{\sum_{t=Q_{MAX}}^{t=Q_{MIN}} Q_v}{V_R}$	
SPECIFIC YIELD	$S_y=0.92\%$	

LEGEND : S_y= Specific yield, t= time, V_R=Rock Volume (see text for determination), V_w=Volume of water pumped, t_R=time since commencement of pumping (Figure 3.7A), t_Q=time when outflow of mine water occurs, t_c= time of mine abandonment. R_v= Recharge volume, Q_{MIN}=minimum discharge, Q_{MAX}=maximum discharge, Q_v=total discharge volume. (For further explanation see text).

$$S_y = \frac{100 \cdot V_w}{V_R} \quad \text{--------- Equation 3.1}$$

Where : S_y= Specific yield, V_w= Volume of water drained, and V_R= Volume of rock.

Equation 3.1 above provides a measure of the extend of void space (either mined or fissure/fracture void) that is present underground. The specific yield of the Pennant Sandstone Aquifer can be calculated by equating the total volume of water removed during coal mine development (the area under the graph Figure 3.7A) with that of the rock volume in the mine unit (Table 3.3). Unfortunately, this requires the determination of the rest water level in the Pennant Sandstone Aquifer prior to mine development. This level is not precisely definable and has been estimated at the level of the Cannop Brook. This elevation was assumed because the dry slades and valleys of the Pennant outcrop indicate that a previously higher groundwater level was present and fed via groundwater springs. The rock volume incorporates both the Yorkley and Coleford High Delf Aquifer Sandstones as it is assumed (discussed above) that both were dewatered. This data produces an estimate of specific yield for the Cannop Colliery Pennant Sandstone directly above the Coleford High Delf coal seam of 0.46 %, while the mine was being developed.

The value of specific yield determined above can be compared to that when the coalfield was abandoned. The specific yield for the abandoned coalfield can be calculated from the amount of net effective precipitation (re-expressed as recharge) for the time interval from cessation of pumping until water discharged from the Norchard Drift and relating this to the rock volume of the Pennant Sandstone below the altitude of the Norchard Drift (Table 3.3 and 3.4). (It should be noted, firstly, that the volume of water that was calculated using the effective precipitation as defined in Table 3.3 does not account for the additional induced recharge due to river leakage and free-drainage level drainage barrier leakage and secondly, that the estimate will include any open mined voids in the Coleford High Delf coal seam. This later point was ignored for two reasons, firstly because the volume of mined void was very small in comparison to the total rock volume and secondly, the method of longwall coal mining was extensively used in the deep basin and this method allows the roof to collapse on coal extraction, which lessens the extent of open mined void present). The specific yield value is 1.1 %, much higher than that calculated above. This value reflects the increased void space caused by coal extraction, and increased fracturing caused by subsidence.

From data obtained during this study it is possible to obtain a third estimate of the specific yield for the Pennant Sandstone 19 years after coalmine abandonment. This is derived by equating the total volume of water drained from the Pennant Sandstone and Coleford High Delf coal seam at the Norchard Drift between maximum and minimum discharge values from the recession curve, and calculating the volume of rock drained by using the maximum and minimum groundwater levels for the Pennant Sandstone. The specific yield of 0.92 % is smaller than that at abandonment suggesting that settlement and closure of the voids has occurred, but the value is also higher than that during coalfield development indicating that an enhanced void space still remains. These calculations provide only approximate estimates of specific yield, but they do indicate the trend in hydrogeological properties that would be expected. There accuracy should however be treated with care, as their values are reliant upon data with relatively high uncertainties.

3.5 DATA SOURCES

The majority of the history of mining activity and coalfield development outlined above has been collated from historical documentation, both published sources and public record collections (The Gloucestershire Records Office, Gloucester). In the Forest of Dean the Mineral Concessions were controlled by one single person, the Deputy Gaveller. The Deputy Gaveller is directly responsible to the Crown and controls the legalities of all mineral extraction in the Forest of Dean, a direct result of the early organisation of mining described earlier (Hart 1953). The Deputy Gaveller holds all the available abandonment mine plans, legal documents involving territorial disputes, concessions and coal levy's.

However, after the formation of the National Coal Board (NCB) in 1947, the major deep mine documentation was held by the British Coal Regional Head Offices. Unfortunately during the transition of mine ownership in 1947 from the private companies to the the National Coal Board many documents were lost. Abandonment plans for the deep basin mines do exist and are available for inspection at the British Coal Archives (Llanishen, Cardiff). Although these plans should follow the guidelines endorsed by the Quarries and Mines Act of 1954 (as mention in Chapter 1), they seldom do and are not a comprehensive data base. Information such as pumping volumes and flooded areas are often not included, and where adjacent barriers have been removed to facilitate drainage, these changes are frequently not marked.

3.6 CONCLUSIONS.

The available information from historic and archive sources is limited, non-specific and lacks the detailed data required to reconstruct and quantify the effects of mining on the hydrogeology of the Coal Measure Aquifers. The data presented here is thus only sufficient for a general understanding of aquifer configuration and properties, and is not suitable for specific management studies such as the siting of landfill sites or open cast coal mining operations. The following general points may thus be made:

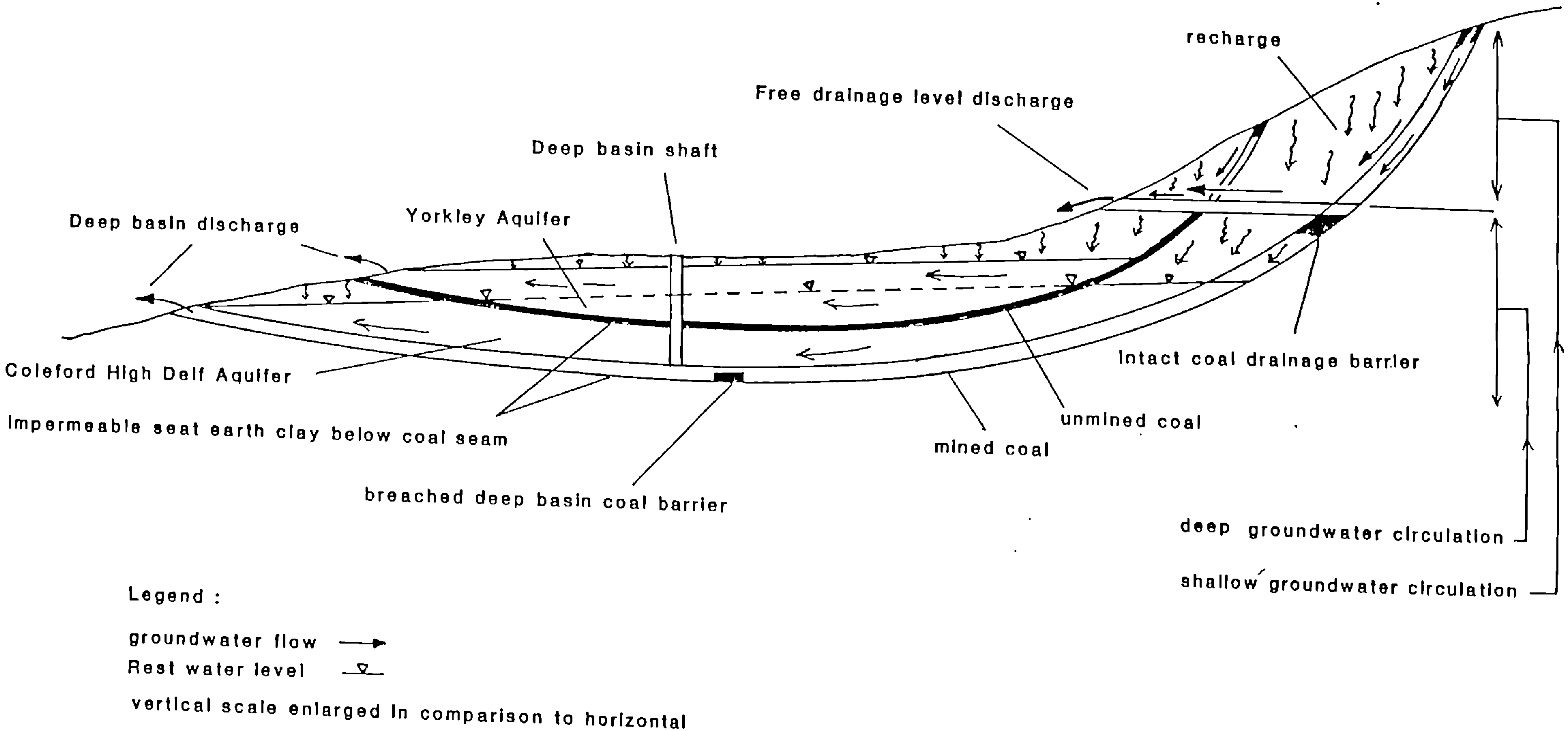
1. The different mining methods used, from shallow unsupported workings at outcrop, to supported pillar and stall workings and finally unsupported longwall methods at depth, determines the extent of the void space that is present underground when mines are abandoned. Furthermore, the parallel progression through time to successively deeper workings neccessitated artificial drainage, and the introduction of drainage barriers and free-drainage levels, which still control present day groundwater flows.

2. With the development of the coalfield and the numerous territorial disputes, an organised legal scheme for coal extraction evolved. This is important today because, it is based on the division of coal seams by coal barriers to retard drainage and control groundwater flow paths. The retention or removal of such barriers drastically effects the post abandonment groundwater flow systems present.

3. Following the organised scheme for coal mining, the production of coal mine plans was required. These provide the only data base available to determine where mining has taken place and the location of coal barriers in abandoned coalfields as is discussed in more detail in chapter 6.

4. The drainage barriers associated with the free-drainage levels subdivides the Pennant Sandstone into two different components; a section above the drainage barrier and above river level, which discharges outcrop recharge waters to the nearest surface water course, and are termed 'shallow groundwater circulation adits', while below the river level drainage barriers the groundwater regime present in the deep basin is termed the 'deep basin groundwater circulation' (Figure 3.8).

FIGURE 3.8 : SCHEMATIC DIAGRAM SHOWING THE DEEP AND SHALLOW GROUNDWATER CIRCULATIONS AND THE ROLE OF INTACT COAL DRAINAGE BARRIERS IN CONTOLLING GROUNDWATER MOVEMENT.



CHAPTER 4.

RESEARCH DESIGN AND METHODOLOGY

4.1 INTRODUCTION.

The previous chapters have indicated four general points which are important in the understanding of the hydrogeological properties and management of abandoned coal-mined aquifers. These are:

1. There is little previous knowledge of the hydrogeological properties and behaviour of coal-mined aquifer systems (chapter 1), which has precluded the use of predictive modelling techniques to simulate groundwater conditions present and assist the effective management and protection of groundwater resources.

2. From available hydrogeological and geological information of the properties of Coal Measure rocks, five major aquifer units in the Forest of Dean (Trenchard, Coleford High Delf, Yorkley, Brazilly and Serridge) have been predicted (chapter 2). This classification compares favourably with the aquifer behaviour determined from historic records (chapter 3). However, the validity of the predictions, the extent, effect of coal removal and integrity of coal-mined aquifer systems classified by this method remains unknown.

3. River level drainage barriers, separate the groundwater flow system into deep and shallow components and also control recharge to the deep basin. Removal of the drainage and boundary barriers is known to occur on coalfield or colliery closure and this may determine the post abandonment groundwater flow patterns and pathways. An understanding of the behaviour and role of the coal barriers is therefore important for the prediction of pollutant pathways and future groundwater resource protection in abandoned coal-mined aquifers (chapter 3).

4. Chapter 3 has demonstrated that coal mine abandonment plans, although imperfect, are the only readily available documented data source for the determination of catchment boundaries for specific groundwater discharges and site investigations in coal-mined aquifer systems. However, the validity of the use of this technique is unknown.

The following five chapters will investigate these four important points, and identify the processes that occur and control the groundwater conditions present in abandoned coal mined aquifers. The results from these chapters will be used to develope a conceptual model of aquifer behaviour in coal mined aquifers for use as a pragmatic groundwater management tool. (At this time in the research into the behaviour of groundwater in abandoned coal mined aquifers the understanding of the processes that occur is paramount, because then and only then can more sophisticated modelling techniques be used to aid resource management). It is the fundamental aim of the following five chapters to identify the processes that control the flow of groundwater in abandoned coal-mined aquifers. The areas of investigation, techniques used and data required in the five chapters is summarised below :

1. Chapter 5, validates the prediction of aquifer units from hydrogeological and geological data and determines regional groundwater flow paths and patterns present in the major Forest of Dean Aquifers, by the use of water budget techniques.

2. Chapter 6, investigates the validity of determining catchment areas for free-drainage levels from coal mine abandonment plans, by using water budget techniques. Also the role of free-drainage levels and coal barriers in determining groundwater flow paths and recharge mechanisms is determined from both water budget and quantitat ive fluorescent dye tracer techniques.

3. Chapter 7, quantitfies the aquifer parameters of transmissivity, and storage for the major sandstone aquifers and coal mined voids, from discharge and groundwater level recession curves, tracer tests and pumping test analysis.

4. Chapter 8, interpretates changes in the hydrogeological behaviour of deep basin coal workings after mine abandonment from 20 years of archive chemical data.

5. Chapter 9, uses present day water chemistry to predict groundwater flow sources and proportions, and develop s a chemical mixing model technique for use in unmonitored coal mined aquifers.

The following sections of this chapter will outline the data that was collected during the fieldwork year in the Forest of Dean which was required in the chapters outlined above. The majority of the data consisted of measuring the parameters of the hydrological cycle (rainfall, evapotranspiration, soil moisture and discharge) the techniques and methods used are discussed below.

TABLE 4.1 LOCATIONS OF PRECIPITATION GAUGES.

LOCATION	NGR	INSTRUMENT AND SITE DESCRIPTION
Bixslade	SO 59951000	5" Snowdon catch gauge. Clearfelled woodland.
Cannop Cross	SO 60941153	5" Snowdon catch gauge. Rough grassland and bracken.
Blackpool	SO 65250880	5" Snowdon catch gauge. Clearfelled woodland
New Fancy	SO 62601620	5" Snowdon catch gauge. Open grassland.
Tufts Level	SO 62050485	5" Snowdon catch gauge. Open grassland.
Kensley Lodge	SO 62751275	5" Snowdon catch gauge. Open grassland.
Kensley Lodge	SO 62751275	9" Tipping bucket (Dines) event recording rain gauge. Open grassland.
Crumpmeadow	SO 64601380	9" Tipping bucket (Dines) event recording rain gauge. Open grassland.

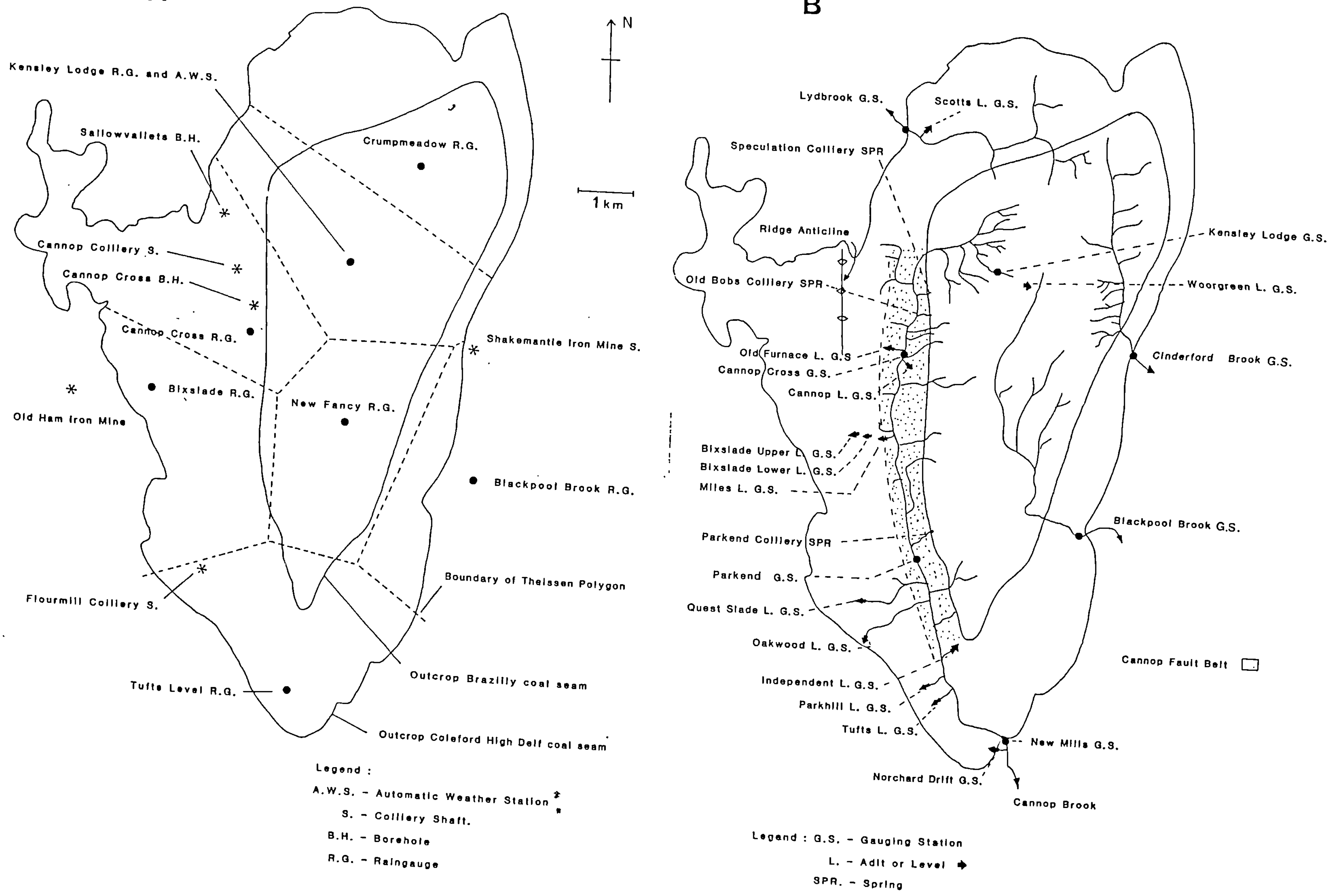
TABLE 4.3

COMPARISON OF OBSERVED RAINFALL AT KENSLEY LODGE AND OBSERVED RAINFALL BELOW CONIFEROUS AND DECIDUOUS WOODLAND CANOPIES.

DATE	CONIFEROUS OBSERVED THROUGHFALL	S.D.	KENSLEY OBSERVED GROSS RAINFALL	DATE	DECIDUOUS OBSERVED THROUGHFALL	S.D.	KENSLEY OBSERVED GROSS RAINFALL
201283	30.0	8.6	28.0	280184	24.5	3.7	24.5
201283	24.9	9.1	28.0	280184	24.3	2.9	24.5
281283	13.5	3.7	15.0	300184	20.1	3.4	20.5
281283	9.9	3.6	15.0	300184	18.1	1.3	20.5
040184	15.5	4.6	16.5				
040184	16.0	4.5	16.5				
050184	0.0	0.1	0.0				
050184	0.0	0.0	0.0				
070184	0.1	0.0	0.5				
070184	0.1	0.0	0.5				
120184	1.3	1.0	3.0				
120184	2.1	1.1	3.0				
170184	13.5	3.5	16.5				
170184	13.0	3.7	16.5				

LEGEND : Observed throughfall values are the average of the 20 raingauges located in each of the 100 m^2 field plots, the standard deviation also refers to this figure.

FIGURE 4.1 : Location of field equipment installed in the Forest of Dean Coalfield and determination of Thiessen Polygons for precipitation gauges.



The raingauges formed a spatial network of nodal points, this data was converted to areal amounts by the polygon method of Thiessen (1911) (Figure 4.1) (see chapters 5 and 6).

4.2.2 INTERCEPTION.

The Forest of Dean is extensively forested and contains some of the largest remaining deciduous oak tree enclosures in England. Where oak have been felled, replanting with conifers and varied deciduous species has now produced a very diverse forest cover. Therefore the effect of the forest canopy on the net effective rainfall reaching the ground had to be assessed.

When rain falls onto a forested area, its movement to the ground surface is not direct, being interrupted by the canopy structure. Rain which falls onto the forest canopy initially only wets the leaves and branches and no water reaches the ground, this amount of water is called the canopy storage capacity. When the rainfall has saturated the canopy (ie filled the canopy storage capacity), further movement towards the ground surface occurs in two forms, namely throughfall and stemflow. Throughfall is water which either falls through spaces in the canopy or drips from leaves and branches, to the forest floor. Stemflow is water which trickles along the branches and finally down the main trunk to the ground surface. Thus the interception of rainfall by the forest canopy represents a loss of rainfall to the ground and ultimately the soil moisture.

Many investigations of the role and interplay between intercepted rainfall, evaporation and evapotranspiration in the water balance of the forest/soil system have been made (Murphy and Knoerr 1975, Rutter 1967, Stewart 1977 and Stewart and Thom 1973). It has been suggested that the evaporation of intercepted water from the forest cover suppresses evapotranspiration while the canopy is wet by Stewart (1977) and Stewart and Thom (1973). This is not taken into account in the calculations here and it is assummed that the interception component is a direct loss of rainfall to the soil.

The stemflow component, when related to the total gross rainfall amount (above the canopy) is small. Generally only 2-4 % (Kitteridge 1948), although some higher values (10 %) have been reported (Rowe,P 1941). This component was considered to be unimportant in this study, due to its small contribution to net rainfall amounts. Furthermore, during the rainfall interception measurements (see below) stemflow was observed on only one occasion and this corresponded to the occurrence of the highest rainfall amount (20/12/83) (see Table 4.3). Thus for this study, which is solely interested in the net effective rainfall reaching the ground surface, only the throughfall component was considered to be important for evaluation.

Calder (1977,1979), Gash and Stewart (1977) and Stewart (1977) have shown that rainfall interception is important in determining the water yield of forested catchments. The analytical model of Gash et al (1980), (a simplifield derivation of the physically based model devised by Rutter et al (1975) and Rutter and Morton (1977)), was not used to quantify throughfall amounts due to the models extensive data requirements. Therefore weekly cumulative throughfall amounts were measured by using twenty 5" raingauges randomly located within a 100 m^2 plot (Law 1958 and Calder 1979). After reading each gauge it was randomly relocated within the field plot. Field measurements started in December 1983 with two plots under coniferous woodland, these were moved to deciduous oak woodland in late January. Unfortunately, a small data set (only two weekly totals of rainfall) was collected for this second site, because of the early start to a very dry summer.

The throughfall values for both coniferous and deciduous sites compared with gross precipitation measured at the Kensley Lodge AWS station are in Table 4.3 and Figure 4.2. The regression equations of gross rainfall and throughfall values both have gradients equal to 1.0 and x axis intercepts of <1.28 mm. This indicates that there is no difference between the two data sets because if the data were identical the gradient would be 1.0 and the intercept 0.0. The former case is true and the latter value is very small in comparison to the probable 5 % error associated with the gross rainfall measurements and 10 % error with those beneath the respective canopies. Therefore it is concluded that although previous workers have proven that a net loss of rainfall occurs at ground level below forested areas during rain storms, the net effect associated with a cumulative weekly rainfall period is negligible, and no correction to gross rainfall amounts was required in the water budget calculations.

4.2.3 MEASUREMENT OF EVAPOTRANSPIRATION AND DETERMINATION OF SOIL MOISTURE AND RECHARGE VALUES.

The determination of evapotranspiration was essiential for the calculation of the water budgets outlined in (1) and (2) of the introduction, and also to determine the volume of recharge (3 in the introduction).

The measurement of the parameters for the calculation of evapotranspiration is the most difficult and least accurate component of the water budget. Normally

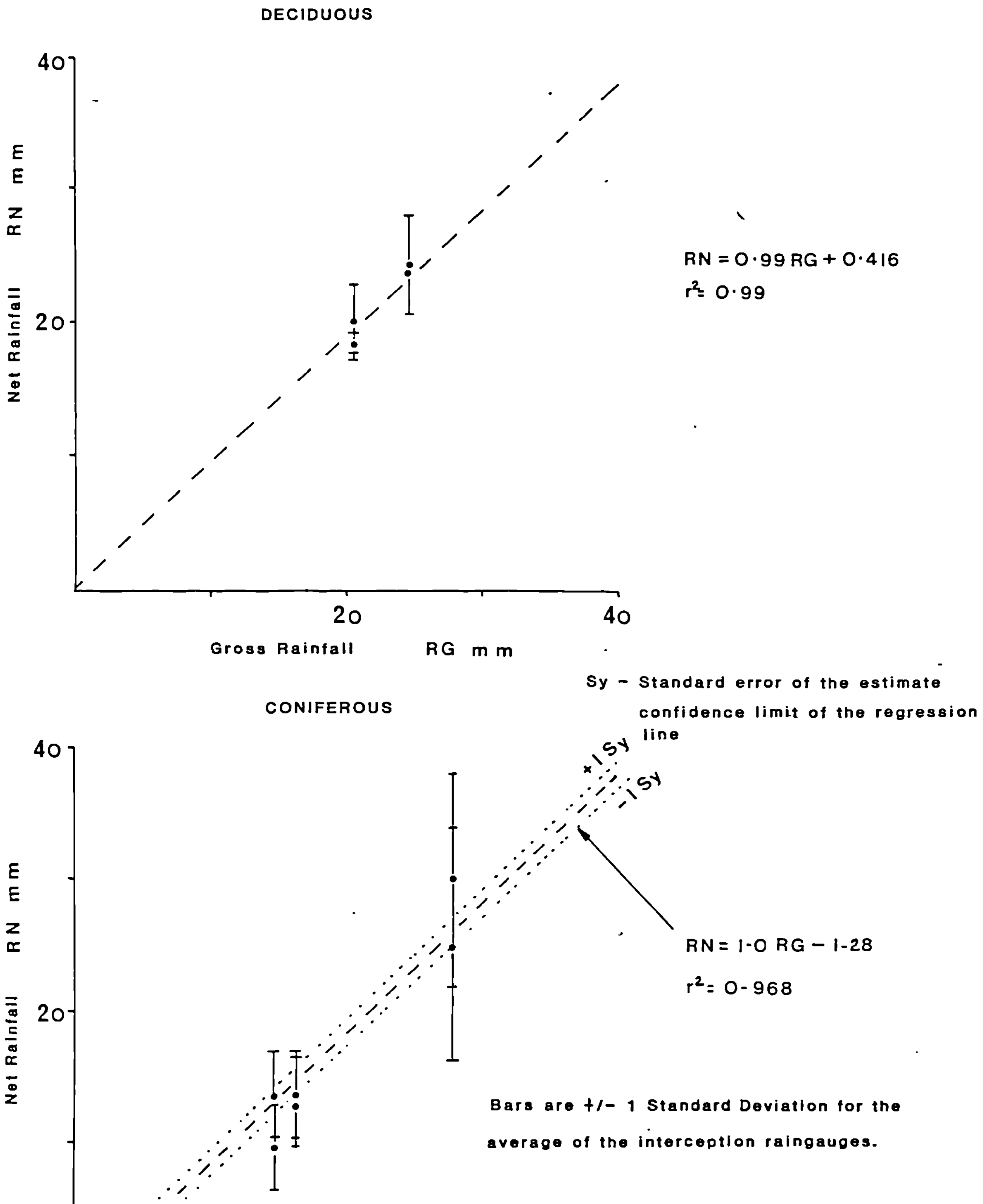


Figure 4.2 : Relationship between gross and net rainfall for Kensley Lodge raingauge and inteception plots beneath deciduous and coniferous woodland.

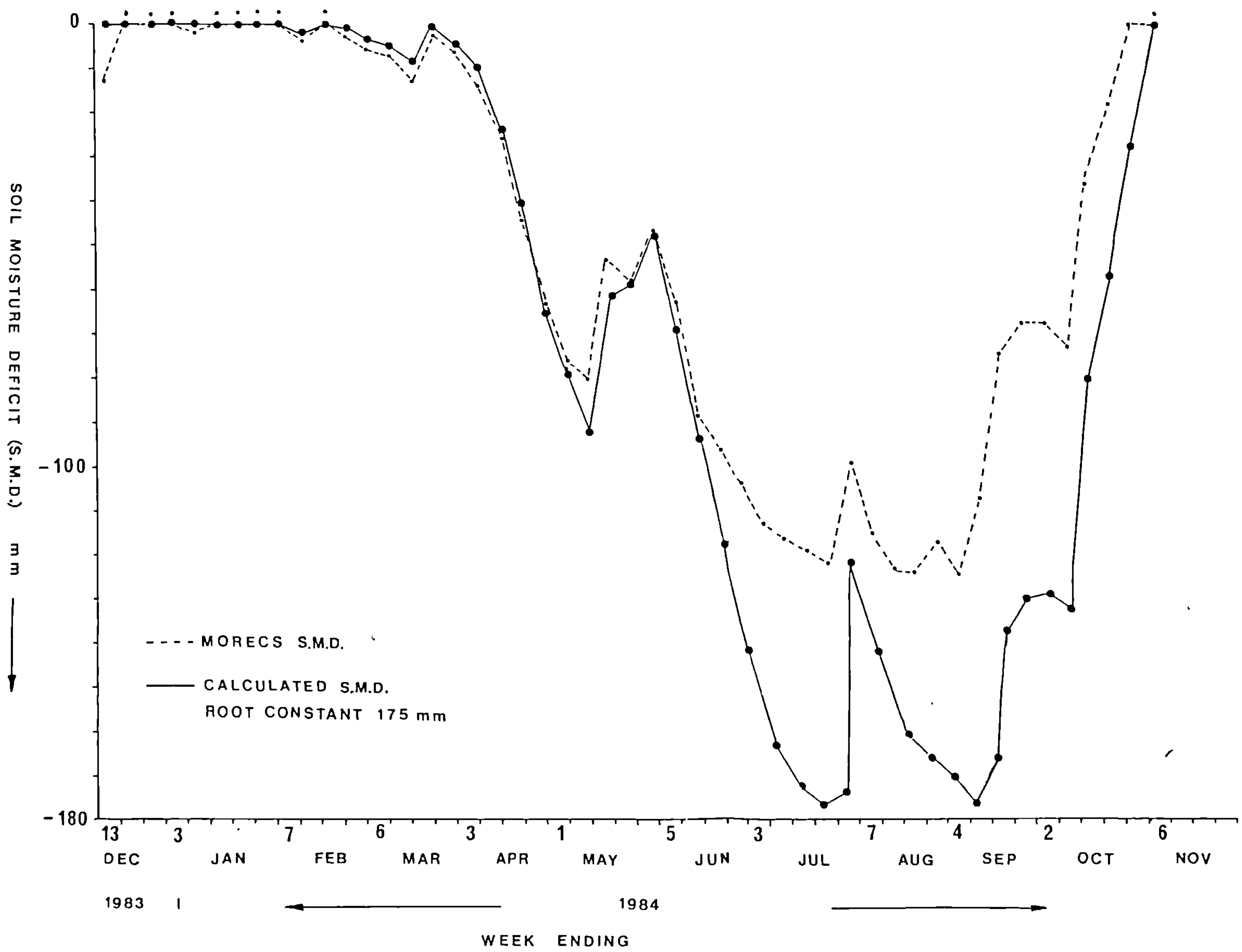
data interpolated from widely separated meteorological stations has to be used to calculate potential evapotranspiration. However this study was fortunate to obtain an Automatic Weather Station (AWS) from the Institute of Hydrology. This was sited at Kensley Lodge (Figure 4.1). The parameters for potential evapotranspiartion were measured and calculations followed the method of Penman (1948). Although the station was remote and power was supplied from batteries, no loss of data occurred.

Precise measurements of areal soil moisture is time consuming and difficult. Therefore for this study the method adopted was to determine soil moisture deficits and recharge values following the principles and methods outlined by Grindley (1967) and Rushton and Ward (1979). Recharge is assumed to occur only when there is no soil moisture deficit and the soil is at 'field capacity' (this is when the soil cannot hold any more water in storage). The determination of soil moisture deficits relies upon the balance between precipitation and evapotranspiration. The difference between these two later variables being the soil moisture deficit. It is assumed that the evapotranspiration component occurs at the potential rate (PE), until the soil moisture deficit reaches the root constant value applicable to the vegetation cover in the catchment area. The root constant value is a level of soil moisture below which potential evapotranspiration is limited and can only occur at one tenth of the potential rate. Typical root constant values for woodland areas are between 150 and 200mm (R odda et al 1976 and Headworth 1970).

This method of soil moisture determination has been criticised, because of its oversimplification of the processes involved in determining soil moisture conditions in comparison to more recently developed complex models involving the Priestly-Taylor or Thom-Oliver equations for determining evapotranspiration. However, the work of Calder et al (1983) has shown that this approach provided equally reliable estimates of soil moisture deficit as the more complex method .

The calculated soil moisture deficits were compared with data from MORECS (Meteorological Office Rainfall and Evaporation Calculation System). MORECS provides estimates of weekly evaporation and soil moisture deficits in the form of averages for 40 x 40 km squares, using daily synoptic weather data (Thompson et al 1981). The current MORECS system (introduced in 1981) is superior to that of 1978 when the method was first introduced and gives results which compare favourably with field estimates of soil moisture (Gardner 1983 and I.O.H. 1981).

FIGURE 4.3 : Comparison of calculated and predicted soil moisture deficit (SMD) (MORECS data) for the Miles Level catchment area.



The values determined for the field study catchment area of the Miles Level mirror those from the MORECS system (Figure 4.3). The MORECS data significantly under estimates soil moisture deficits because a proportion of the 40 x 40 km square is proportioned to grassland with a lower root constant, while the actual catchment area considered here is totally forested. The MORECS data was therefore not used because the field data method of calculation was more site specific.

4.2.4 GROUNDWATER LEVEL MONITORING SITES

The groundwater level sites monitored, using a 250 m well dipper (Wuidart Engineering) are described in Table 4.4.

During groundwater resource evaluation of the Pennant Sandstone Aquifer by STWA in 1977 (see chapter 7), two 150 m deep, 0.2 m diameter boreholes were drilled at Cannop Cross and Sallow Vallets. The former is located in the Cannop Fault Belt which follows the Cannop Valley and the latter is 1.0 km to the northwest of Cannop Colliery near to the Ridge Anticline (Figure 4.1). No other boreholes were available or had been registered with the IGS (Institute of Geological Sciences, now BGS, the British Geological Survey). Field data for these two sites was collected from April 1983 to November 1984 and supplemented the archive data available from STWA.

On field inspection the majority of the previous coalmine shafts were found to be infilled, this precluded access to present day water levels. All minor shafts have collapsed, (with debris cones only a few feet below the surface (Plate 4.1) or have been backfilled for safety reasons. However, two major NCB shafts were 'capped' without backfilling in 1959, allowing access to the groundwater levels. These were Cannop Colliery and Flourmill Colliery (Figure 4.1). Thus the extensive monitoring of groundwater levels was not possible. However, all available sites were utilised.

In addition to these sites, groundwater levels were monitored at two other locations, Shakemantle Iron Mine and Old Ham Iron Mine, both of which are located in the Carboniferous Limestone surrounding the coalfield. These are also shown on Figure 4.1 and included in Table 4.4. It was necessary to include these because in numerous locations iron ore was mined at depth in the limestone through adit drivages and shafts that originated within the coal measure rocks. It was therefore important to determine whether the two geological units were in hydraulic continuity.

Plate 4.1 : Collapsed shaft in the Miles Level Gale area, showing the accumulated debris cone, a few metres below the surface. The brick lined retaining wall has also collapsed, and the remaining surface masonary appears to be in a precarious state. Numerous shafts such as these exist in the Forest of Dean, but their condition precludes the extensive measurement of rest water levels.

TABLE 4.4 GROUNDWATER LEVEL MONITORING SITES

LOCATION	NGR	GEOLOGY AND REMARKS
Cannop Colliery	SO60851250	Abandoned NCB mine shaft. Water level measured weekly. (Coleford High Delf coal seam, Pennant Group).
Flourmill Colliery	SO60600685	Abandoned NCB mine shaft. Water level measured weekly. (Coleford High Delf coal seam. Pennant Group).
Sallow Vallets Borehole	SO60101350	Severn Trent Water Authority borehole drilled 1979. Water Level measured weekly. (Pennant Sandstone Group).
Cannop Cross Borehole	SO60951170	Severn Trent Water Authority borehole drilled 1979. Water Level measured weekly. (Pennant Sandstone Group).
Shakemantle Iron Mine Shaft	SO65111120	Shaft in Carboniferous Limestone outcrop on eastern edge of coalfield Water level measured weekly.
Old Ham Iron Mine	SO57500950	Water level monitoring system installed underground. Measurements weekly by local caving groups. Located in western Carboniferous Limestone outcrop.

4.2.5. MEASUREMENT OF DISCHARGE

The sites chosen for the measurement of discharge are listed in Tables 4.5 and 4.6, which includes the recording interval, method employed and site description, and the locations are shown on Figure 4.1. The sites monitored fall into two categories surface water sites and groundwater sites.

Seven surface water sites were monitored, Lydbrook, Cinderford Brook, Blackpool Brook, and Cannop Brook at New Mills, Parkend, Cannop Cross, and Kensley (Table 4.5). Four of these sites were located where the major streams discharged from the coalfield basin. These were on the Lydbrook, Cinderford Brook, Blackpool Brook, and Cannop Brook (New Mills) and were monitored to determine the total outflow so that a complete coalfield basin water budget could be calculated. It was ess ential that this was possible because the coalfield represented a complete isolated hydrological unit which would provide a basis for assessing the errors involved in the water budgets (Chapters 5 and 6). The sites on the Lydbrook, and Cannop Brook were calibrated natural control features, while those on the Cinderford and Blackpool Brooks were calibrated control structures (Plate 4.2). The gauging stations at Parkend and Cannop Cross are on the main stream of the Cannop Brook, these had previously been installed by STWA in 1979, and were maintained so that the contributions of flow (bed leakage, free-drainage level discharges and runoff) into the Cannop Brook could be assessed (Chapter 5). The site at Kensley on the tributary of the Cannop Brook, was installed so that the runoff characteristics of the Supra Pennant Series could be determined for the water budget, soil moisture and recharge calculations (Chapters 5 and 6).

The groundwater discharges can be subdivided into four groups, those that drain the Supra Pennant Series (Group 1), those that drain the Pennant Series deep basin (Group 2), Pennant shallow groundwater drainage (Group 3) and finally mixed Pennant and Carboniferous Limestone shallow groundwater drainage (Group 4):

Group 1 : Independent level, Cannop Level, Speculation Colliery Spring, Parkend Colliery Spring, Old Bobs Colliery spring and Woorgreens Adit.

Group 2 : Norchard Drift.

Group 3 : Old Furnace Level, Miles Level, Quest Slade Level, Bixslade Upper Level, Bixslade Lower Level and Scotts Level.

Group 4 : Parkhill Level, Tufts Level and Oakwood Level.

The locations of these sites are shown on Figure 4.1, the structures installed, measurement method and frequency are also shown in Table 4.6.

Plate 4.2 : Bed control structure and water level recorder installed on the Cinderford Brook.

TABLE 4.5 FLOW GAUGING STRUCTURES INSTALLED (SURFACE WATERS).

LOCATION	NGR	STRUCTURE	RECORD	REMARKS
Cannop Brook (New Mills)	SO62860460	Natural Control Feature	Continuous	Bridge control feature Stage/discharge curve developed. Munro vertical level recorder.
Cannop Brook (Parkend)	SO61750745	Crump Weir (1:5/1:2)	Continuous	Installed by STWA 1978 Ott vertical level recorder.
Cannop Brook (Cannop Cross)	SO60951155	Flat-V Crump Weir	Continuous	Installed by STWA 1979 Ott vertical level recorder.
Cannop Brook (Kensely Lodge)	SO62001280	90° V-notch Weir	Continuous	BS calibration. Munro horizontal level recorder.
Cinderford Brook	SO65201100	Bed-control Structure	Continuous	Stage/discharge rating curve calibration. Munro horizontal level recorder.
Blackpool Brook	SO64200855	Bed-control Structure	Continuous	Stage/discharge rating curve calibration. Munrc horizontal level recorder.
Lydbook	SO60011600	Bed-control Feature	Weekly	Stage/discharge rating curve calibration.

LEGEND : BS Calibration refers to British Standards (see text).
: Pre- Calibrated refers to calibration supplied by manufacturer
: (see text). Stage/discharge rating curve calibration refers to
: relationship obtained during fieldwork period.

TABLE 4.6 FLOW GAUGING STRUCTURES INSTALLED (GROUNDWATERS)

LOCATION	NGR	STRUCTURE	RECORD	REMARKS
GROUP 1.				
Independent Level	SO61850460	Trapezoidal Flume	Continuous	Pre-calibrated. Munro horizontal level recorder.
Cannop Level	SO61101140	Control Feature	Weekly	Stage/discharge rating curve calibration.
Speculation Colliery Spring	SO61151330	-	Monthly	Graduated Bucket
Parkend Colliery Spring	SO61750760	-	Monthly	Current meter
Old Bobs Colliery Spring	SO60901255	-	Occas ional	Current meter
Woorgreen Adit	SO62601285	-	Occas ional	V-notch weir
GROUP 2.				
Norchard Drift	SO62850430	Crump Weir (1:2/1:2)	Continuous	Pre-fabricated marine plyboard weir. Calibration checked by current meter. Munro vertical level recorder.
GROUP 3				
Old Furnace Level	SO60501160	90° V-notch Weir	Continuous	BS calibration. Munro horizontal level recorder.
Miles Level	SO60800990	Trapezoidal Flume	Continuous	Pre-calibrated. Munro horizontal level recorder.
Quest Slade	SO59850850	90° V-notch Weir	Continuous	BS calibration. Munro horizontal recorder.
Bixslade Upper Level	SO60001025	Control Feature	Weekly	Stage/discharge rating curve
Bixslade Lower Level	SO60251000	-	Monthly	Current meter
Scotts Level	SO60551540	-	Monthly	Graduated Bucket
GROUP 4.				
Tufts Level	SO62050485	Trapezoidal Flume	Continuous	Pre-calibrated. Munro horizontal level recorder.
Parkhill Level	SO61700580	Bed-control Feature	Weekly	Stage/discharge rating curve calibration.
Oakwood Level	SO60010630	-	Monthly	Current meter

LEGEND : BS Calibration refers to British Standards and pre-calibrated refers to calibration supplied by manufacturer (see text).
Stage/discharge rating curve calibration refers to relationship obtained during fieldwork period

The measurement of discharge was necessary at these sites to determine (i) the water budgets for the Pennant and Supra Pennant Aquifers (all groups) (Chapter 5) (ii) the effect of free-drainage level coal barrier removal (Group 3) (Chapters 6 and 10) (iii) the validity of coal mine plans and water budget techniques for catchment area determination of coal mine groundwater discharges (All sites except group 2) (Chapter 6) (iv) the hydrogeological parameters of the aquifer being drained (incuding recession constants, transmissivities, and storage volumes)(all groups) (Chapter 7) (v) the separation of coal measure and limestone flow proportions (Group 4) (chapter 9) and (vi) to calculate flow volumes developed from hydrochemical facies mixing models (chapter 9) (all groups).

All structures were installed in accordance with the British Standards Institution Specifications (BSI) (1971, 1974, and 1980). The choice of structure installed was controlled by fundamental logistics such as the nature of the water course and economics. Most adit discharges were measured using trapezoidal flumes (Forth River Board) because these eliminated backwater effects, sedimentation and reduced ochre deposition. The crump weir installed in the Norchard Drift was a purpose built prefabricated marine plyboard structure, which fulfilled the two criteria outlined previously and would also accomodate high discharges (ranging between 100 and 500 ls^{-1}). During the monitoring period no weir or flume was 'overtopped' or calibration curve exceeded. The site on Blackpool Brook was vandalised and not repaired, because this stream only discharges surface water and was dry between March and November 1984.

The occ asional or monthly gaugings at the minor sites mentioned above (Table 4.6), were conducted using both current meter (British Standards Institution 1964, 1973a and 1973b) and graduated bucket techniques.

4.3 WATER SAMPLING.

Water samples were obtained from the major springs, adits, boreholes, and shafts within the study area. The aim of this exercise was to determine the groundwater and surface water chemistry so that it was possible to define the different hydrochemical facies present (and source areas), develop chemical mixing models to proportion flow volumes, and assess the suitability of flow separation techniques for ungauged and unmonitored coal measure catchments (Chapter 9). Field samples were collected on a regular weekly basis from the major discharge stations outlined above, two samples being taken using glass bottles. A 1 l sample was filtered in the field using an Antilla pressure filter system (Scleicher and Schull AG) incorporating a 4.5 μ filter membrane (Sartoris Ltd), and sent to the STWA regional analytical laboratory (Great Malvern) for analysis of both major and minor elements. (The author acknowledges this assistance with extreme gratitude). An unfiltered sample of 250 ml was analysed for pH and alkalinity on return to the university laboratory. This was necessary because the major sample may have been delayed before analysis allowing degasing which affects carbonate equilibrium and changes the pH and alkalinity of the water sample. Correct pH and alkalinity values were ess ential for the later calculation of the partial pressure of carbon dioxide and saturation indices for calcite (see below). In practice, no significant difference between the samples were detected. Field measurements of conductivity and temperature were also made using a combination electrode conductivity meter (WTW Ltd). Regular samples were supplemented by those collected on underground excursions in various mines. These samples were analysed on return to Bristol (or within 24 hours of sampling) following the same techniques used by STWA. The analytical techniques used in all analyses are outlined in Table 4.7.

The reliability of chemical results was determined by calculating the ion balance error for each analysis. If there was an imbalance of <5 %, the analysis was used, if the imbalance was >5 % but <10 % the result was only used if the total number of samples from that particular site was small and a larger population sample was required. Samples that contained ion balance errors of >10 % were not used.

TABLE 4.7

LABORATORY METHODS USED FOR CHEMICAL ANALYSIS OF WATER SAMPLES

ANALYSIS	ANALYTICAL METHOD	DETECTION LIMIT (mgl^{-1})	REFERENCE
HCO_3	HCL Titration to pH 4.5	1.0	Rainwater and Thatcher 1960
Ca	Atomic Absorption	1.0	Whiteside and Milner 1981
Cl	Auto Analyser+	1.0	Environment Canada 1979 Cook and Miles 1980
Cr	Atomic Absorption	0.03	Whiteside and Milner 1981
Cu	Atomic Absorption	0.02	Whiteside and Milner 1981
Fe	Atomic Absorption	0.04	Whiteside and Milner 1981
HPO_4	Atomic Absorption	0.05	Murphy and Riley 1962
K	Atomic Absorption or Flame Photometry	0.1	Whiteside and Milner 1981 Ure and Mitchell 1975
Mg	Atomic Absorption	1.0	Whiteside and Milner 1981
Mn	Atomic Absorption	0.04	Whiteside and Milner 1981
Na	Flame Photometry	1.0	Ure and Mitchell 1975
Ni	Atomic Absorption	0.03	Whiteside and Milner 1981
NO_3-N	Spectrophotometer(UV)	0.1	Miles and Espejo 1977
SO_4	Auto Analyser*	5.0	Fritz and Yamamura 1955 Cook and Miles 1980
Zn	Atomic Absorption	0.03	Whiteside and Milner 1981

LEGEND : + Methylthymol Blue method.
: * Barium perchlorate and thorin indicator method.
: HCO_3 - Bicarbonate, Ca - Calcium, Cl - Chloride,
: Cr - Chromium, Cu - Copper, Fe - Iron, HPO_4 - Orthophosphate
: K - Potassium, Mg - Magnesium, Mn - Manganese, Na - Sodium,
: Ni - Nickel, NO_3-N - Nitrate, SO_4 - Sulphate
: Zn - Zinc.

CHAPTER 5

THE ESTABLISHMENT OF GROUNDWATER FLOW PATHS AND PATTERNS IN ABANDONED COAL MINED AQUIFERS : 1. THE PENNANT AND SUPRA PENNANT AQUIFER UNITS.

5.1 INTRODUCTION

The previous chapters have concluded the following two important points :

(i) Regional aquifer determination can be predicted from both hydrogeological properties of Coal Measure rocks and a knowledge of the extent of coal mining. In the Forest of Dean, five aquifers units were predicted (Table 2. and Figure 2 Chapter 2).:

1. The Trenchard Aquifer
2. The Coleford High Delf Aquifer
3. The Yorkley Aquifer
4. The Brazilly Aquifer
5. The Serridge Aquifer.

(ii) The method of coalfield development determines the post abandonment groundwater flow paths. This is dependent upon the presence of river level drainage barriers of intact coal. These effect natural drainage of recharge waters from outcrop areas to depth. In the Forest of Dean, the presence of the river level drainage barriers in association with free-drainage levels in the Coleford High Delf and Yorkley Aquifers, divides the groundwater circulation present into two components, a deep groundwater circulation and a shallow groundwater circulation. (Figure 3.8 Chapter 3)

This chapter presents the results of water budget techniques, which have been used to determine :

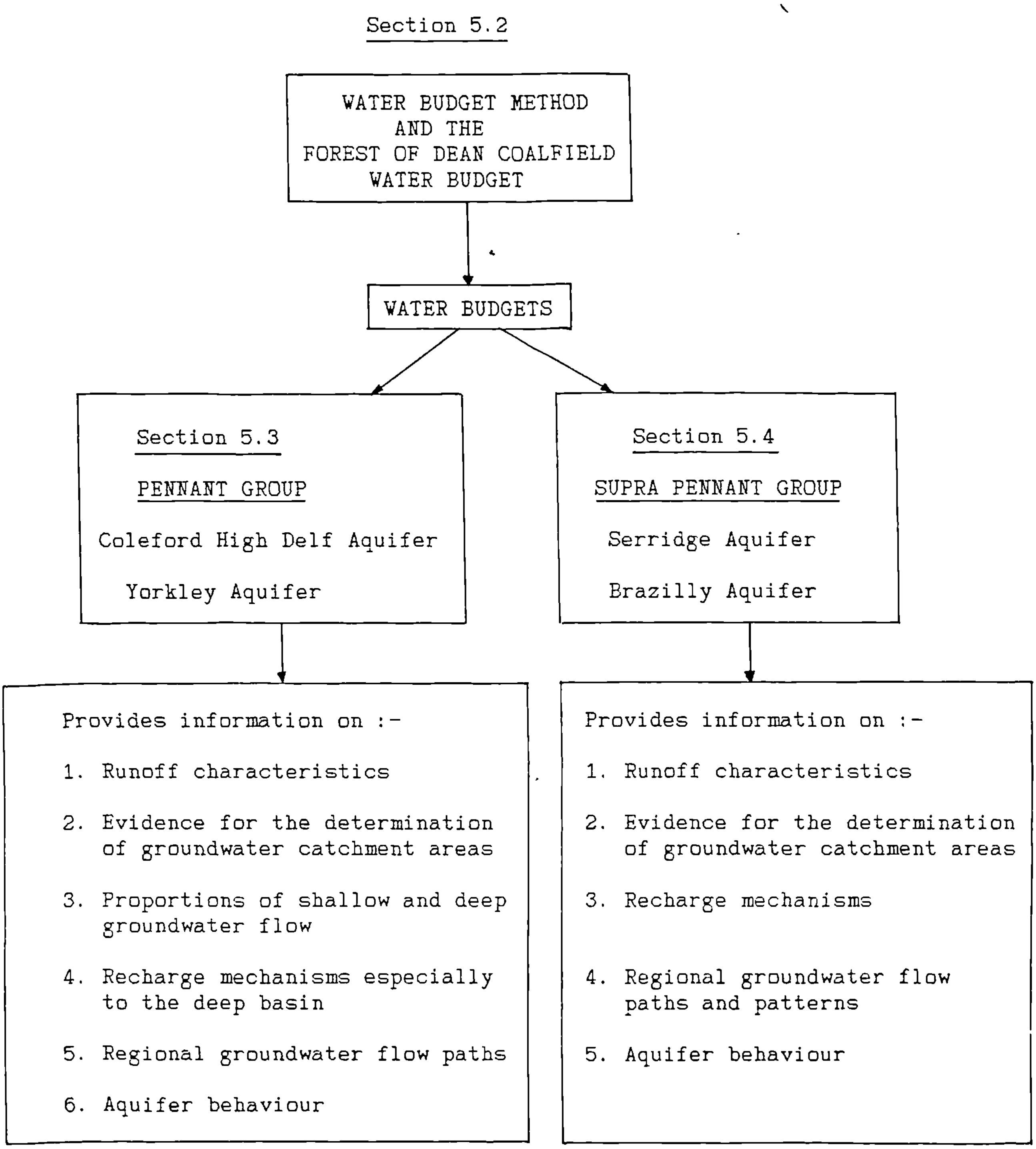
(i) the aquifers predicted in chapter 2 (and to validate this prediction)

(ii) regional groundwater flow paths and patterns,

and (iii) the relationship between the proportions of shallow and deep groundwater discharges.

A schematic flow diagram of the contents of this chapter is shown in Figure 5.1. The chapter is primarily sub-divided into three sections, the first section 5.2 details the general water budgeting method employed, calculation techniques used and the common errors involved with such analysis, this includes a water budget for the whole coalfield (section 5.3). This is followed by two further sections which details surface water runoff characteristics,

FIGURE 5.1 : A guide to the structure of chapter 5.



groundwater catchment areas and groundwater flow patterns present for the major aquifers of the Pennant Group (section 5.4) and Supra Pennant Group of rocks (section 5.5).

5.2 THE WATER BUDGETING METHOD.

The conventional notation for the water budget can be expressed :-

$$Q = P - ET +/- \Delta S \quad \text{...................... Equation 5.1}$$

Where : P = Gross rainfall, ET = Evapotranspiration, Q = Discharge and ΔS = the change in storage.

The determination of a water (or groundwater) budget requires the calculation of effective precipitation (or recharge) volumes (from precipitation, soil moisture and evapotranspiration data (see section 5.3)) for a specific catchment area and the comparison of this volume with the cumulative discharge over a specified time period. Precipitation, evapotranspiration and discharge were all measured directly in the field (as disscussed in chapter 4), and the calculation of soil moisture deficits has also been discussed in chapter 4.

5.3 THE VALIDATION OF THE WATER BUDGETING TECHNIQUES.

As described earlier in chapter 2, the Forest of Dean forms an isolated elongated north-south asymmetrical basin (Figure 5.2). Therefore, the water balance for the whole coalfield catchment area should be : -

$$P - ET +/- \Delta S = Q \quad \text{...................... Equation 5.2}$$

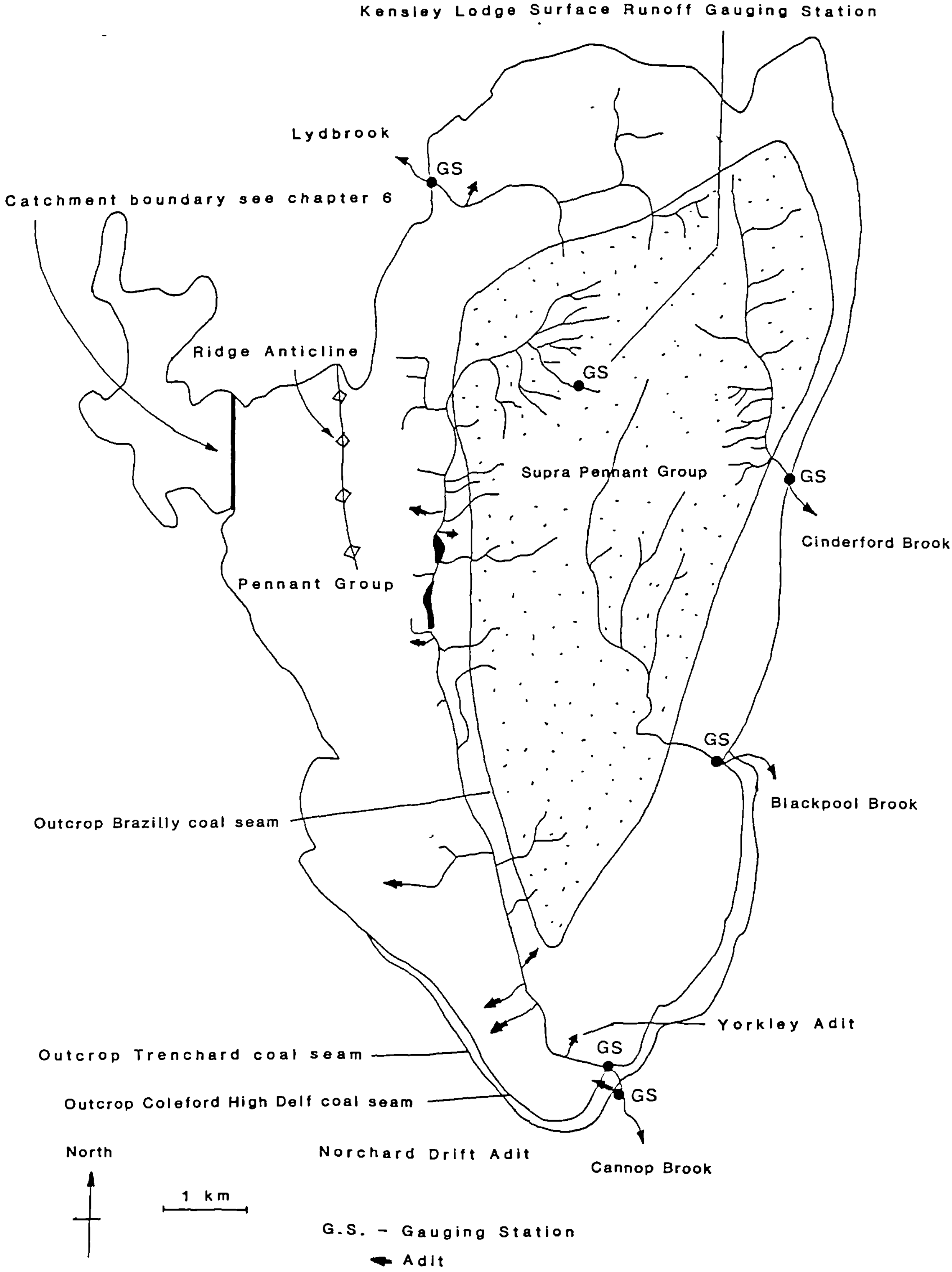
and $Q = Q_{gw} + Q_{sw}$

Where Q - the discharge from the Coalfield comprises of Q_{gw} - Groundwater discharge and Q_{sw} - Surface water discharge, which is the discharges from the Cannop Brook, Cinderford Brook, Blackpool Brook, and Lydbrook. The surface stream discharges include the shallow free-drainage level discharges (corrected for inputs from the surrounding limestones at Tufts and Parkhill Levels (see chapter 9)) and the deep basin groundwater discharge (Norchard Drift) completes the total basin outflow volume). P = is the areal effective precipitation as equated from the Thiessen polygons described in chapter 4. ET = is Evapotranspiration and ΔS = is the change in groundwater storage.

It is necessary to determine that this large scale budget for the 65 km^2 catchment area of the coalfield balanced so that the use of the technique for smaller catchment areas could be validated.

The water budget as stated in Equation 5.2 was calculated for the time period starting on the 6th of December 1983 and finishing on the 6th November 1984. On

FIGURE 5.2 : Map of the Forest of Dean showing the major surface streams and gauging stations.



the former date the first rise in groundwater levels in the Pennant Sandstone Aquifer were recorded at the Flourmill Colliery Shaft. It is assummed that when the groundwater levels began to rise that the soil moisture deficit was equal to zero, and that the saturated zone recharge had then began (Figure 5.3). In fact, the period of recharge (the time when the soil moisture deficit was zero (SMD = 0)) is identical to that for the rise of groundwater levels at the Flourmill Shaft. This indicates that no lag exists between recharge and saturated zone replenishment, and that recharge waters are quickly transmitted to the saturated zone via the fractures of the Pennant Sandstone (see chapter 7). The later date (6th November 1984) was also when the groundwater levels started to rise, and on that date the level at the Flourmill Shaft was identical to that at the beginning of the budget period. Therefore it can be assumed that for the water budget period there was no change in groundwater storage (+/- ΔS in Equation 5.2)

The areal effective precipitation (effective precipitation is gross precipitation minus evapotranspiration) was calculated for each of the Thiessen polygons (Figure 4.1) using the soil moisture deficit method (outlined in chapter 4). This was calculated on a daily basis and then cumulated to a monthly value. Effective rainfall was only present in the months of December (1983), January (1984), February, and March, when the soil moisture deficit was zero and evapotranspiration very small (Figure 5.4). A small amount of effective rainfall is present in the last month (November), when the soil moisture deficit returned to zero. However, amounts of effective rainfall during this month were small (Kensley 7.1 mm, Bixslade 3.3 mm, Blackpool 11.8 mm), except for the Tufts Level polygon where this end of balance contribution amounted to 84.9 mm. This can be explained by the data for the month of August during which a particularly severe storm was cent red near to this raingauge (chapter 4) and the total catch was 40 mm higher than any other gauge, therefore the soil moisture deficit was replenished more quickly than the other sites. At the end of the budgeting period Kensley, Bixslade, Blackpool, and Tufts Level all had soil moisture deficits of zero, while the other polygons contained a small deficit (New Fancy -13.67 mm, Crumpmeadow -5.82 mm, and Cannop Cross -24.32 mm). This small imbalance at the end of the budgeting period is insignificant and attributed to areal variability in rainfall amounts and the accuracy of the initial rainfall measurements (see below). The effective precipitation amounts are equated for each of the Theissen polygons to calculate the total effective precipitation input into the coalfield (Table 5.1). This is 19.65 x 10^6 m^3, and represents the component P - ET +/- ΔS of Equation 5.2.

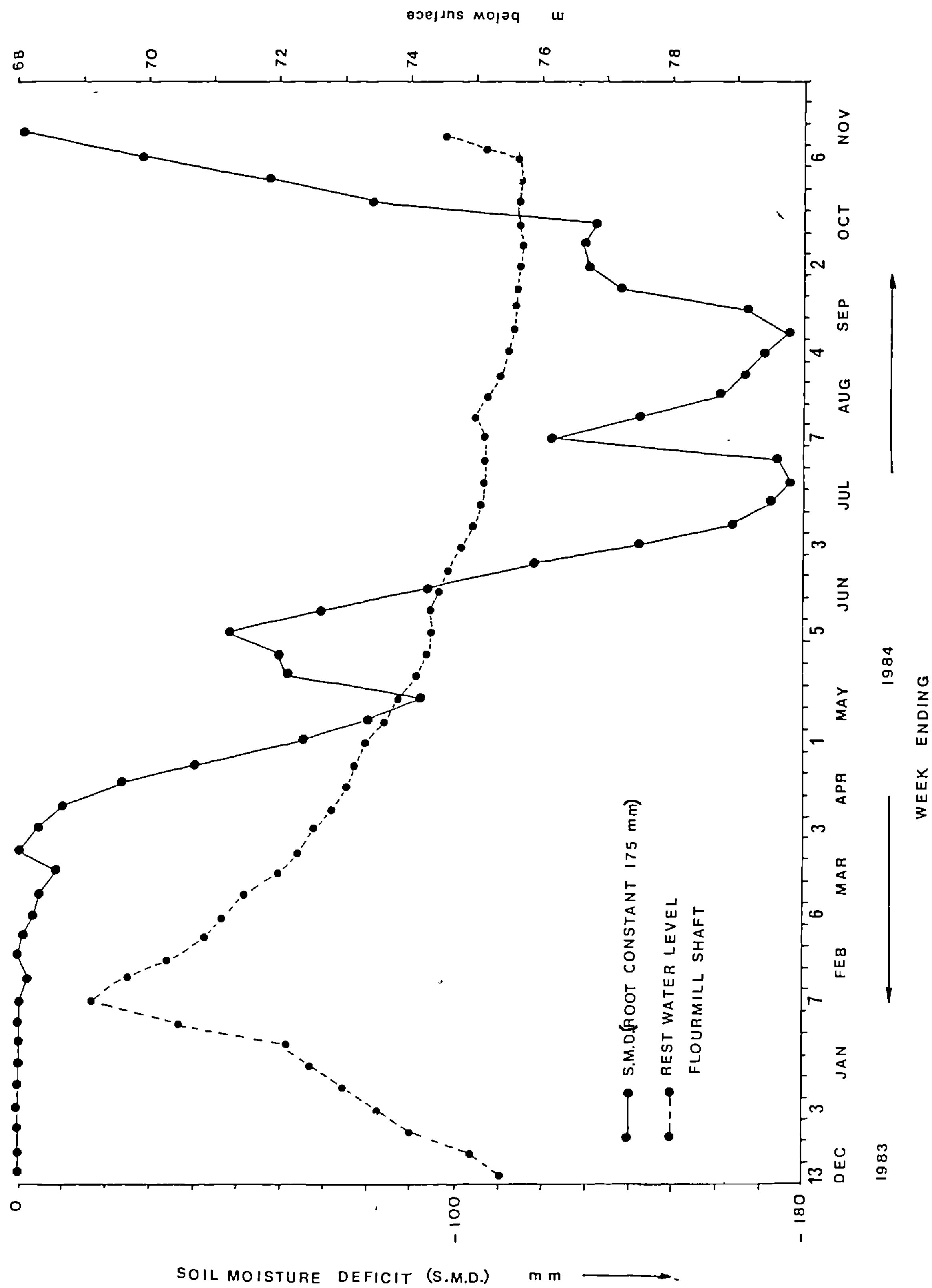


Figure 5.3 : Comparison between soil moisture deficit and response and recession of groundwater levels.

FIGURE 5.4 : Precipitation, evapotranspiration, recharge (effective rainfall) and soil moisture deficits calculated for the Thiessen polygons from December 1983 until November 1984.

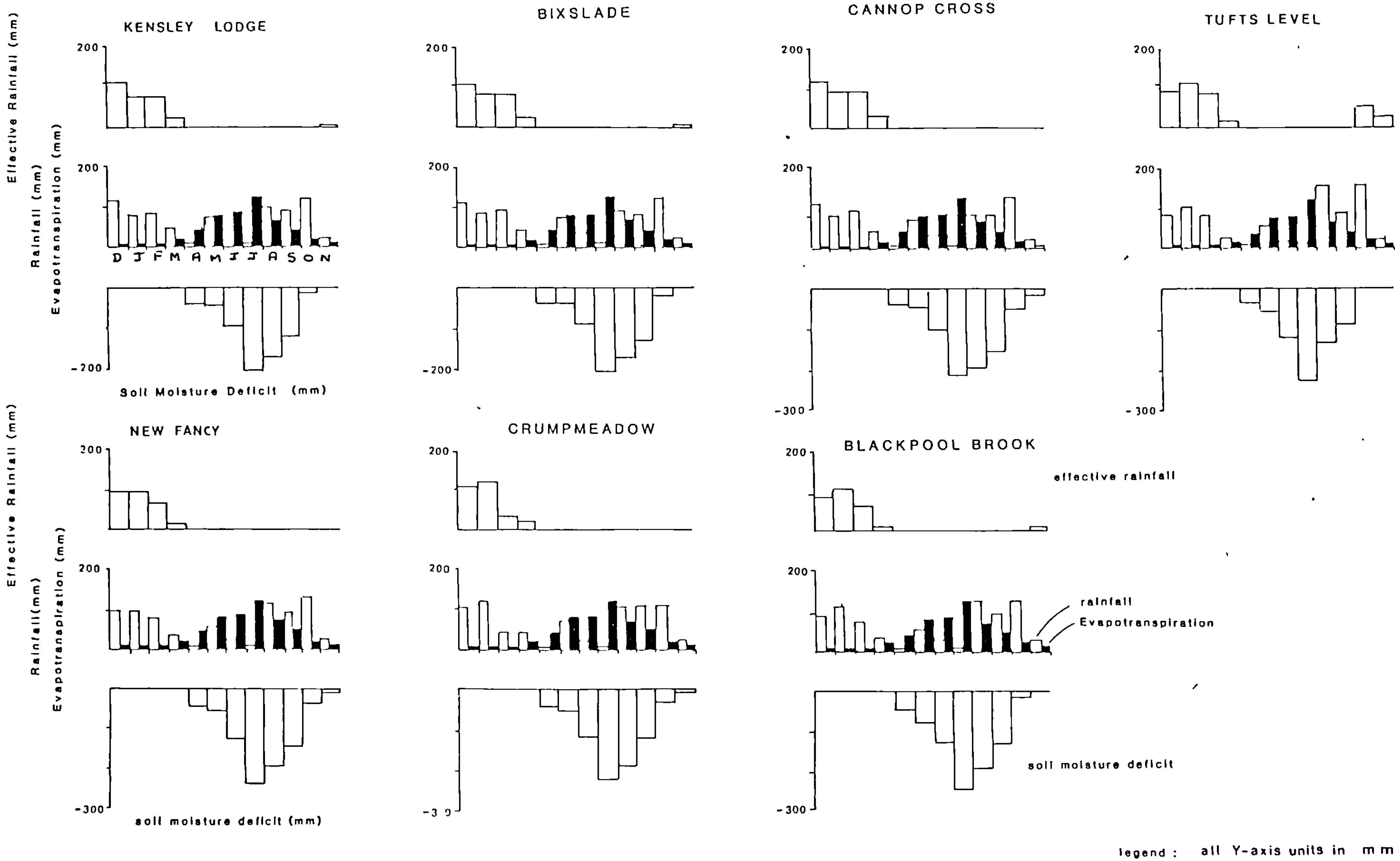


TABLE 5.1

DATA FROM THE COALFIELD BASIN CATCHMENT AREA AND WATER BUDGET VALIDATION.

CUMULATIVE DISCHARGES FOR THE WATER BUDGET PERIOD 6.12.83 - 6.11.84

CINDERFORD BROOK	=	2.72×10^6 m^3
CANNOP BROOK	=	8.52×10^6 m^3
BLACKPOOL BROOK	=	0.35×10^6 m^3
LYDBROOK	=	2.84×10^6 m^3
NORCHARD DRIFT	=	6.20×10^6 m^3
TOTAL	=	20.63×10^6 m^3

RAINGAUGE	EFFECTIVE PRECIPITATION mm	CATCHMENT AREA km^2	TOTAL EFFECTIVE INPUTS m^3
CRUMPMEADOW	281.1	14.05	3.95×10^6
TUFTS LEVEL	371.0	9.06	3.36×10^6
NEW FANCY	273.8	9.17	2.51×10^6
CANNOP CROSS	305.8	8.01	2.45×10^6
BLACKPOOL	289.4	3.19	0.92×10^6
KENSLEY	296.2	11.09	3.28×10^6
BIXSLADE	310.3	10.26	3.18×10^6
			TOTAL = 19.65×10^6

TABLE 5.2

CANNOP BROOK DISCHARGE COMPONENTS FOR THE GAUGING STATIONS AT CANNOP CROSS, PARKEND AND NEW MILLS.

The discharge components of any gauging station on the Cannop Brook can be expressed by the following equation :-

$$Q_S = Q_{FDL} + Q_{SUPRA} + Q_{GW}$$

Where subscripts are :- $_S$ = any gauging station (Cannop Cross, Parkend or New Mills), $_{FDL}$ = free-drainage discharge up stream of gauging station, $_{SUPRA}$ = Supra Pennant Discharge (Runoff and groundwater) and $_{GW}$ = groundwater component contributing to Cannop Brook discharge.

GAUGING STATION	TOTAL DISCHARGE		FREE DRAINAGE DISCHARGE		SUPRA PENNANT DISCHARGE		GROUNDWATER DISCHARGE
CANNOP CROSS	2.2	=	0.88	+	1.3		
PARKEND	6.17	=	2.01	+	2.36	+	1.8
NEW MILLS	8.52	=	2.44	+	2.71	+	3.37

Legend :- All units x 10^6 m^3. Total discharge and free drainage level discharge are measured values, Supra Pennant discharge is calculated from runoff characteristics and the groundwater discharge is calculated by difference.

The total volume of water discharged from the coalfield basin (Q in equation 5.2) is equal to the combined surface flows of Cannop Brook, Blackpool Brook, Lydbrook, and Cinderford Brook, and the deep groundwater discharge at Norchard Drift (Figure 5.2). The total volume of water discharging from the coalfield is equal to 20.63 x 10^6 m^3 (Table 5.1). If the expected catchment area is correct and the measurements accurate the two values for P - ET +/- ΔS and Q should balance. Unfortunately, there is an imbalance of 4.75 % (19.65 x 10^6 and 20.63 x 10^6 m^3) between the two values. This can be attributed to two factors :

(i) A miscalculation of the catchment area, probably around the area of the Worcester Syncline and Ridge Anticline of 3.1 km^2. The catchment area determination in this area is discussed in detail in chapter 6.

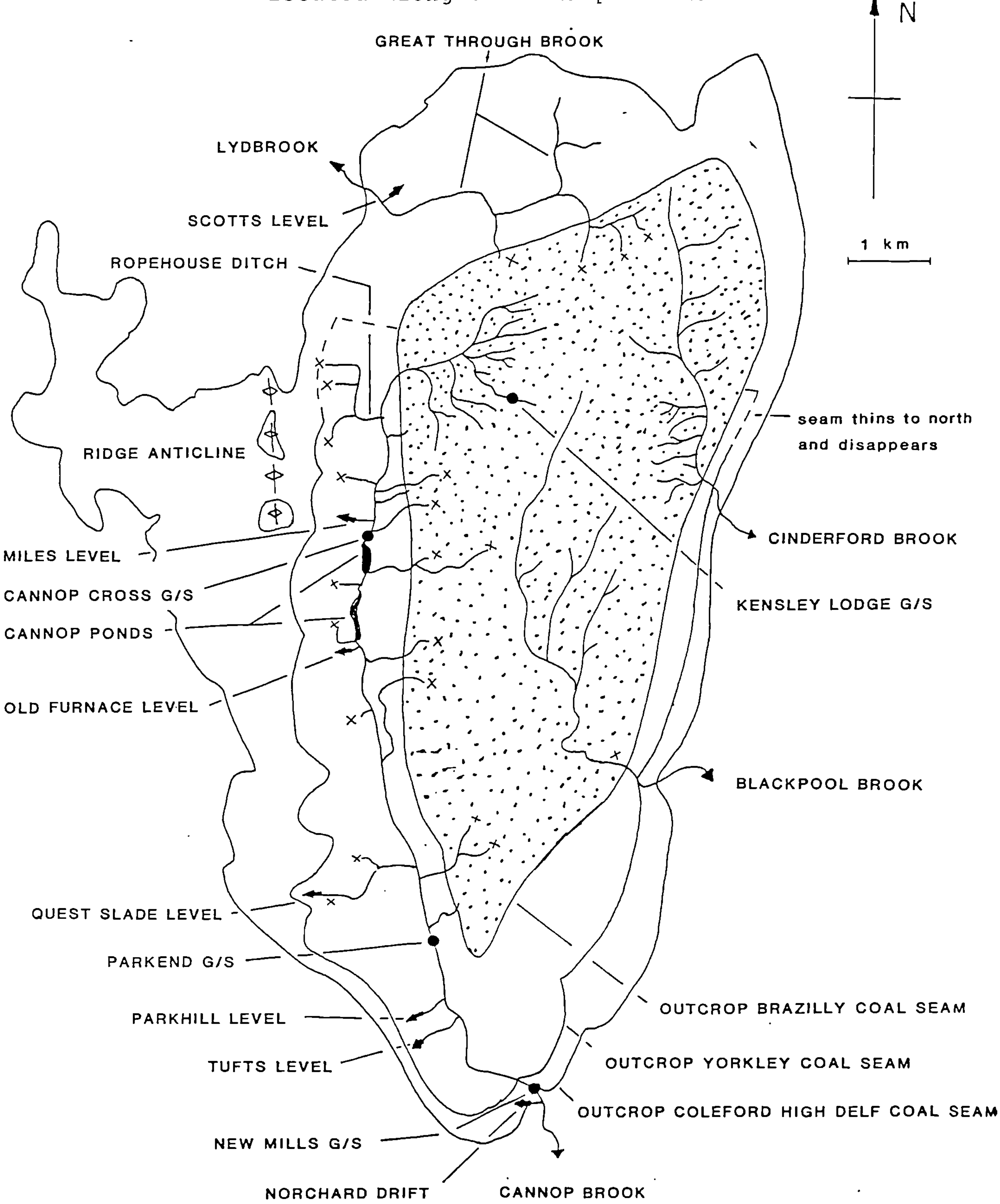
(ii) Errors associated with the measurement of the field parameters, which could possibly be an under estimation of gross precipitation or over estimation of evapotranspiration or discharge. Typical errors in the measurement of the variables for the water budget are : rainfall +/- 5 %, evapotranspiration +/- 15 %, discharge +/- 5 % and soil moisture +/- 10 %. The error of 4.75 % in comparison to the size of the catchment area of 65 km^2 and that for the variables measured is small.

5.4 CALIBRATION OF RUNOFF COMPONENTS.

In the equation stated above (Equation 5.2), for the water balance from the whole coalfield basin it was not necessary to determine between the surface and groundwater proportions (surface runoff and recharge volumes) of effective rainfall because this was accounted for in the total discharge leaving the basin in the major streams. However, for the calculation of more specific budgets (for instance for individual free-drainage levels or stream catchment areas) the runoff characteristics (infiltration and runoff coefficients) of both the Pennant and Supra Pennant geological series require determination to allow an accurate calculation of the amount of effective rainfall and recharge.

There is a marked lack of surface drainage on the arenaceous Pennant Series, and the major contributions to the discharge of the Cannop Brook are from the free-drainage levels. In fact, the deeply incised valleys or 'slades' present on the western, southern and northern outcrops contain neither permanent streams, nor evidence of channels occupied during higher flow conditions. However, there are seven small streams which drain eastwards into the Cannop Brook (Figure 5.5) from the western outcrop of the Pennant Sandstone. These spring sources are all at elevations close to that of the Cannop Brook, and

FIGURE 5.5 : Map of the Forest of Dean showing other monitored discharges, especially those located along the Cannop Brook.



LEGEND : x – no summer flow 1984 (May to September) classed as ephemeral stream, unmarked streams have permanent flow

G/S – Gauging station ●

SUPRA PENNANT GROUP OF ROCKS

PENNANT GROUP OF ROCKS

thus only flow over short distances. There typical discharges are < 2 ls^{-1} and have a total wet weather flow of < 20 ls^{-1}. The northern outcrop has two slightly larger such streams (Ropehouse Ditch and Greathrough Brook), the former drains to the Cannop Brook and the later to Lydbrook. These Pennant outcrop surface streams were observed to flow only during wet periods (December (1983), January, February and March (1984)), with a combined discharge from three possible source areas; forestry ditches, clear felled areas and shallow unsaturated zone throughflow in the Pennant aquifer. There are no streams emanating from the eastern Pennant outcrop. Because of the lack of surface runoff it is assummed that all of the effective precipitation infiltrates into the Pennant Sandstone to be discharged as groundwater via the numerous shallow free-drainage levels or the deep basin discharge at Norchard Drift, and that the total volume discharged from the small Pennant springs is not significant.

The overlying arenaceous Supra Pennant Series is completely different in hydrological character. It is dominanted by the presence of numerous streams draining westwards into the Cannop Valley, and provides the total discharges of the Blackpool and Cinderford Brooks and the majority of the flow in the Lydbrook stream. These streams respond rapidly to single rainfall events showing a direct runoff component during flood discharges (Figure 5.6). Therefore, all of the rainfall does not infiltrate directly to the groundwater regime, but a percentage is transmitted directly as runoff to the surface streams.

The gauging station at Kensley Lodge (Figure 5.5) was specifically installed to monitor the run-off component of storm flows of the Supra Pennant. For each specific storm event that was recorded (thirteen in total) at the Kensley Lodge gauging station, the runoff percentage (runoff coefficient) of the storm event was calculated. Unfortunately due to the extremely dry conditions of the early spring and summer, the storm events were not distributed evenly through out the year (Figure 5.7) and where more than one storm has occurred in any particular month the average runoff coefficient was calculated. The calculated run-off co-efficent curve mirrors the soil moisture deficit curve, with high runoff volumes corresponding to low soil moisture deficits. The highest runoff coefficients were recorded for the initial two months (November and December) of the water budget period. These averaged 0.91 and 0.8 respectively. While the lowest of 0.23 was for an isolated storm in May. In conclusion, the runoff coefficient is determined by the antecendent soil moisture conditions, and this shows a strong seasonal variation.

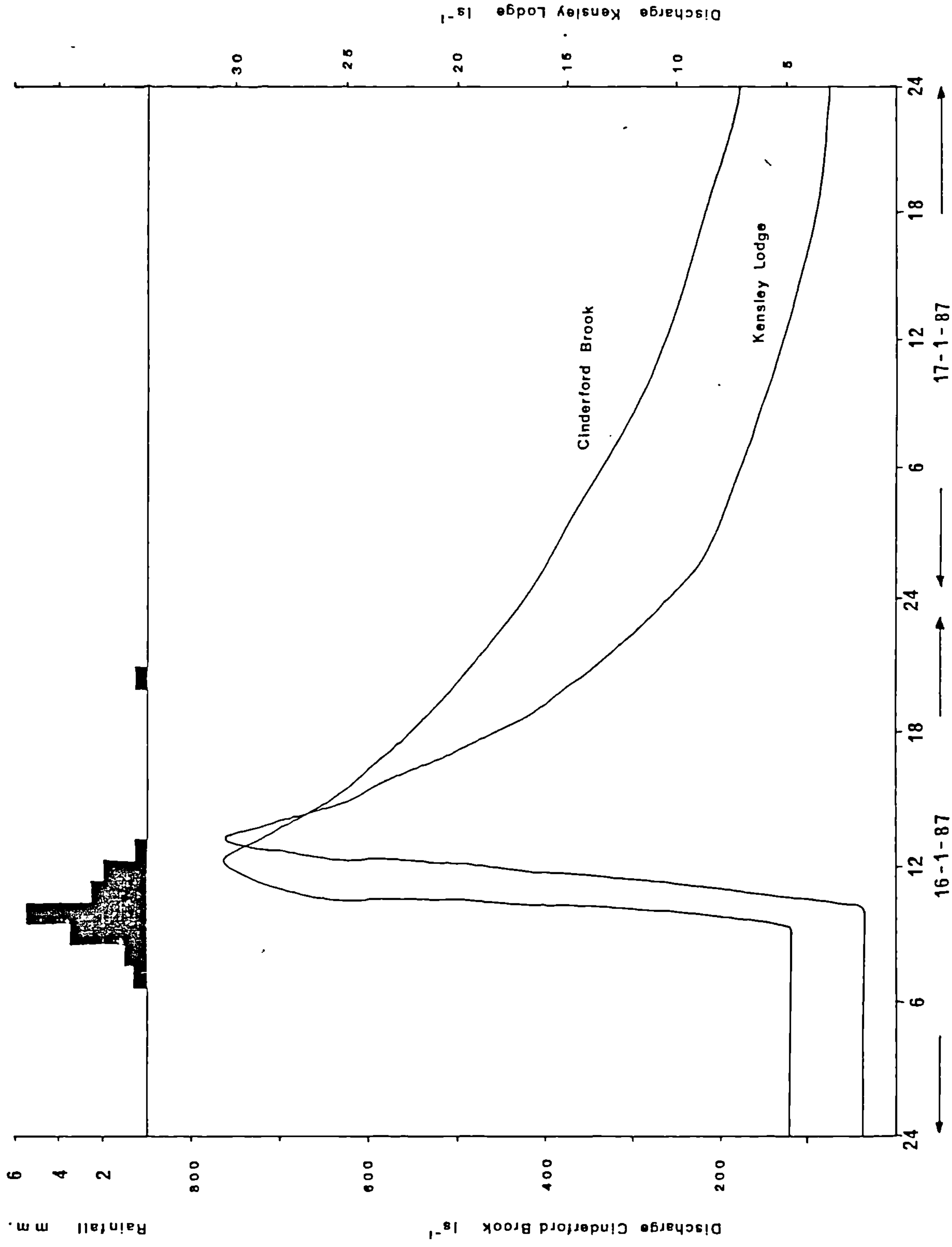
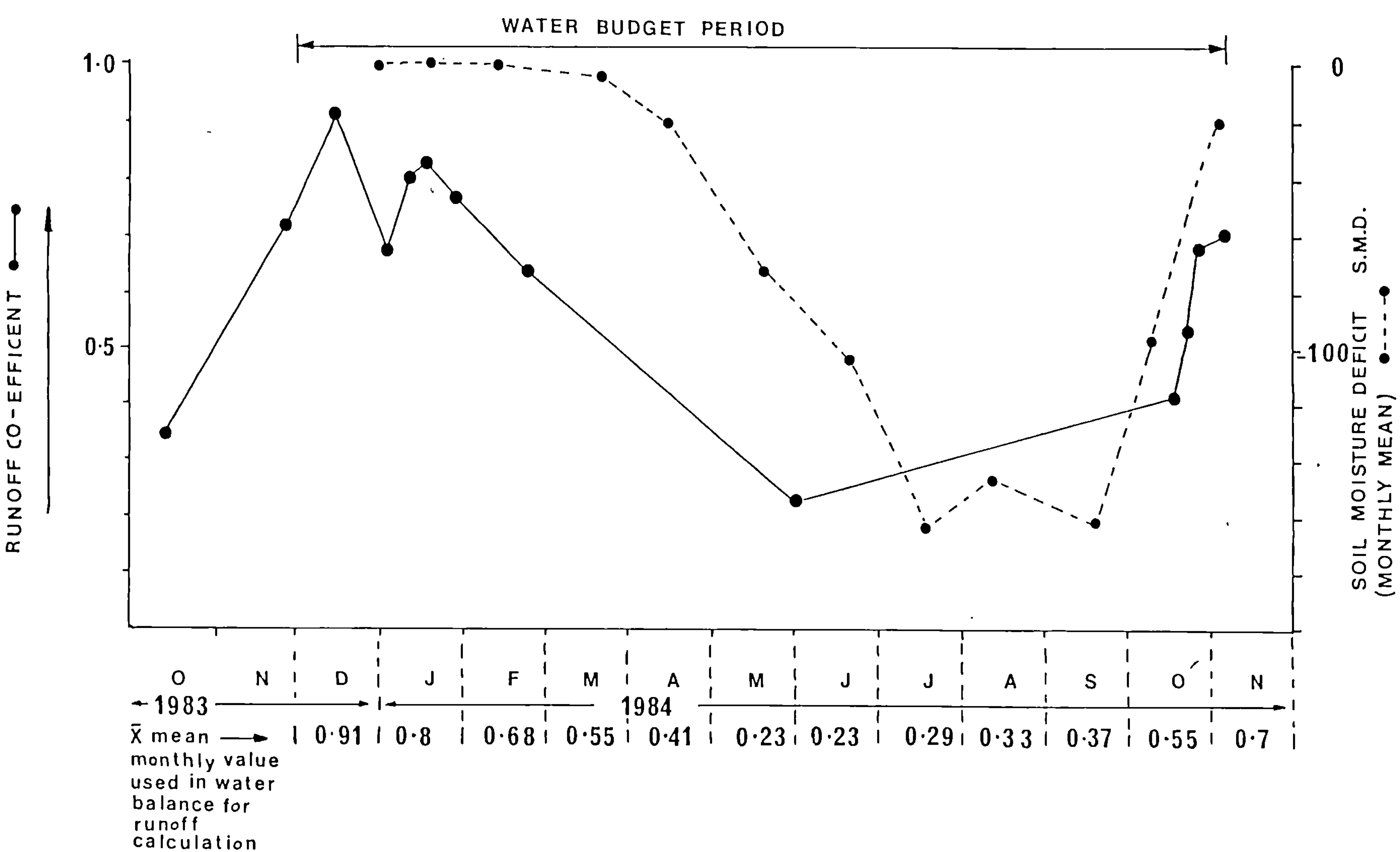


FIGURE 5.6 : Response of stream discharges at the Kensley Lodge and Cinderford Brook gauging stations, which drain the arenaceous Supra Pennant Series. The storm of the 16th of January was very severe leading to erosional and flooding damage along the lower reaches of the Cinderford Brook. The quicker response of the larger discharge is attributed to a difference in catchment cover. The Cinderford Brook is fed by a series of large storm water drains which drain the impervious concrete area of the town.

Figure 5.7 : Change in runoff coefficient for the Kensley Lodge stream during the field monitoring year. (Serridge Aquifer of the Supra Penant Group).



5.5 THE PENNANT GROUP AQUIFER WATER BUDGET.

The purpose of the Pennant Group Aquifer water budget is to validate the catchment boundaries for the Coleford High Delf and Yorkley Aquifers as predicted in Chapter 2 and determine the geological controls on groundwater movement and quantify the proportions of groundwater flow that are discharged by the shallow free-drainage levels and the deep groundwater circulation (Norchard Drift).

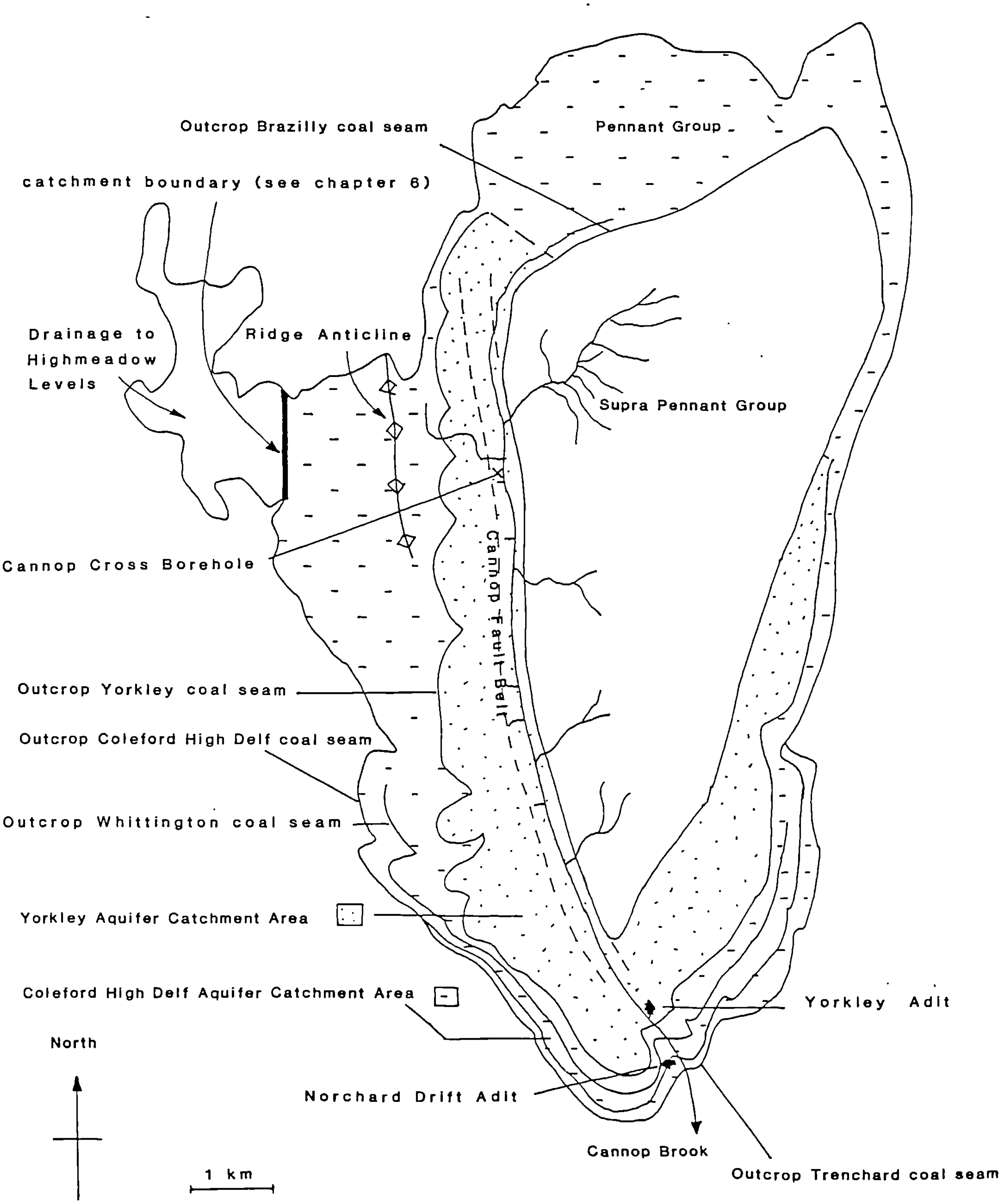
The Pennant Group Aquifer can be subdivided into two sub-units:

(i) the Pennant Sandstone between the Coleford High Delf and Yorkley coal seams, and the Trenchard Series (referred to collectively as the Coleford High Delf Aquifer, Chapter 2).

(ii) the Pennant Sandstone above the Yorkley coal seam and below the base of the Supra Pennant Rocks (referred to as the Yorkley Aquifer, Chapter 2).

The outer edge of the catchment area for the Coleford High Delf Aquifer is clearly defined by the outcrop of the coal seam (Figure 5.8), except in the north-west, where the Worcester Syncline and Ridge Anticline disrupt this clear cut boundary. Here the boundary has been defined by both the geological structure and mining method employed (determined from mine plans, see chapter 6) and is described in detail when the Miles and Old Furnace Level catchment areas are determined in the next chapter. In addition in the southern part of the coalfield the Trenchard Series is included, although defined as a separate aquifer in chapter 2. The Trenchard Aquifer has an outcrop area of only 1.9 km^2, and is included because the coal workings in the Trenchard coal seam were extensively interconnected with those of the Coleford High Delf coal seam, particularly those of the Norchard Colliery which discharges from the deep basin at the Norchard Drift and also contributes to the shallow free-drainage level discharges from the Tufts and Parkhill Levels. No adjustment to the infiltration coefficient for the Trenchard Series compared to the Pennant Series has been made (and it is assumed to be 1.0 also) because the strata is dipping very steeply below the Pennant Rocks and no surface streams are wholly maintained by groundwater or surface water draining from the outcrop. The Yorkley coal seam outcrop defines the inner catchment boundary for the Coleford High Delf Aquifer and outer boundary for the Yorkley catchment, because the Yorkley coal seam (0.5 m) and associated seat earth clay (0.9 m) form an aquiclude. Also, the Yorkley coal seam has only been worked close to the outcrop, and these workings are isolated from the deep workings in the Whittington, Coleford High Delf and Trenchard coals (Chapter 2).

FIGURE 5.8 : Map showing the catchment areas of the Coleford High Delf and Yorkley Aquifers.



Between the Coleford High Delf and Yorkley coal seam lies the Whittington coal seam (Figure 5.8). This is included in the Coleford High Delf catchment area and not considered as a separate aquifer like the Yorkley Aquifer associated with the Yorkley coal seam because :

(i) - it is limited to the southern half of the coalfield and thus has a very small catchment area.

(ii) - where it has been worked these workings are interconnected to the Coleford High Delf seam.

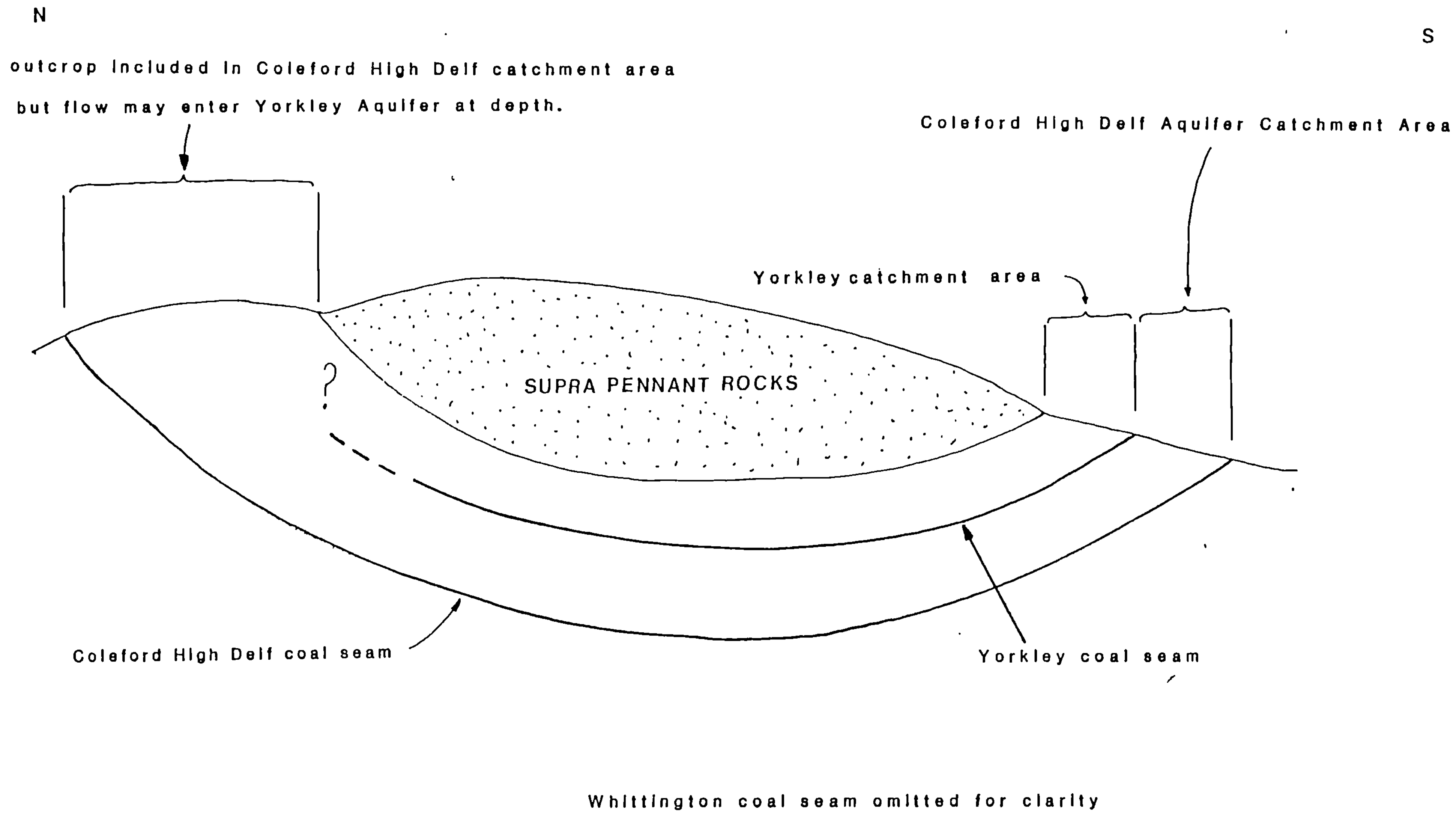
and (iii) - where subsidence has occurred vertical fracturing is more likely to have caused disruption to the Whittington coal because it lies between two shale bands and is not underlain by a thick seat earth clay.

Unlike the Coleford High Delf coal seam, the Yorkley coal seam is not a continous outcrop but thins to the north and finally disappears. The northern boundary of the Yorkley Aquifer has thus been defined as a line drawn between the two ends of the outcrop, and where this meets the overlying Supra Pennant Rocks. Although in plan view this boundary is small, because it is covered by the Supra Pennant Rocks, it may have an effect on the budgeting of recharge waters moving through the Pennant Sandstone in the northern most area. All the recharge north of the northern Yorkley boundary is considered in the Coleford High Delf Aquifer, although a proportion may move laterally southwards towards the Yorkley Aquifer (Figure 5.9). However, this is not the case as a higher piezometric level is present in the upper Yorkley Aquifer and the opposite case occurs (Figure 5.12) with the groundwater movement from the Yorkley to the Coleford High Delf Aquifer and the catchment areas as defined above are correct. This will be discussed in more detail later in this chapter where borehole levels and field observations are presented to validate the groundwater flow paths in the Yorkley Aquifer catchment area. The remaining part of the Yorkley catchment area is defined by the edge of the Supra Pennant Series. The Coleford High Delf Aquifer catchment area is 27.7 km^2 and the Yorkley Aquifer 11.23 km^2.

Of the total coalfield recharge (19.65 x 10^6 m^3) 12.21 x 10^6 m^3 is recharge to the Pennant Group outcrop area (Figure 5.10). Using the catchment areas defined above, the Coleford High Delf Aquifer recharge is 8.53 x 10^6 m and the Yorkley Aquifer, 3.68 x 10^6 m^3.

The Coleford High Delf Aquifer discharges via two outlets the shallow free-drainage levels (Miles, Old Furnace, Scotts, Quest Slade, Parkhill and Tufts Levels) and the deep basin drainage to the Norchard Drift Adit. The former

FIGURE 5.9 : Cross section of the coalfield showing the complication of the northern boundary for the Yorkley Aquifer.



accumulatively contributes 2.46 x 10^6 m^3 and is the actual value measured in the field (no adjustment for the Yorkley Aquifer contribution to the free-drainage level discharges at the Old Furnace Level, Miles, Parkhill and Tufts Levels have been made, this is discussed below. This value (2.46) would indicate that the Norchard Drift discharge should be 6.07 x 10^6 m^3 (8.53 - 2.46), calculated by difference (Figure 5.10). However, the actual discharge measured at the Norchard Drift was 6.2 x 10^6 m^3. If it is assumed that the discharge at the Norchard Drift is comprised totally of Coleford High Delf Aquifer groundwater and no other source supplements the discharge, this represents an error for the water budget of 2.1 %, or a gain in discharge of 0.13 x 10^6 m^3. This difference will be discussed later, after the presentation of the results of the Yorkley Aquifer water budget.

The Yorkley Aquifer has only two apparent discharge outlets, firstly a small collapsed adit contributing to the flow in the Cannop Brook (Figure 5.2), and secondly, a contribution to the free-drainage level discharges from Miles, Old Furnace, Tufts and Parkhill Levels (Figure 4.1) (not Scotts or Quest Slade levels as these do not intersect the Yorkley coal seam). The former discharge is only 0.04 x 10^6 m^3 (1.1 % of the total Yorkley Aquifer recharge (Figure 5.10), and the later is also small. The Yorkley long measure level contributes only 0.009 x 10^6 m^3 (~1 %) to the annual discharge of 0.88 x 10^6 m^3 from the Old Furnace Level. This is not surprising considering the much smaller extent of workings draining to the free-drainage level in the Yorkley coal seam than that of the Coleford High Delf coal seam. Therefore, it is unlikely that even the accumulative discharge from this outlet would account for the remaining 3.64 x 10^6 m^3 (3.68 - 0.04 x 10^6 m^3) of recharge. Furthermore, this is larger than the total discharge from the free-drainage levels including the Coleford High Delf Aquifer component) and another significant discharge outlet must exist.

The rest water levels measured in the Cannop Cross borehole (78 m AOD) are those for the Yorkley Sandstone (Figure 5.11), although the borehole was drilled to a depth of -72 m AOD penetrating both the Coleford High Delf and Yorkley Aquifer units. The coal seams are at depths of -100 and -13 m AOD below the borehole respectively. When the borehole was first drilled in January 1979 the initial rest water level was between 48 and 38 m AOD. However, during the winter of 1979/1980 the rest water level continued to rise above the previous winters level reaching a much higher average level of 58 m AOD. The original rest water level (1979) (Figure 5.11 and 5.12) corresponds with the rest water level for the Coleford High Delf Aquifer as measured at the Cannop Colliery

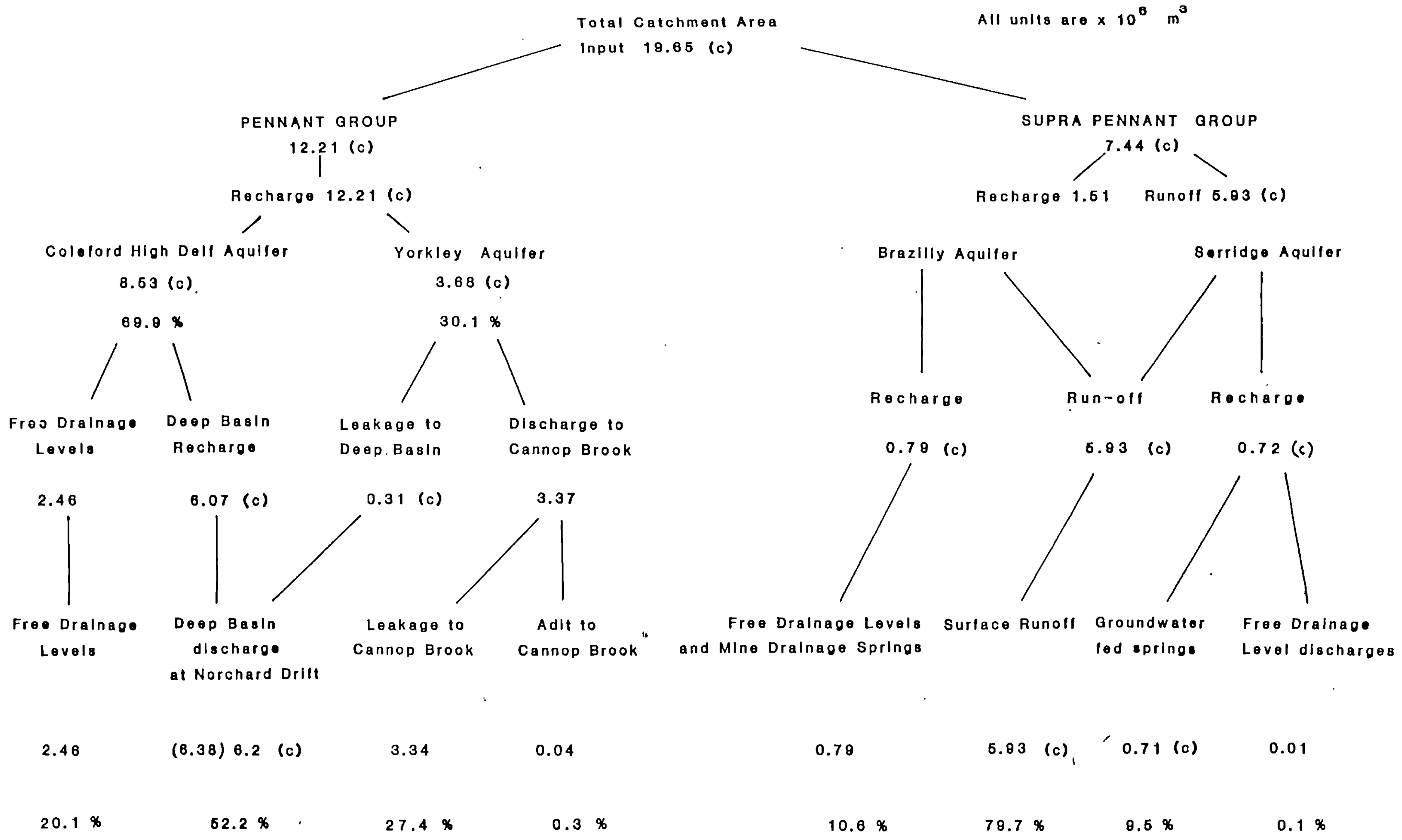
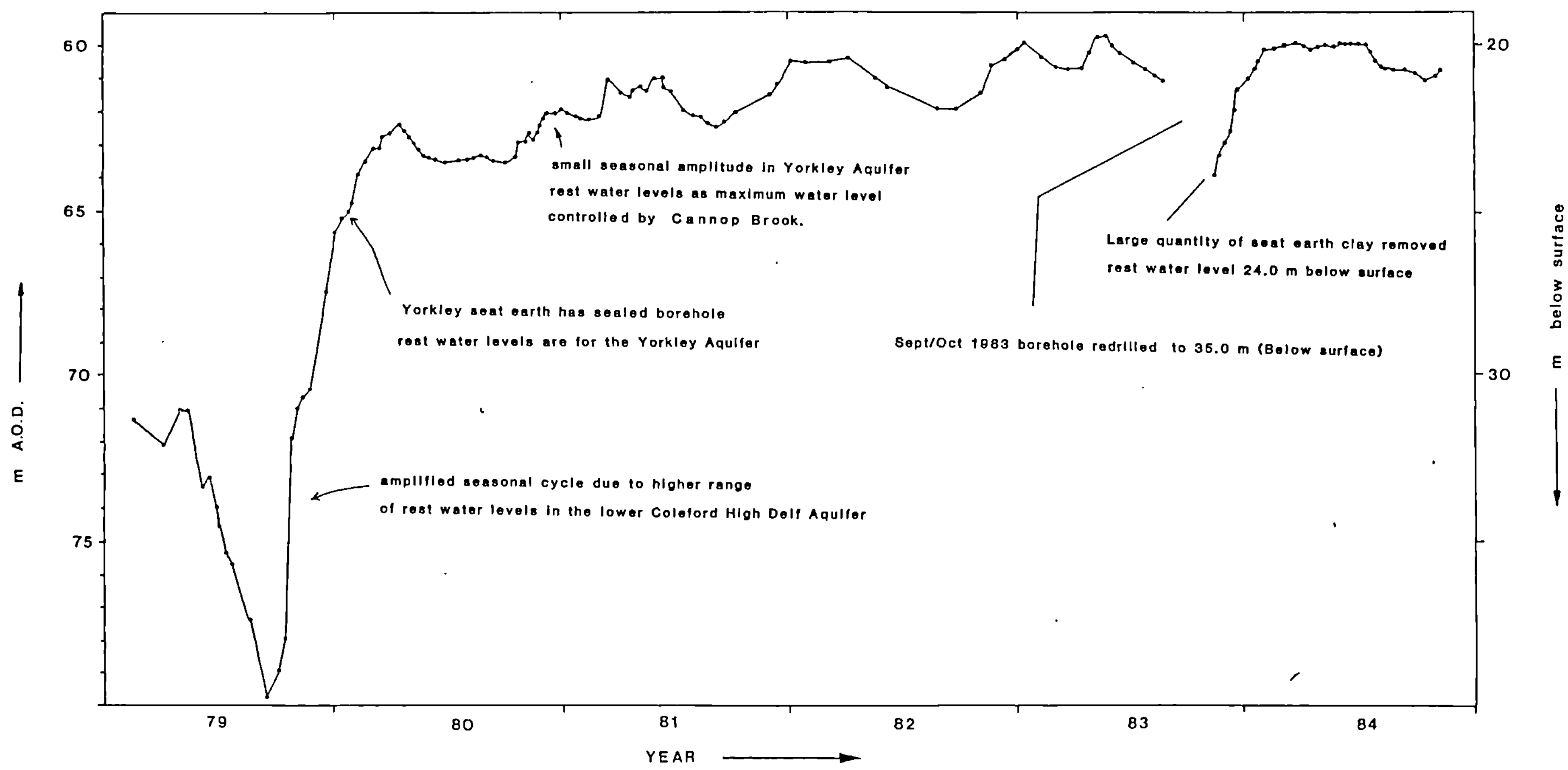


Figure 5.10 FLOW DIAGRAM SHOWING WATER BUDGET PROPORTIONS FOR THE FOREST OF DEAN COALFIELD AND MAJOR PATHWAYS FOR GROUNDWATER FLOW

Figures (c) - calculated others measured

Figure 5. 11 : Groundwater level hydrograph for the period of 1979 to 1984 for the Cannop Cross borehole (Yorkley Aquifer).



Shaft. The rise in rest water level is attributed to the sealing of the borehole by the seat earth clay below the Yorkley coal seam, and the rest water level is that for the Yorkley Aquifer. Attempts to redrill the borehole during July and August 1983 failed to penetrate past the seat earth, but did confirm that a substantial blockage existed and that it consisted of a blue-grey seat earth clay.

If the rest water level for the Yorkley Aquifer is projected southwards with a slight gradient (unfortunately no gradient is known) it cuts the Cannop Valley 1.25 km north of the Parkend gauging station (Figure 5.12). It is therefore possible that the Yorkley Aquifer discharges close to its southern outcrop. There are no springs visible on the surface, and the remaining outlet is via the bed of the Cannop Brook. The shape of the annual water level curve (Figure 5.11) would also agree with this hypothesis because there is a very small annual change in level as significant increases in head are controlled by increased discharge to the Cannop Brook from which flow is not restricted. Groundwater flow southwards in this manner would follow the faulting in the Pennant Sandstone associated with the Cannop Fault Belt (Figure 5.8).

Along the length of the Cannop Brook, there are three gauging stations, Cannop Cross, Parkend and New Mills (Figure 5.12 and 5.5). By water budgeting for the catchment area of the Cannop Brook for each of the gauging stations it is possible to determine where this Yorkley Aquifer groundwater emerges and the total volume of water which is discharged via this outlet.

The discharge of the Cannop Brook at any location will be comprised of the following components (Table 5.2):

(i) Discharge from the Pennant free-drainage levels, which includes groundwater discharged from both the Coleford High Delf and Yorkley Aquifers.

(ii) Surface runoff and baseflow from the Supra Pennant Series.

(iii) Discharge from the Supra Pennant free drainage levels (including mine drainage springs, see later).

and (iv) Discharge of groundwater from the Pennant Sandstone of the Yorkley Aquifer.

If all the components can be calculated except (iv), and the total discharge is known it is possible to determine the final component; the discharge from the Yorkley Aquifer to the Cannop Brook. The first and third components (i) and (iii), were measured at all the outlets which discharge to the Cannop Brook

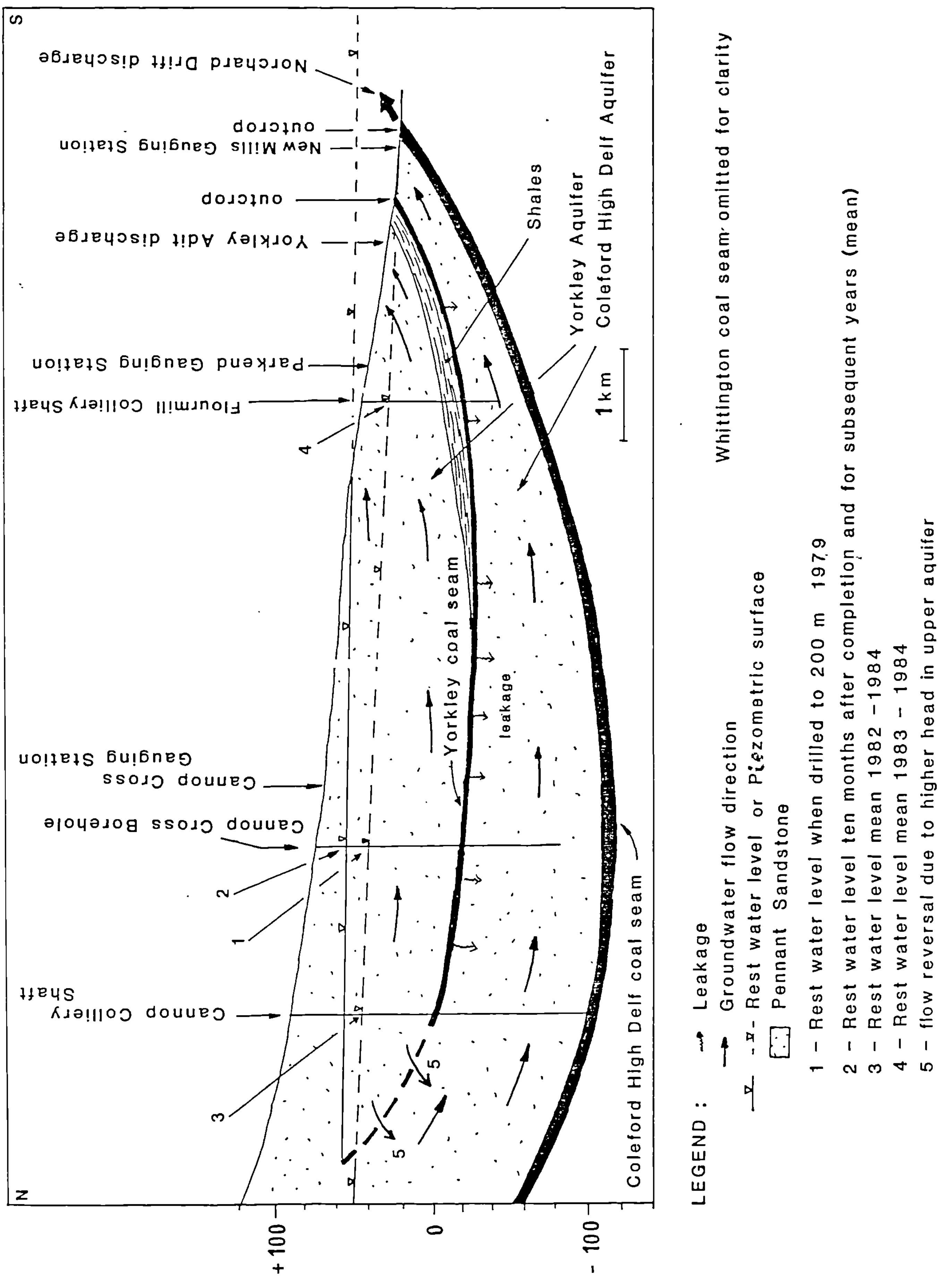


FIGURE 5.12 : Cross section along the Cannop Brook Valley showing rest water levels and geological controls on groundwater movement in the Coleford High Delf and Yorkley Aquifers.

(Chapter 4), the second component (ii), can be calculated using the water budget technique for the Kensley Lodge gauging station extrapolated for any Supra Pennant catchment area (section 5.3 and 5.4).

The measured discharge at the Cannop Cross gauging station is equal to 2.2 x 10^6 m^3 while the computed discharge (Table 5.2) (from the components above) is equal to 2.18 x 10^6 m^3, which gives an imbalance of 1.0 %. However, for the Parkend and New Mills gauging stations, the differences between measured and predicted discharges are 29.0 and 39.5 % respectively and cannot be attributed to errors in measurement (gauging and rainfall are both +/- 5 % (see section 5.3)). The measured discharge is far greater than that predicted indicating a net gain. This gain at the Parkend gauging station is equal to 1.8 x 10^6 m^3 and for New Mills 3.37 x 10^6 m^3. If the 0.04 x 10^6 m^3 from the Yorkley adit discharge is accounted for the gain in discharge attributed to groundwater leakage from the Yorkley Aquifer to the Cannop Brook is 3.34 x 10^6 m^3 (Figure 5.10).

The difference between the calculated discharge value of 3.38 x 10^6 m^3 (3.34 + 0.04 x 10^6) and the recharge value of 3.68 x 10^6 m^3 (Figure 5.10) is 0.31 x 10^6 m^3. This can be explained initially in two ways:

(i) An error in measurement and calculation equal to 8 %. This case can not be dismissed, as the calculation of the majority of the Yorkley Aquifer discharge was by an indirect method.

and (ii) A leakage component from the upper Yorkley Aquifer into the lower Coleford High Delf Aquifer of 0.31 x 10^6 m^3 which would contribute to the discharge of the Norchard Drift. Leakage most probably does occur but this value must be treated with care because its size lies within an acceptable 10% error for a budget of this type.

5.6 DEEP BASIN DRAINAGE CHARACTERISTICS

5.6.1 THE NORCHARD DRIFT DISCHARGE AND THE COLEFORD HIGH DELF AQUIFER

The previous section has discussed the hydrogeological nature of the two Pennant Aquifer sub units (the Coleford High Delf and Yorkley Aquifers) and determined the volumes that are discharged via the three discharge routes present, namely the deep basin flow to the Norchard Drift, shallow groundwater flow which is discharged via the free-drainage levels and a diffuse discharge of groundwater to the Cannop Brook. This section will consider in more detail the relationships between recharge and discharge for the deep basin, while the free-drainage levels in both the Pennant and Supra Pennant Group will be discussed in the next chapter.

Figure 5.13 shows a monthly calculation of rainfall, evapotranspiration, soil moisture deficit and change in groundwater storage for the Norchard Drift. The recharge budget data is an average weighted by area for the catchment area. The increase in discharge between December and early February is a direct response to recharge and indicates that although the discharge station is both geologically distant from the recharge area and isolated by the presence of a ring of drainage barriers in the Coleford High Delf coal seam, there is a surprisingly rapid response in discharge. This may be related to a combination of four factors:

(i) The free-drainage level coal drainage barriers have little effect in controlling the amount of recharge to the deep basin and do not discharge the majority of recharge to the surface rivers. This would indicate that they may be either breached or when ponding occurs in the mined void leakage through the adjacent Pennant Sandstone to the deep basin is present (see chapter 6).

(ii) The initial movement of recharge waters is dominated by fast fracture flow in the Pennant Sandstone.

(iii) When recharge waters reach the saturated zone, groundwater is displaced from storage and rapidly discharged (analogous to a pressure wave).

and (iv) The rapid transfer and flow of groundwater is concentrated within the major haulage roadways which run at low gradients around the edge of the basinal structure of the Coleford High Delf coal seam converging to the south and finally discharging at the Norchard Drift (Figure 5.14).

The monthly changes in storage indicate that all the recharge has occurred during the months of December, January and February, and the total change in storage over the water budget period was equal to 0.5×10^{6} m^{3}. This value when equated over the Coleford High Delf catchment area represents an 18 mm effective rainfall amount (excess in the recharge amounts), or an 8 % error in the discharge measurments (total discharge 6.2×10^{6} m^{3}).

5.6.2 THE YORKLEY AQUIFER.

Figure 5.15 A., shows the cumulative monthly discharge for the New Mills gauging station, and the flow proportions that are derived from Pennant free-drainage levels, Supra Pennant runoff, Supra Pennant free-drainage and the Yorkley Aquifer. The monthly cumulative flow for the Yorkley Aquifer (Figure

FIGURE 5.13 : Rainfall, evapotranspiration, soil moisture deficit, effective rainfall, discharge and storage changes for the Norchard Drift.

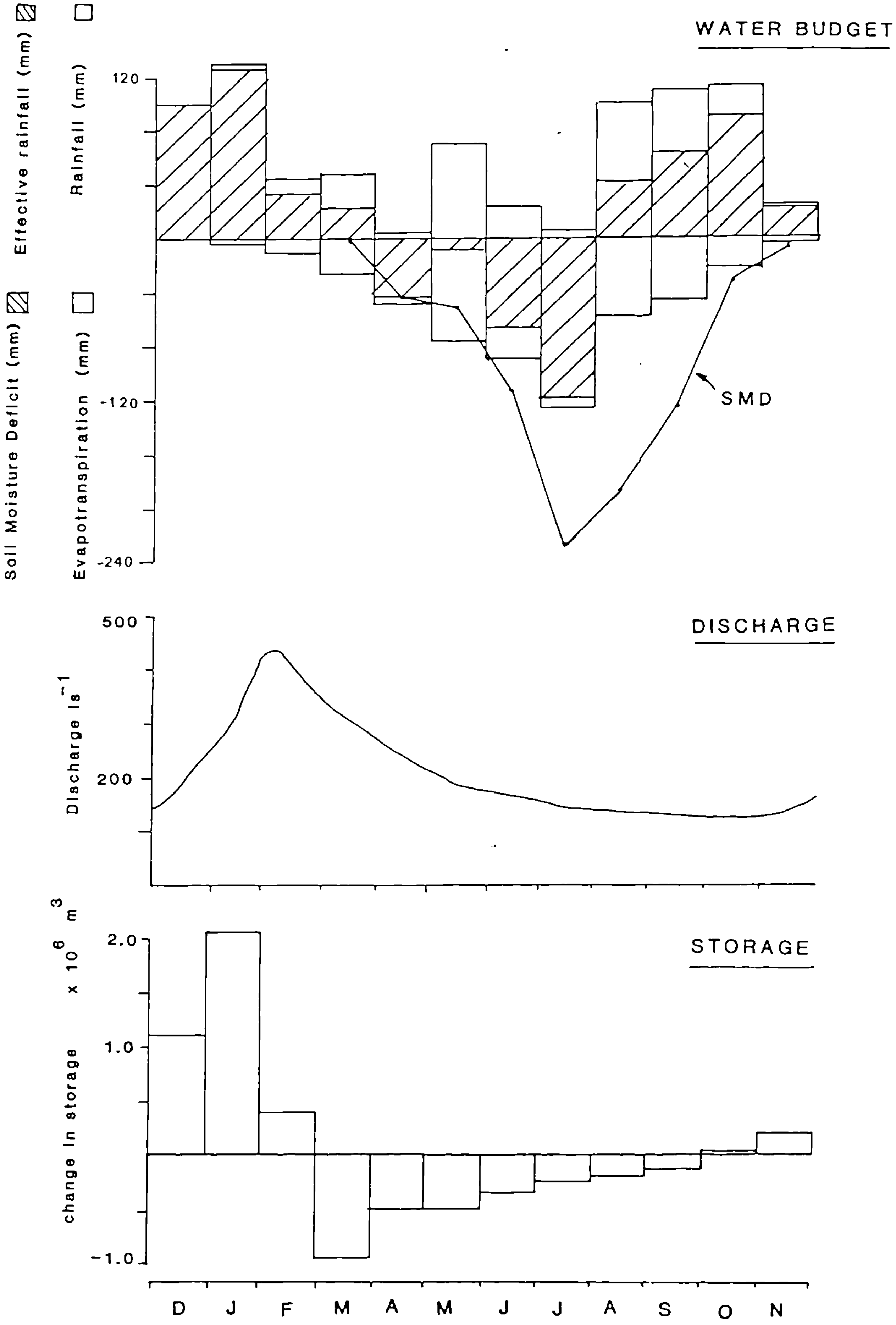


FIGURE 5.14 : Map of the Coleford High Delf coal seam workings showing the major haulage roadways which circumnavigate the deep basin.

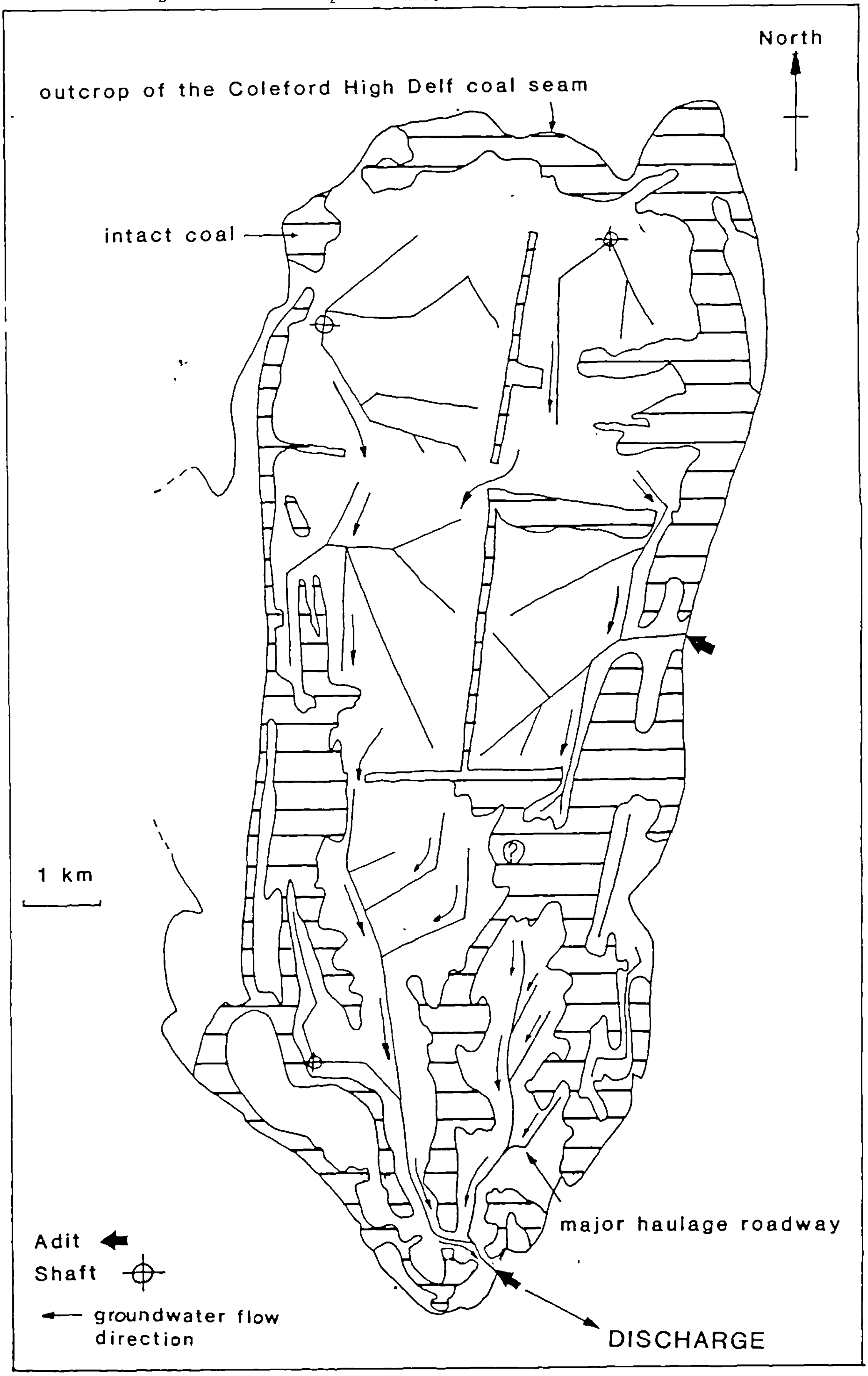


Figure 5.15 A

Monthly cumulative discharge for Cannop Brook at New Mills subdivided into Supra Pennant drainage, Supra Pennant and Pennant Free Drainage Level discharges and Yorkley Aquifer discharge

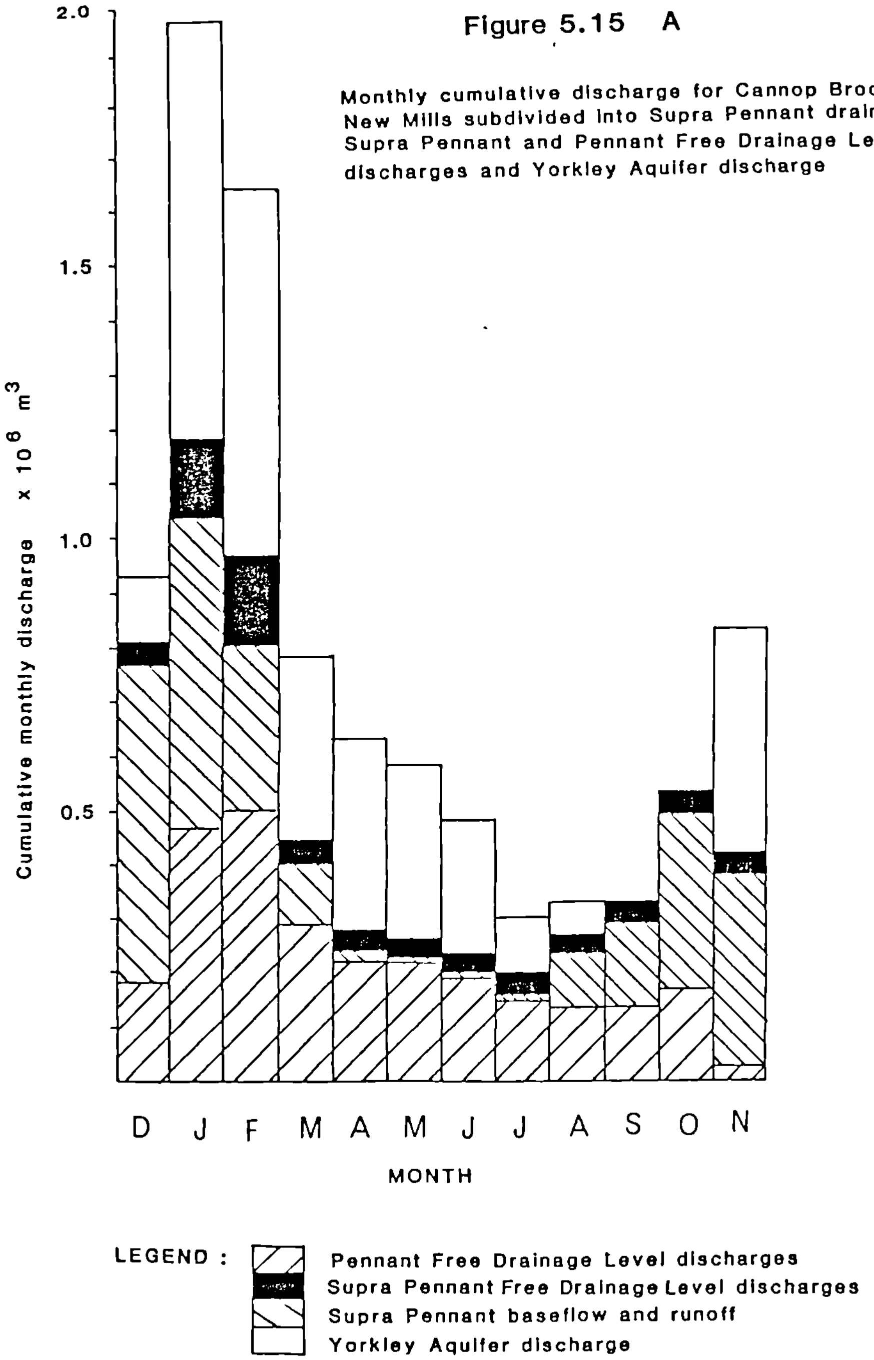
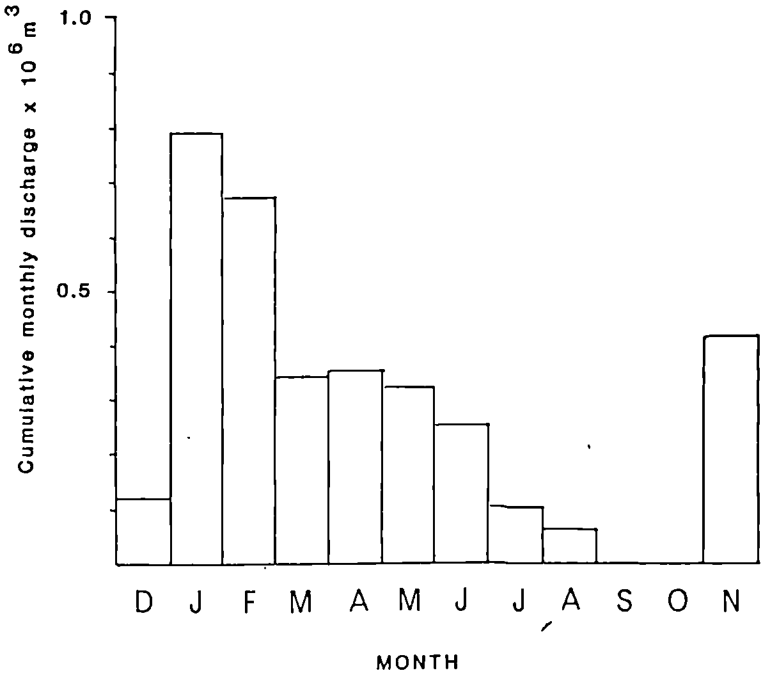


Figure 5.15 B

Calculated monthly cumulative Yorkley Aquifer discharge at New Mills, Cannop Brook.



5.15 B) shows a similar shape to that for the Norchard Drift, except that the peak discharge is during the month of January compared with February. The discharge recession continues until August. With a marked stable discharge period between March and June. During the months of September and October no detectable amounts of Yorkley groundwater were measured in the Cannop Brook. This may be due to either a low flow calibration gauging error for the stage discharge relationship at the New Mills site indicating that if flow was present the volume was small, or that there was no Yorkley groundwater discharge. Unfortunately due to the diffuse outflow of the Yorkley Aquifer it is not possible to quantify in any more detail the hydrogeological characteristics of the aquifer from the data presented. This could be the concern of future research work.

5.7 SUPRA PENNANT GROUP WATER BUDGET.

The water budget for the Supra Pennant Group is simpler in form than that for the Pennant, because the coal seams of the Lower Division of the Supra Pennant Group (referred to as the Brazilly Aquifer) are wholly drained by a series of ferruginous springs and two free-drainage levels, and the Upper Division (referred to as the Serridge Aquifer), is drained by numerous small springs and one free-drainage adit (Figure 5.16).

The Brazilly Aquifer catchment is 6.4 km^2 in area, and lies between the outcrop of the Brazilly and Shaftnel coal seams. This includes all the major coals located within the Supra Pennant Group (Brazilly, No Coal, Churchway, Smart, Rockey, Starkey, Lowery (Parkend High Delf) and Twenty Inch coal seams). The major workings where confined to the thicker seams, namely the Churchway, Rockey, Starkey, Twenty Inch, and Lowery, and the extent of workings are shown in figures 6.1 and 6.4. The Brazilly coal seam is underlain by thick shales and this forms the base of the aquifer unit acting as an aquiclude. Between the coal seams lie thin seat earth clays, shale layers and intermediate sandstones. The seat earth clays are not as thick as those encountered in the Pennant Group (generally 0.1 - 0.3 m compared to 1.0 - 2.7 m) and w ere often removed with the coal seam in the Supra Pennant Group because the coal seams themselves were thinner (typically 0.9 - 0.3 m in thickness). This then allowed larger haulage roadways to be constructed for easier access. Therefore many of the intermediate aquicludes (seat earth clays) have been removed allowing easier movement of groundwater between seams, this is further enhanced by the 'spoiling' or 'flaking' of the shale roof caused by subsidence.

The Brazilly catchment is drained by two free-drainage levels, the Independent Level (or Whitecroft Waterlevel) (NGR 61850640) and Cannop Level (NGR 061101140), and three major ferruginous springs. Namely, Parkend Colliery Spring (NGR 61800765), Old Bobs Colliery Spring (NGR 60951255) and Speculation Colliery Spring (NGR 60951255) (Figure 5.16). Both the Cannop and Independent Levels are driven across the coal seams of the Supra Pennant, intersecting all the coal seams between the Brazilly and the Lowery. However, it is also known that all the coal seams above the Lowery drain to these two levels (see Chapter 6). The Parkend Colliery Spring is located at the junction between the Brazilly coal seam and the Cannop Fault Belt, and drains water from the Brazilly coal seam workings. The Old Bobs Colliery and Speculation Colliery Springs are all located on the outcrop of the Lowery coal seam. No surface streams emanate from this aquifer. Therefore the total volume of recharge is discharged via the ferruginous springs and free-drainage levels.

The Serridge Aquifer is situated directly above the Brazilly Aquifer and forms the upper most aquifer in the coalfield basin (Figure 5.16). The highest part of the catchment is associated with the Woorgreen coal seam and this is drained by the Woorgreen adit. The hydrology is dominated by the presence of thick stagnogley clay soils which are very impermeable and produce large volumes of surface runoff. However, groundwater is discharged from two series of springs which drain the major sandstones of this upper most division of the Supra Pennant Series. These are situated where both the Crabtreehill and Serridge Sandstones lie above shale layers.

The total input into the Supra Pennant outcrop is equal to 7.44 x 10^6 m^3 (Figure 5.10) of which 1.51 x 10^6 m^3 is recharge and 5.93 x 10^6 m^3 (79.7 %) is runoff. Of the recharge amount 10.6 % (0.8 x 10^6 m^3) is discharged from Supra Pennant free-drainage levels of the Brazilly Aquifer (Cannop Level and Independent Level), and the remaining 48 % is discharged by the Serridge Aquifer. This is dominated by 0.71 x 10^6 m^3 (9.5 % of the total recharge) being discharged by the small groundwater fed springs. Only 0.01 x 10^6 m^3 (0.1 % of the total rechrge) is discharged by the Woorgreens adit.

5.8 CONCLUSIONS.

The water budget conducted for the whole coalfield has indicated that typical errors associated with these techniques can be small and in this example only + 4.75 %. The error was an excess of recharge and this can be explained by either an over estimate of net rainfall amounts or under estimate of discharge at the major discharge outlets on the Cannop Brook, Blackpool Brook, Lydbrook or

Cinderford Brook. Further budgets have determined the catchment areas for the major aquifer units present. The catchment areas determined by these budgets agree with those predicted from an interpretation of the geology and hydrogeological properties of Coal Measure Rocks (Chapter 2). The aquifers predicted were correct for those associated with both mined (Coleford High Delf and Brazilly Aquifers) and unmined coal seams (Yorkley Aquifer). This indicates that although coal extraction occurs where seat earth clays are thick or not removed (the Coleford High Delf Aquifer), the clay remains intact and forms the regional aquiclude. Where the seat earth clays have been removed (Brazilly Aquifer) vertical groundwater movement between mined coal seams and adjacent sandstones occurs and the only controls of vertical groundwater movement are shale layers unaffected from spalling or flaking or mining subsidence. Where the shales are thin they form aquitards and where they are thick, aquicludes are present.

The Coleford High Delf Aquifer water budget indicated that only 29 % of outcrop recharge was discharged via the free-drainage levels, the remainder moving to depth in the deep basin and being discharged via the Norchard Drift.

The water budget for the Yorkley Aquifer identified a diffuse discharge outlet for the deep basin via the Cannop Brook (this was not apparent until the water budget was conducted). Similar discharge outlets may exist in other coalfields and it is not unreasonable to speculate that a diffuse discharge outlet existed to the Cannop Brook from the Coleford High Delf Aquifer before mining occurred.

The Brazilly Aquifer water budget identified that although the aquifer is drained from five locations, comprising a sequence of multiple cyclotherm units, the many aquifers and aquitards present can be considered together and on a regional scale assumed to behave as a separate aquifer unit.

It cannot be disputed that there are errors associated with the use of these techniques as the results and calculations are dependent upon the accurate measurement of the parameters: rainfall, interception, evapotranspiration, and discharge. However, the small differences that do occur are considered acceptable, and can be explained by either one or a combination of minor hydrological processes, such are inter aquifer leakage or small unmonitored discharge outlets. Although these later processes are of little significance to specific groundwater resource management studies for site appraisals, they do however, provide useful data and further hypotheses towards understanding the more detailed regional hydrogeological behaviour of Coal Measure Aquifers. The results from the water budgets presented here warrant the use of this low cost and reproducible technique for catchment area and groundwater flow path determination on the regional aquifer (macro) scale, before more detailed computer based groundwater modelling is undertaken.

This chapter and chapter 2 has considered the determination and analysis of regional groundwater catchment areas and aquifers within the deep basin or deep groundwater circulation of the Forest of Dean Coalfield. The next chapter will use similar water budget techniques to analyse the major processes present that control groundwater movement in the shallow groundwater circulation, where drainage is dominated by the presence of numerous free-drainage levels.

CHAPTER 6.

THE ESTABLISHMENT OF GROUNDWATER FLOW PATHS AND PATTERNS IN ABANDONED COAL MINED AQUIFERS: 2. THE ROLE OF COAL BARRIERS AND FREE-DRAINAGE LEVELS.

6.1 INTRODUCTION.

The previous chapter has presented and discussed the results of water budgeting methods for determining the relative discharges from and identifying the major aquifer units present in abandoned coalfields. However, frequently in groundwater resource management and pollution protection operations there is a necessity for rapid and simple techniques to demonstrate catchment areas for discharging adits and free-drainage levels, for instance to assess the effects of landfill and opencast coalmining operations. Many regional Water Authorities, District Councils and Local Authorities employ the use of (i) topographical and geological maps and (ii) coal mine abandonment plans for catchment determination. However the reliability of this is not known.

This chapter presents the results and conclusions from water budgeting techniques which have been used to (i) indicate the role of coal barriers in determining groundwater flow paths and groundwater recharge mechanisms present in abandoned coal workings and (ii) assess the validity of using coal mine plans for catchment area determination.

The water budgeting method employed is identical to that outlined in section 5.2 of the previous chapter. By using the total discharge, the change in storage over the water budget period and the effective rainfall amounts (equation 6.1) the catchment area for each of the levels can be calculated. The change in storage over the water budget period is calculated from the recession curve.

$$\text{Catchment area } (m^2) = \frac{Q \quad +/- \; \Delta S}{\text{Eff. P}} \qquad \text{----- Equation 6.1}$$

Where : Q = the total discharge volume (m^3)

: S = the change in storage (m^3)

: Eff. P. = the total effective rainfall (m)

This catchment area can then be compared with that determined from the available coal mine plans and geological structure.

The structure of the chapter takes two discrete parts, firstly the Supra Pennant Group free-drainage levels is considered, and secondly, the Pennant Group free-drainage levels. In both cases, the results and analysis conclude with the development of a conceptual model, for use as a groundwater management tool. The two models illustrate the role of coal barriers and free-drainage levels in controlling groundwater flow paths.

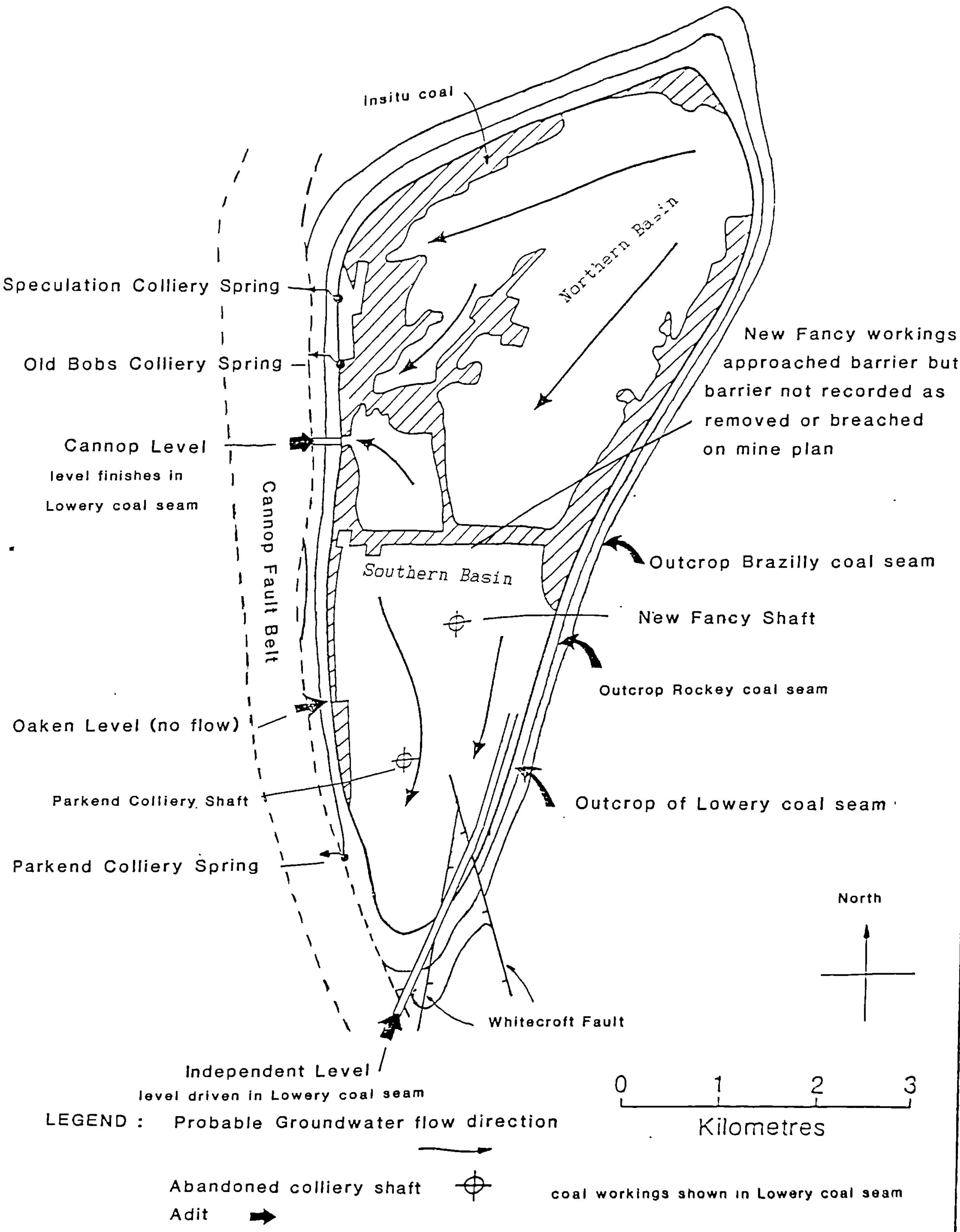
6.2 DETAILED AQUIFER CLASSIFICATION, CATCHMENT AREA DETERMINATION AND HYDROGEOLOGICAL BEHAVIOUR OF THE SUPRA PENNANT GROUP.

In summary, the predominantly argillaceous Supra Pennant Series forms a basin structure, the axis dipping from north to south with the western outcrop at a lower elevation than the eastern (Chapter 2). It is primarily drained by two free-drainage levels, the Independent Level (or Whitecroft Water Level) (NGR 61850640) and the Cannop Level (NGR 61101140)(Figure 6.1). Because of the method of coal working (discussed in Chapter 3 section 3.2) there are five springs which drain from the western outcrop into the Cannop Brook. The three major springs which were occasionally monitored are; Parkend Colliery (NGR 61800765); Old Bobs Colliery (NGR 60951255) and Speculation Colliery (NGR 6110 1345), which all have discharges of <5 ls^{-1}, while the remaining two have maximum flows of <0.1 ls^{-1} and were not monitored.

The Independent Level is driven at an inclination of 1:295, across the western outcrop of the Lower Division coal seams (Brazilly to Lowery) until it re-intersects the Lowrey coal where it runs in a north-easterly direction parallel to the eastern outcrop. The Cannop Level is also driven from the Brazilly to the Lowery coal seam (Figure 6.1) but only trends in an orthogonal direction to the outcrop and ends at its intersection with the Lowery coal seam.

The discharge graphs for both Independent and Cannop Level, have a similar shape (Figures 6.2 and 6.3), with a rapid rise in discharge (December - February) followed by a slow recession, and a period of constant discharge. The initial response to recharge and peak discharges for both levels are synchronous. However, unlike that for the Independent Level, the Cannop Level hydrograph shows a double peak response. This can be explained by a combination of the expected catchment areas, aquifer storage characteristics and rainfall distribution. The peak discharges are 14 ls^{-1} for the Cannop Level and 48 ls^{-1} for the Independent level, this suggests that the catchment area for the Independent Level is larger than that for the Cannop Level and would also lead to the primary conclusion that the aquifer storage volume within the catchment areas differ similarly (discussed in Chapter 7). The rainfall pattern over the

FIGURE 6.1 : Diagram showing discharges, outcrop and workings in the Lowery coal seam for the Brazilly Aquifer of the Supra Pennant Group.



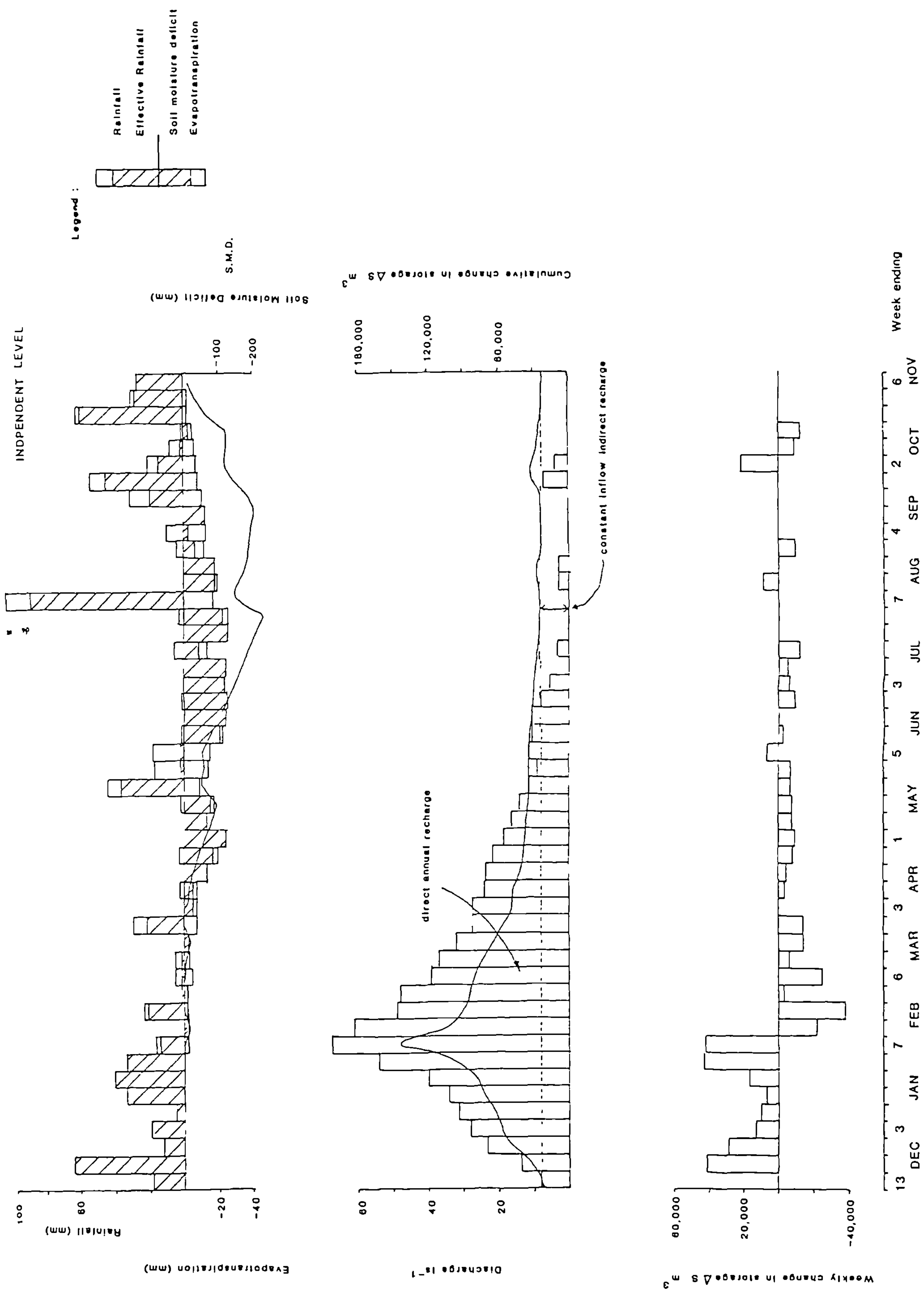


Figure 6.2 : Rainfall, evapotranspiration, soil moisture discharge and storage changes for the Independent Level.

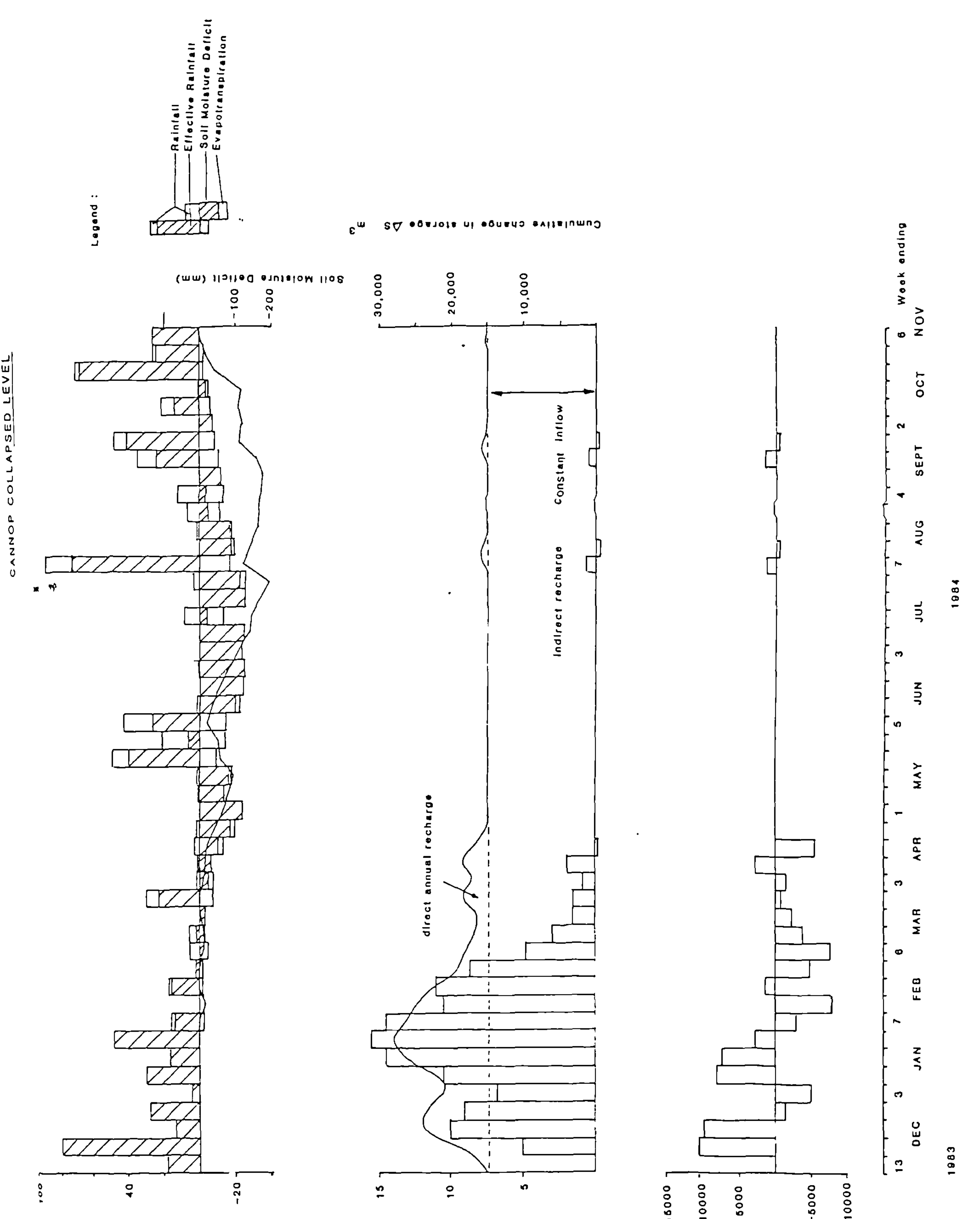


FIGURE 6.3 : Rainfall, evapotranspiration, soil moisture, discharge and storage changes for the Cannop Level.

rise in discharge period also indicates a general bimodal shape. Therefore the decrease in discharge at the Cannop Level between the 27th December and 10th January represents a reduction in storage because the volume of recharge is not large enough to maintain the flow, while the Independent Level discharge is maintained (it does not increase dramatically and the previous rapid rise in discharge is lessened). Also the discharge recession occurs over a much longer time period for the Independent Level (7th February until 17th July), than for the Cannop Level (7th February until 24th April). The length of recession directly reflects the total volume of storage within the aquifer being drained (the longer the recession the larger the volume of storage) and this therefore compliments the initial conclusion that the storage within the Cannop Level catchment area was less than that within the Independent Level catchment area.

After this period of recession the discharges for both free-drainage levels remain at a constant level, 7.5 ls^{-1} for the Cannop Level and 9.0 ls^{-1} for the Independent Level. There are only two possible situations where a constant discharge can be attained, these are :

(i) where the discharge is controlled by a constant head

and (ii) where the discharge is maintained by constant leakage (a constant inflow) from a much larger reservoir.

It is difficult to envisage the first situation and the later is discussed here. An inflow of this type within the Supra Pennant Group of rocks would originate from leakage from confined aquifers at elevations above those that the Cannop and Independent free-drainage levels drain directly. These aquifers would be within the No Coal, Twenty Inch, and Shaftnel coal seams of the Lower Division (these are above the Lowery coal seam in which the Independent and Cannop Levels are predominantly driven) and the Serridge and Crabtreehill Sandstones of the Upper Division. Therefore as the constant discharge actually represents a constant inflow which occurs throughout the water budget time period, the response to direct annual recharge and the total direct recharge volume must be equal to the rise and fall in discharge levels (that is to say the hydrograph 'bump', referred to as the recharge hydrograph (Figure 6.2 and 6.3)), and that the constant discharge is composed of indirect recharge originating from another aquifer unit. The constant discharge volume 7.5 and 9.0 ls^{-1} is small because the leaking aquitard, most probably a shale has a low permeability, also the discharge remains constant as there is little change in head.

Therefore the primary conclusion can be made that the direct recharge area for the Independent and Cannop levels lies between the Lowery and Brazilly coal seams (Figure 6.1). This can be proven by using the water budgeting method outlined above.

The geological outcrop area for the Lower Division of the Supra Pennant coals (Brazilly to Lowery coal seams) is 6.4 km^2 and equating the effective rainfall (effective recharge after considering the runoff component using the run-off coefficients determined in chapter 5, and soil moisture and evapotranspiration budget calculations also discussed in chapter 5) for the thiessen polygons this gives an annual total recharge of 0.31 x 10^6 m^3, compared with a cumulative discharge of 0.28 x 10^6 m^3.

Table 6.1 : Water budget calculations to determine the catchment areas of the annual direct recharge component of the free-drainage level discharges.

Catchment Area km^2	Effective Recharge m	Discharge Location	Cumulative Discharge m^3 x 10^6
6.4	0.048	Independent Level	0.19
		Cannop Level	0.03
		Parkend Colliery Spring	0.03
		Old Bobs Colliery Spring	0.02
		Speculation Colliery Spring	0.01
Total Recharge :	0.31 x 10^6 m^3	Total Discharge :	0.28 x 10^6 m^3

This gives an imbalance of 8.2 %, which is a cumulative discharge deficit, this may be partially explained by unmentioned minor seeps which were not monitored. It can be concluded that the catchment area above, which was interpretated from the geology, hydrology and mining records is correct.

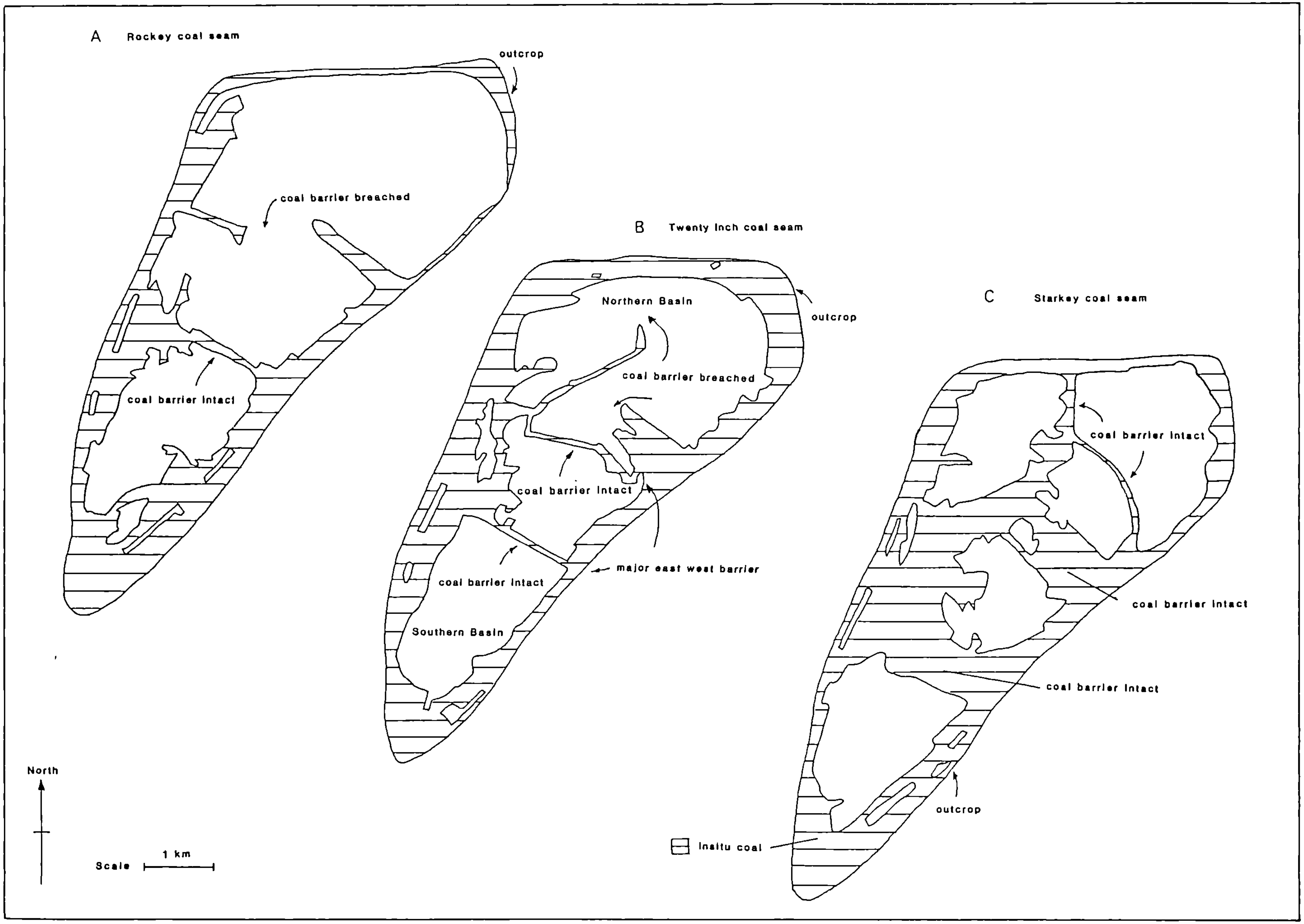
Before, further interpretation of the Cannop and Independent catchment areas it is important to discuss the locations and drainage areas for the Parkend Colliery, Old Bobs Colliery and Speculation Colliery springs. The Parkend Colliery spring is located where the Rockey coal seam and the Cannop Fault Belt meet (Figure 6.1), and therefore it is suggested that this spring only drains water from the Rockey coal seam workings (but may contain a Pennant Group Yorkley Aquifer flow component as it is located along the Cannop valley south of the Yorkley Aquifer peizometric surface (see chapter 5)). No abandonment plans were located for the Parkend Colliery except those shown in Figure 6.1, which indicates that the Lowery coal seam exclusively drains to the Independent Level and no Lowery component would be discharged from Parkend Colliery spring. The mine layout and mining method for the Rockey coal seam is indentical to that for the Lowery coal seam with a major east-west barrier across the basin (Figure 6.4 A) (the same situation is also present in the Twenty Inch and Starkey coal workings (Figure 6.4 B and C)). Therefore if the east-west barrier is intact in the Rockey coal seam, as the mine plans suggest, the southern sector should drain to the Parkend Colliery spring and Independent Level, while the northern sector drains only to the Cannop Level, (because the Old Bobs Colliery and Speculation Colliery springs are all located on the outcrop of the Lowery coal seam)(Figure 6.1). Another distinction between the Parkend Colliery spring and the other discharges is that the flow does not decline to a constant discharge but shows a continued discharge recession, this would indicate that the spring drains an aquifer lower in the sequence than the Lowery coal seam in which the Cannop and Independent Levels are located because these levels intersect and drain the constant leakage from above the Lowery coal seam. The continued downward movement of the leakage being impeded by the 1.0 m thick seat earth floor of the Lowery coal seam. Furthermore the Old Bobs Colliery spring does show a constant discharge volume after the recharge recession, while the Speculation Colliery spring ceases to discharge after the recharge recession. This later condition is not interpreted as the spring discharging another aquifer other than the Lowery coal seam, because mine plan documentation shows that this colliery did exclusively work the Lowery coal seam (Figure 6.1). The cessation of flow is therefore interpret ed as the leakage from the aquifers above draining southwards to the Cannop Level and Old Bobs Colliery spring, and by passing the Speculation Colliery spring.

The mining records also indicated that a major east-west coal barrier existed in the Lowery, Starkey and Rockey workings (Figures 6.1 and 6.4 C and D) which divided the mined coals into two separate drainage basins (refered to as the northern basin and southern basin) (Figure 6.4 B). These separate basins would be recharged by the outcrop that is also divided by the coal barrier. There are no east-west barriers in the Brazilly, No coal, Breadless, Smart and Churchway High Delf coal seams, but these coals seams are intersected by the Cannop Level and Independent Level cross-measure drivages. The amount of flow which would be intersected by the Cannop Level would be small as most would be confined in the central basin and drains southwards to the Independent level.

Therefore the interpret ed catchment areas are :-

(i) The Cannop Level, Speculation Colliery Spring and Old Bobs Colliery spring drain the outcrop of the Rockey coal seam to the seat earth clay of the Twenty Inch coal seam (thus including the sandstone above the Lowery coal seam). north of the east-west coal barrier. This is an area of 2.0 km^2. (Figure 6.5)

Figure 6.4 : Abandonedworkings in : A - Rockey, B - Twenty Inch and C - Starkey coal seams of the Supra Pennant Group.



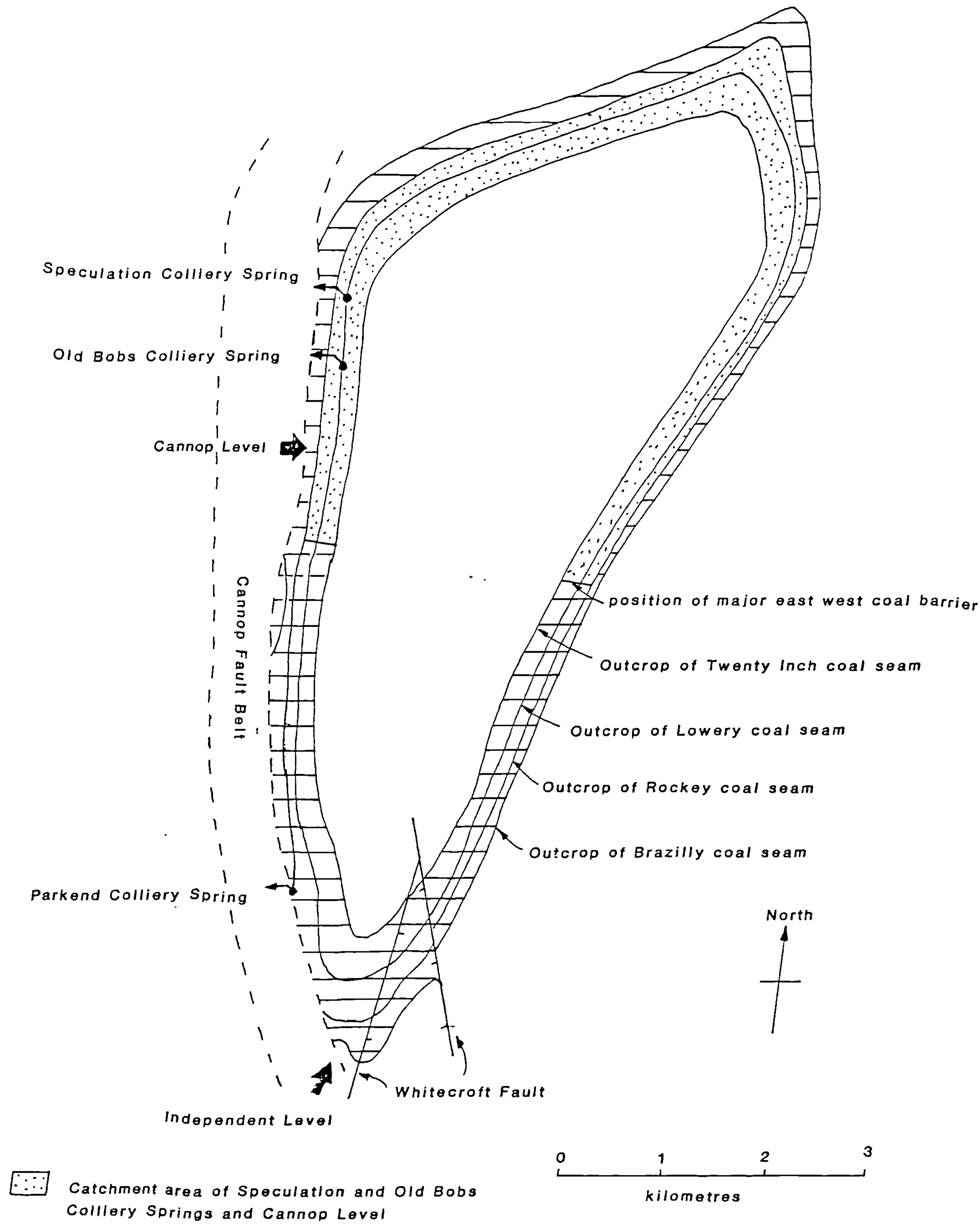
and (ii) The Independent Level and Parkend Colliery spring drain the sequence of rocks from the outcrop of the Brazilly to the seat earth floor of the Rockey coal seam for the whole Supra Pennant Group, plus the outcrop of the Rockey to the seat earth clay below the twenty inch coal seam (thus including the sandstone above the Lowery coal seam), south of the east-west coal barrier. This is an area of 4.5 km^2 (Figure 6.5).

By using the catchment area determination method (discussed above) the catchment areas for both basins can be determined. The change in groundwater storage is very small for both levels (Figures 6.2 and 6.3) (this was only calculated for the levels, because, insufficient data was available for the spring sites) because the recharge hydrograph measures the total inflow (rising limb) and total outflow (falling limb), with the discharge returning to the same level as that at the start. It should be stated that if it was not for the constant discharge component the levels would be dry during the summer months. However the change in storage was very small (0.02 % for the Independent Level and 3.2 % for the Cannop Level) this can be explained by errors in the gauging method, frequency of discharge measurements (Cannop Level was weekly and Independent Level was continuous), and arithmetic approxi mations associated with the recession curve calculations. Furthermore, these water budget calculations assume that the leakage component of discharge remains constant during the direct annual recharge hydrograph.

The water budget catchment area for the Lower Division outcrop from the Brazilly to the Rockey coal seam plus the outcrop for Rockey, Starkey and Lowery coal seams south of the east-west barrier, which all drains to the Parkend Colliery Spring and Independent Level is 4.4 km^2. Which compares well with the predicted catchment area of 4.5 km^2. While that for the outcrop of the Rockey coal seam to the Lowery coal seam in the northern basin is equal to 1.4 km^2 compared with 2.0 km^2. The difference in the latter is equal to the difference between the total catchment area from the geological outcrop of 6.4 km^2 and that calculated from the water budgets of 5.9 km^2.

It has now been proven that the recharge catchment areas for the free-drainage levels and springs is the outcrop area of the Lower Division, therefore the leakage component has to originate from above the Lowery Seam. Above the Lowery coal seam lie the Foot, Twenty Inch and Shaftnel coals. The Foot is not continuous and therefore cannot be regarded as a complete areal aquitard. Above lies the Twenty Inch coal seam, the largest and only extensively worked coal seam above the Lowery (Figure 6.4 B). It is therefore suggested that the

Figure 6.5 : Catchment areas within the Brazilly Aquifer of the Supra Pennant Group.



leakage must either originate from this coal seam (a perched aquifer recharged from the outcrop of the Lower Division above the Twenty Inch coal seam) or from recharge originating from the Serridge and Crabtreehill Sandstones which lie above. By equating the total volume of water that has been discharged from the leakage for all the discharges (the total leakage for the water budget period (334 days) was 0.56 x 10^6 m^3 (Cannop Level 0.21 x 10^6 m^3, Old Bobs Colliery Spring 0.06 x 10^6 m^3 and Independent Level 0.29 x 10^6 m^3)) with the surface area of the Twenty Inch coal seam (20.4 km^2), the specific discharge of the aquitard, leakage velocity or permeability (because it has the units of L/T) can be calculated. This is 0.082 x 10^{-3} md^{-1}.

If it is assumed that the two major east-west barriers (which are intact) do not leak (i.e. lose water from the northern to the southern basin), the leakage for the Lowery coal seam south of the east-west barrier is equal to 0.29 x 10^6 m^3, where as that calculated for the Twenty Inch coal seam surface area south of the east-west barrier (6.46 km^2) by using the specific discharge of 0.082 x 10^{-3} md^{-1} computes as 0.18 x 10^6 m^3, and that north of the barrier (13.9 km^2) is 0.38 x 10^6 m^3 where the actual recorded value was 0.27 x 10^6 m^3. This combined imbalance thus indicates that 0.11 x 10^6 m^3 moves through the barrier in the Lowery coal seam (Figure 6.1) and is lost from the northern basin to the southern basin. This analysis, assumes that no flow occurs in the ponded upper aquifer from which the leakage originates, this is most likely the case as no major discharge outlet exists, and the few springs that are located along the lower southern most outcrop area only drain the 'overflow' of direct annual recharge. Also this analysis assumes that the specific discharge is spatially constant over the 20.4 km^2 surface area of the worked Twenty Inch coal seam..

By assuming that all the difference between the northern and southern catchment leakage values (0.11 x10^6 m^3) drains through the Lowery coal seam east-west coal barrier (and that it remains totally intact), the permeability of the barrier can be calculated, by using Dracy's Law (Equation 6.2).

$$Q = K.i.A \quad .... \quad \text{Equation 6.2}$$

Where Q= discharge (m^3d^{-1})

K= permeability or Hydraulic conductivity (md^{-1})

i= hydraulic gradient.

A= cross-sectional area (m^2)

The coal barrier in the Lowery coal seam is 2600 m wide (east to west) and 0.6 m in thickness, and therefore has a cross-sectional area of 1560 m^2. Above the Lowery coal seam lies 3.0 m of shale (geology log of the Parkend Colliery Shaft). It is assumed that the shale acts as a confining layer (aquitard) and that the abandoned workings in the Lowery coal seam is the aquifer unit. The hydraulic gradient within the Lowery coal seam can be calculated by the differences in elevation between the Independent and Cannop Levels, because they both directly drain the Lowery coal seam and are located either side of the barrier. The permeability of the coal barrier is 37 md^{-1}. This is considerably higher than the recorded values for coal permeability. If equation 6.2 is calculated with the maximum and minimum values for coal permeability (0.15 and 0.65 md^{-1}) (reported in chapter 2), the maximum and minimum flow through the barrier for the water budget period is 0.01 x 10^{6} and 0.04 x 10^{6} m^{3} respectively. This is between 2.75 x and 11 x smaller in volume. However, historic documents held by the Deputy Gaveller do indicate a degree of uncertainty as to the status of the east-west barrier to the north of the New Fancy colliery shaft (Figure 6.1). It is possible that the east-west barrier was punctured allowing a direct flow of water from the north-east to the Independent Level. If this was the case the flow through the puncture would be equal to the difference between the calculated flow volume through an intact barrier (because the remaining barrier is very much greater in cross-sectional in comparison to the area of barrier removed, and because, the barrier is predominantly under confined conditions to the north and south) and the calculated flow amount from the observed discharges. This calculates that the flow through the puncture would be between 3.5 and 2.4 ls^{-1}. However, the Lowery east-west coal barrier is 46 m in thickness and the effectiveness of excluding water movement from the north to the south (for instance if no barrier existed the 0.27 x 10^{6} m^{3} of leakage which drains from the Cannop Level and Old Bobs Colliery Spring would drain to the Independent level) is 71 %. The only reported values for coal barrier effectiveness for comparison are those of Miller and Thompson (1974) who quote values of 75 % for a barrier of 30 m thickness, and 53 % for 15 m. In conclusion, the magnitude of the volume of groundwater which appears to pass from the northern to the southern basin precludes the precise definition of its origin and flow path. Also the integrity of the east-west barrier in the Lowery coal seam remains unproven.

6.3 A CONCEPTUAL MODEL OF GROUNDWATER FLOW PATHS IN AN ISOLATED SYNCLINAL COAL MEASURE BASIN.

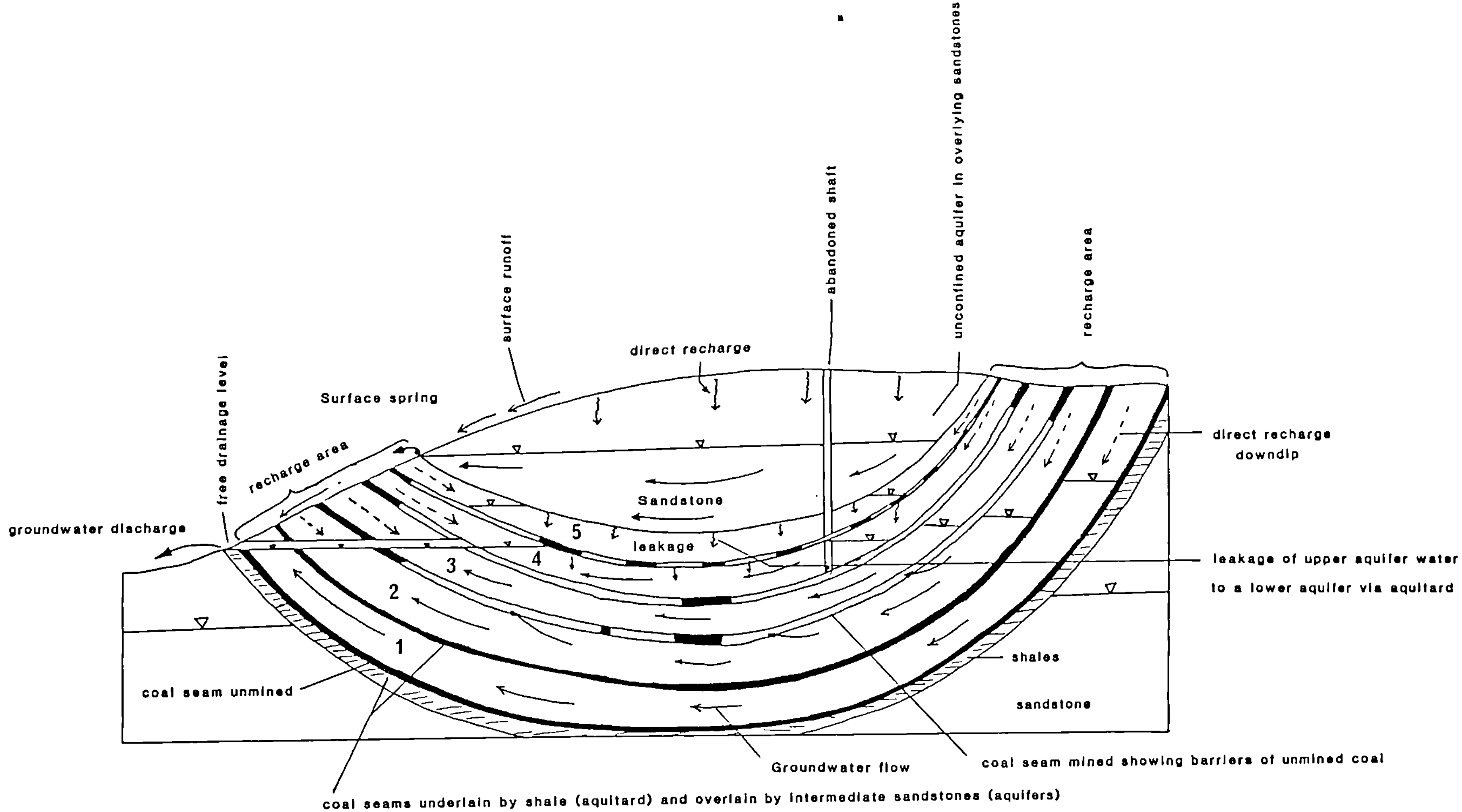
From the results of the Supra Pennant Group catchment area determinations it is possible to predict the general hydrological and hydrogeological behaviour of an isolated synclinal Coal Measure basin because these calculations have indicated the hydrological roles played by coal barriers, free-drainage levels, aquitards and aquifers present, and how these determine groundwater flow paths and patterns.

The model is of a conceptual form and is shown in Figure 6.6. The important control on the presence of the aquifers (within the sandstones and mined coal seams) is the effect of the shale layers (aquitards) which lie above and below the coal seams. All aquifers which occur between the numerous coal seams are confined aquifers (aquifers 1, 2, 3 and 4). The free-drainage level controls the elevations of the rest water levels within the confined aquifers that it intersects, this is true of even the aquifers for which the relevant coal seam was not mined, because where the main cross-measure drivage intersects the aquifer this is the only possible outlet for the groundwater (however, this is an assumption based on the Supra Pennant experience). If this was not the case the aquifer would drain by a series of springs around the lowermost outcrop of the coal below. The aquifers above those that are intersected by the free-drainage level can be classified into two groups. Those that are associated with the coal seams directly above the free-drainage level and are similarly confined aquifers (aquifer 5). These drain by vertical leakage into the lower aquifers which are subsequently drained by the free-drainage level, which is the case present in the Supra Pennant Group. However this case is only present because the recharge area at the outcrop is very small, if the recharge volume was greater than the leakage volume this aquifer would also drain via springs at the lowest outcrop location. The final aquifer is that present in the larger overlying sandstones and is the only unconfined aquifer present in the system. This drains by a combination of the two systems outlined above, vertical leakage and outcrop springs. It is worthy to note that in this situation if the free-drainage level does not intersect the coal seams at their lowest point (their greatest depth) any abandoned workings towards the centre of the basin will become totally waterfilled. This is case for the coal seams associated with aquifers 3 and 4. The coal seams above the free-drainage level which were worked from deep shafts would similarly become waterfilled (aquifer 5).

6.4 CATCHMENT AREA DETERMINATION AND HYDROLOGICAL BEHAVIOUR OF THE PENNANT GROUP FREE DRAINAGE LEVELS.

The previous section has examined the hydrogeological behaviour of the Supra Pennant Group. This section is concerned with the Pennant Group. The previous chapter (Chapter 5) has detailed the aquifer units present in the Pennant Group

FIGURE 6.6.



Conceptual model of groundwater flow, aquifer location and free drainage level dominated drainage in an isolated synclinal coal measure basin.

Aquifers 1 and 2 drain to free drainage level although unmined coal seams exist because free drainage level intersects them

Aquifer 3 drains to free drainage level because mined coal seam is intersected by coal seam free drainage level

Aquifer 4 drains to free drainage level in similar manner to aquifer 3

Aquifer 5 is above main drainage level, leakage to lower aquifer through aquitard occurs. This aquifer has a very small recharge area but leakage is greater than recharge therefore no outcrop springs are present. Leakage is at a constant rate (see text) because change in head is small over annual cycle and in particular analysed the deep basin Coleford High Delf and Yorkley Aquifer catchment areas. The calculations in this section are concerned with the hydrogeological behaviour and catchment areas of the shallow free-drainage levels, which drain the outcrop area of the Pennant Group.

The two major free-drainage levels are the Miles and Old Furnace Levels, these are analysed in detail. But data is also presented from four other levels because these outline specific problems which are associated with the techniques used for catchment area determination.

6.4.1. THE OLD FURNACE AND MILES LEVEL CATCHMENT AREA : DETERMINATION FROM ABANDONED COAL MINE PLANS.

The following section describes the definition of the Old Furnace Level and Miles Levels catchment boundaries in the Coleford High Delf coal seam from the interpretation of the available coal mine plans and structural geology. The catchment boundaries are shown in Figure 6.7 only known intact and removed coal barriers, insitu coal, major long-measure and cross-measure levels and haulage roadways are shown for clarity. This interpretation has involved the analysis of numerous historical documents and the catchment diagram is the combined interpretation of 23 separate coal mine abandonment plans of various scales and ages.

The Miles Level catchment area is simpler to define and will be considered first. Altogether the Miles Level drains 9 gales (Hopewell Engine, Mapleford Engine and Miles Level, Bixslade No. 2, Success and Endeavour, Winnel, Prosper (Gosty Knoll), Gentleman Colliers, Edenwell, and Coalway Hill Gale). All of these gales when initially formed and licensed for extraction contained boundary barriers of coal which would have retarded downdip drainage, however the combined analysis from available abandonment plans indicates that these barriers have either been totally or partially worked, or punctured to provide drainage. The western edge of the catchment area is defined as the outcrop of the Coleford High Delf coal seam, between the Quest Slade Valley and the New Hawkins Gale. The southern extremity of the catchment is partially defined where the Quest Slade Valley cuts east-west across the outcrop, but where the Hopewell Engine and Miles and Mapleford Engine Gales lie at depth below the increasing thickness of the Pennant Sandstone this is more difficult to clarify. There is an area of unworked coal where the Quest Slade Valley lies above the southern end of the Hopewell Engine and Miles and Mapleford Gales but the location of this is uncertain as both of these Gales are supposed to continue further south than the Quest Slade Valley. However, documentation for the southern most area of these Gales does not exist, although the NCB abandonment plans for the whole coalfield dating 1965 show that the area south of Quest Slade was worked from the deep basin colliery at Flourmill, and it is therefore assumed that a coal barrier was left to prevent water entering the deep basin mine. Further to this complication, there is also a record on one of the three available plans for the Miles and Mapleford Engine Gale that the long measure coal drainage barrier was punctured close to the Quest Slade Valley (marked A on Figure 6.7 and discussed in detail in Chapter 10). Therefore the catchment boundary has been assumed to be up dip from this partially removed long measure boundary.

The northern catchment boundary is defined as the area of unmined coal, where the boundary barriers for the Winnel, New Birch and Folly and Bixslade No.2 Gales lie against the Vallets Level No.2 Gale of the Old Furnace Level. Unfortunately no plans exist for the Coalway and New Hawkins Gales and the boundary is defined as where the boundary barrier would have been located. Further south, the boundary barrier has been partially mined to the north of the northern most Low Fault (marked B on Figure 6.7). Although this has been defined as the catchment boundary water movement from the Old Furnace Level workings to the Miles Level is possible, especially as the Old Furnace Level is at a higher elevation than the Miles Level (91 m compared with 76 m). Also as the Bixslade Lower Level long-measure drainage barrier has been removed groundwater flow will continue down dip to the Miles Level long-measure drainage barrier. To the north and adjacent to the Horse Fault, a small part of the Bixslade Lower Level long-measure drainage barrier remains intact, also, and more importantly the Bixslade Lower Level long-measure roadway traverses the Horse Fault (marked C on Figure 6.7) to connect with the major Vallets Level Haulage roadway (marked D on Figure 6.7). This small portion of the Bixslade Lower Level drainage barrier has been included in the Old Furnace Level catchment area because the combined roadways are known to discharge into the Old Furnace Level cross-measure level. The combined discharge from the long-measure level and the haulage roadway into the Old Furnace Level Adit (marked E on Figure 6.7) on the 28.6.84 was 9.4 ls^{-1}, unfortunately it was not possible to determine the flow proportions because access in to the long measure roadway was precluded by roof collapse and subsidence (Plate 6.1). The eastern boundary of the Miles Level catchment area is the intact long measure drainage barriers (marked F on Figure 6.7).

No area of the overlapping Yorkley coal seam has been included, because there are no recorded workings in the Yorkley coal seam from the Miles Level or

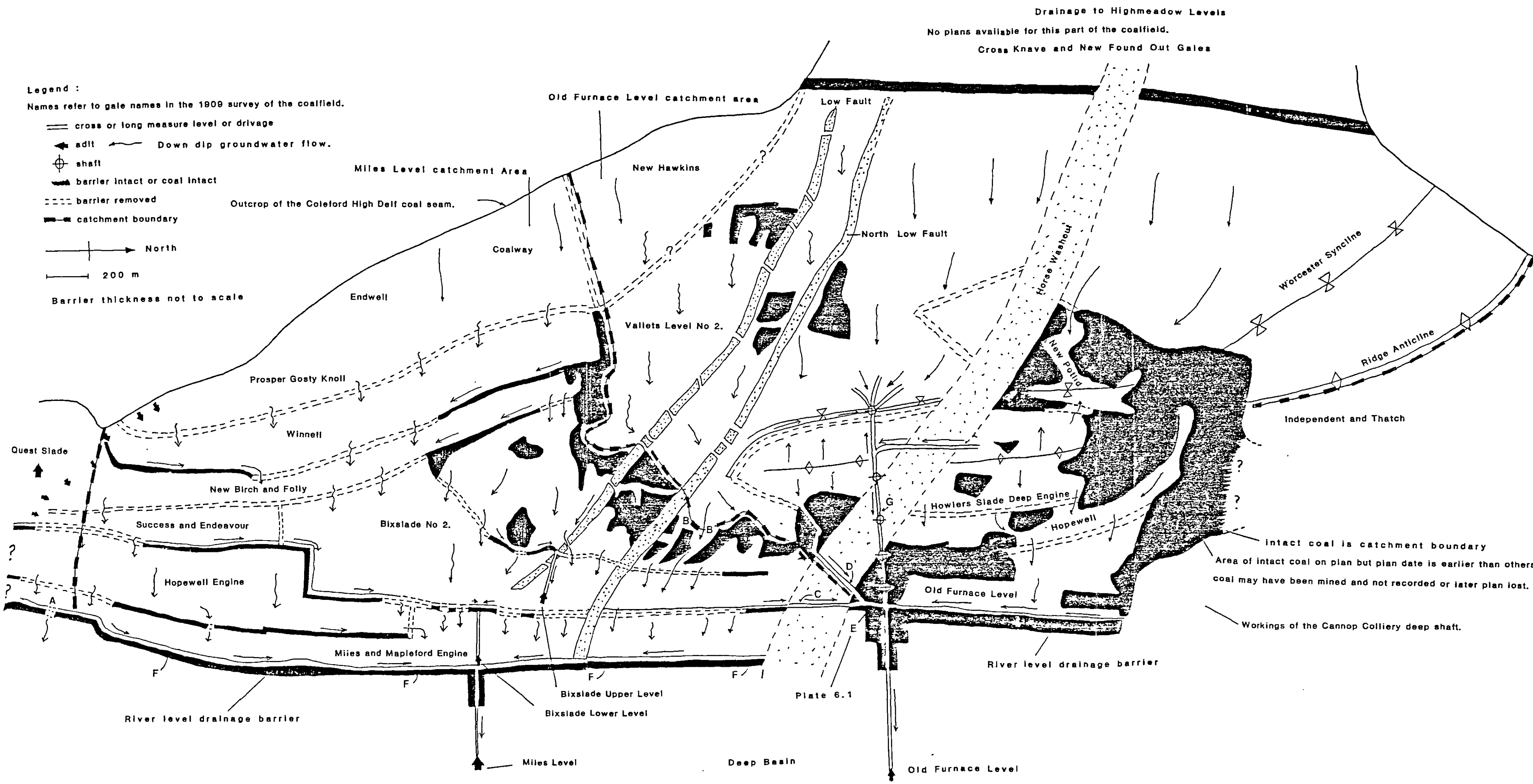


FIGURE 6.7 : Plan showing extent of mine workings and removed, breached and intact coal barriers in the Coleford High Delf coal seam at Miles and Old Furnace Levels. Extent of mining has been compiled from the analysis of abandonment coal mine plans.

adjacent to the Miles Level and the 1.0 m thick impermeable seat earth clay precludes significant downward percolation of groundwater. The catchment area determined for the Miles Level from the coal mine abandonment plans is 3.63 km^2.

The southern boundary of the Old Furnace Level is identical to the northern catchment boundary for the Miles Level. To the west, the edge of the catchment is the outcrop of the Coleford High Delf coal seam, down dip drainage being towards the main Old Furnace Level long-measure levels, the extensive mining in the Coleford High Delf coal seam having removed many of the higher level gale boundary coal barriers. For instance, there is no distinction between New Hawkins Gale and Vallets Level No.2 Gale, and the boundary barrier for Howlers Slade Deep Engine Gale was removed by Trotter and Thomas Colliery Company (as indicated on the same plan).

Unfortunately, to the northwest the mine workings were some of the earliest in the Forest of Dean and no mine plans have survived, and there is therefore no record as to which barriers were left intact. Therefore, the northwest boundary has been defined along the eastern barriers, of Cross Knave and New Found Out Gales, because according to the 1909 Royal Commissioners Report (Chapter 3) these barriers were classified as reserved (the same classification as those associated with the free-drainage level long measure levels). It is considered that this classification was to divide the drainage of the relatively flat outcrop area of the Coleford High Delf coal seam, because to the northwest of this barrier there is drainage towards three levels at Highmeadow (NGR 56801370) (~10 ls^{-1}each, winter 1984). It is therefore assumed that this barrier remains intact and acts as the catchment boundary. To the north few documents again exist and in addition, interpretation of the structural geology is also required, as both the Ridge Anticline and Worcester Syncline lie within the catchment area. The northern most boundary is considered to be the Coleford High Delf coal seam outcrop between the New Found Out Gale boundary barrier and the apex of the Ridge anticline. Drainage being directed down the axis of the Worcester Syncline towards the Howlers Slade Deep Engine Gale and Vallets Level No.2 Gale, possibly via the New Potlid Gale. The areas of unmined coal in the New Potlid Gale should be considered as doubtful as these are shown on the only available coal plan, and probably do not relate to the actual case as the plan was outdated with respect to others workings in the Howlers Slade Deep Engine Gale recorded on a later plan for that gale. The drainage would be intercepted by the long-measure levels which connect to the Old Furnace Level cross-measure level. One long-measure level traverses the Horse Fault to connect the Howlers Slade Deep Engine Gale with the Old Furnace Level, also this Gale is connected to the New Potlid Gale where the boundary barrier has been partially removed. Further west the end of the Old Furnace Level cross-measure level terminates where it intersects the axis of the Worcester Syncline. Two long measure roadways run north south, the northerly one does not cross the Horse Fault. On the 28.6.84 the combined flow of water from the northwest and northern areas (west of the Vallets Level haulage roadway input into the Old Furnace Level mentioned above) was 27.45 ls^{-1} (marked G on Figure 6.7). The outcrop area to the south of the Ridge Anticline and the workings to the south of the anticline in the Thatch and Independent Gale connect directly to the Cannop Colliery which worked the deep basin, and therefore downdip drainage is to the deep basin. Also drainage to the Old Furnace Level long-measure level is precluded by an area of unmined coal, which forms part of the northern catchment boundary. The isolated areas of Yorkley coal seam outcrop produced by the Worchester Syncline are included in the Coleford High Delf coal seam catchment area, as these areas are extensively worked (Figure 6.8) and no springs are located at the outcrop. Therefore it is assumed that considerable disruption of the seat earth clay has occured due to coal extraction and vertical movement of groundwater into the Pennant Sandstone below the Yorkley coal seam occurs.

Further to the catchment area described above for the Coleford High Delf Coal Seam, the segement of abandoned workings which are intersected by the major cross-measure drivage in the Yorkley coal seam require including. Two long measure levels drain these workings. The northern long measure level has a small discharge into the Old Furnace Level of 0.1 ls^{-1}, while the southern, has no discharge although there is evidence that a flow has occured in the past. The extremities of the Yorkley coal seam catchment are the same as the Coleford High Delf coal seam in the northerly and southerly directions and the outcrop of the seam to the west (Figure 6.8). The catchment area for the Old Furnace Level determine from coal mine abandonment plans and structural geology is therefore 5.14 km^2.

6.4.2 CATCHMENT AREA DETERMINATION FOR MILES AND OLD FURNACE LEVEL BY THE WATER BUDGET METHOD.

Figures 6.9 and 6.10 show the weekly rainfall, effective rainfall, soil moisture deficit and evapotranspiration amounts for the Miles and Old Furnace Level adits during the water budget period. The effective recharge is limited to the period 13th December - 31st January, subsequent rainfall merely

FIGURE 6.8 : Diagram showing the isolated outcrop locations of the Yorkley coal seam and the Ridge Anticline within the Old Furnace Level catchment boundary.

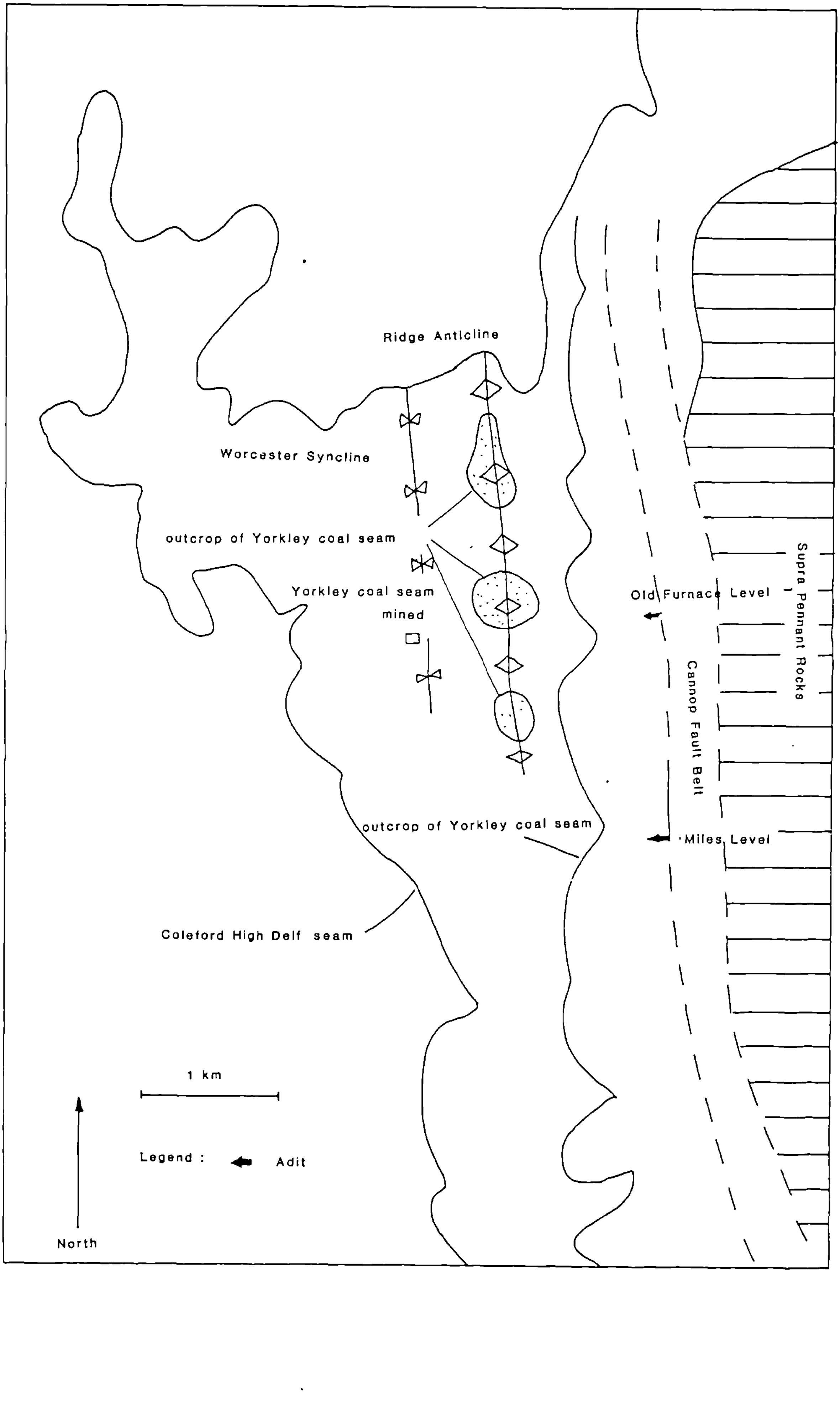
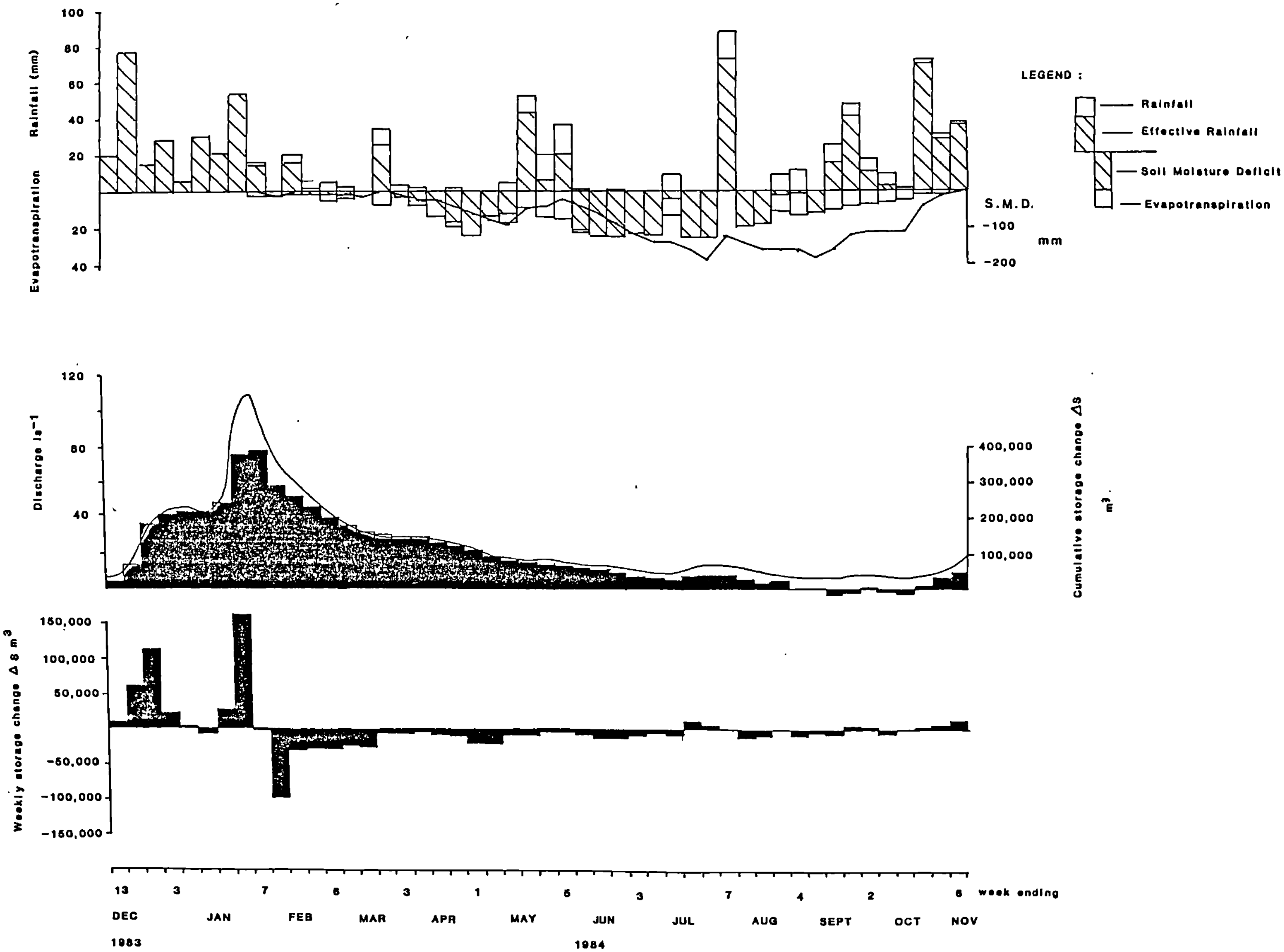


Figure 6.9 : Rainfall, evapotranspiration, soil moisture deficit, discharge and storage changes for the Miles Level.



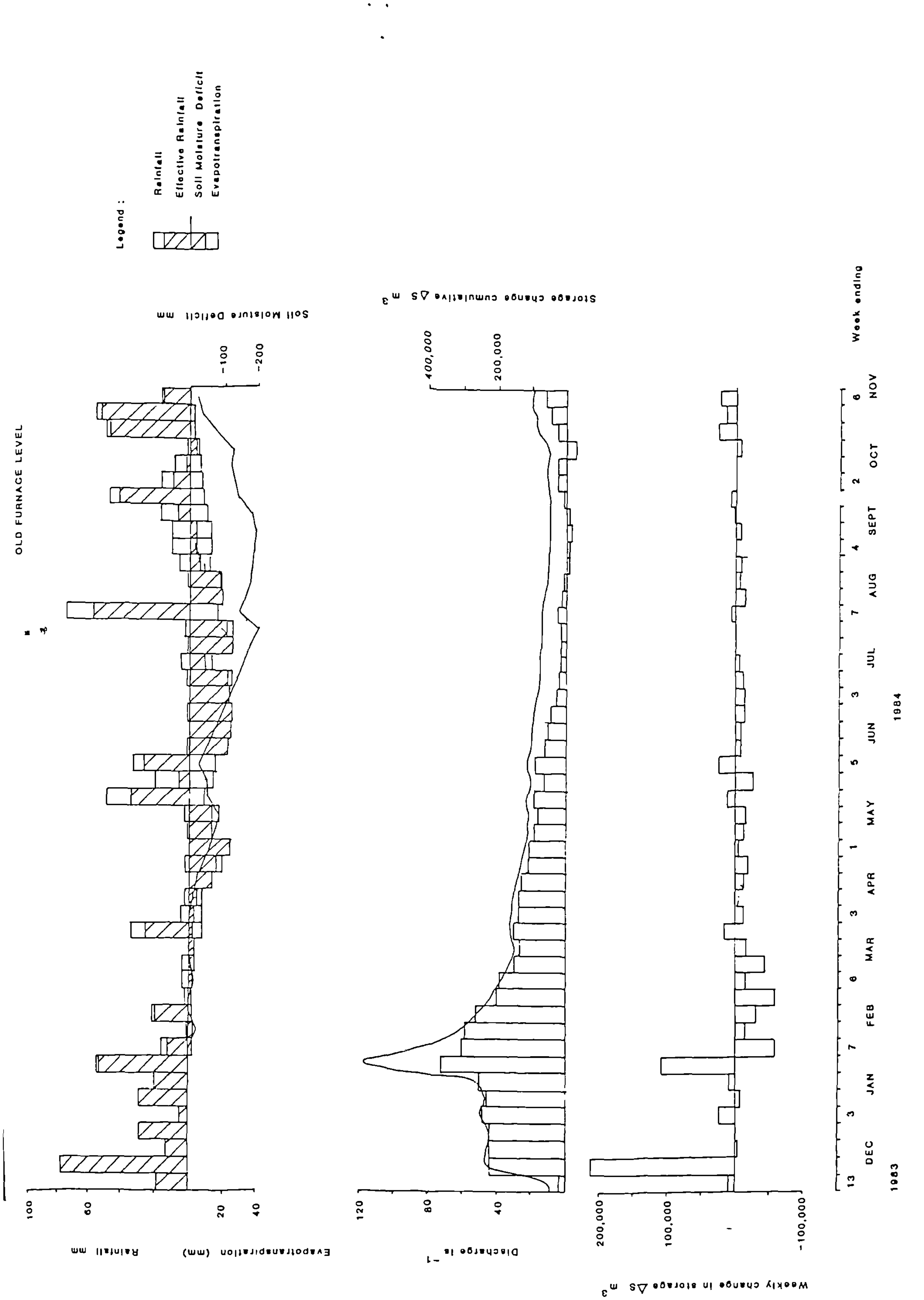


FIGURE 6.10 : Rainfall, evapotranspiration, soil moisture, discharge and storage changes for the Old Furnace Level.

replenishing the soil moisture deficit. The recharge period corresponds directly with the increased discharges at both levels and was confirmed by observations underground. The annual hydrograph is similar at both sites, a rapid rise followed by a continued discharge at the elevated level, followed by a small decline and another rapid rise in discharge. This shape is a product of the temporal distribution of effective rainfall, but also indicates a relatively rapid response to recharge. The rapid recharge must occur through the fractures of the Pennant Sandstone Aquifer (Plate 6.2). During the weeks 27th March, 22nd May, 29th May, 5th June, and 7th August, recharge occurred over the Old Furnace Level catchment area because the discharge increased slightly (20 to 23.5 ls^{-1}), although there was still a soil moisture deficit present. These fluctuations were not measured at Miles Level except for the 7th August when the discharge increased from 9 to 11.5 ls^{-1}. The week of the 7th of August was exceptional with a weekly total rainfall of in excess of 80 mm, and an effective rainfall of between 55 and 60 mm. This indicates that rapid recharge, which short circuits the soil and enters directly into the fissure and fracture system is occurring either via soil macro pores or direct into the aquifer via open quarries or direct disposal of storm runoff via drains into soakaways and abandoned workings. Such processes are not included in the simple soil moisture deficit calculations used in the calculation of the water budgets, which would be expected to under represent recharge volumes.

The catchment areas determined from the water budgets method (Table 6.2) are 3.07 km^2 for the Old Furnace Level and 2.52 km^2 for the Miles Level these are significantly smaller than those determined from the mine plans. In fact a difference of 2.07 km^2 smaller in the case of the Old Furnace Level and 1.1 km^2 for the Miles Level.

6.5 DISCUSSION OF ABANDONMENT MINE PLAN AND WATER BUDGET TECHNIQUES FOR CATCHMENT AREA DETERMINATION.

It is important to note that although the difference between the techniques is a measurement of catchment area it is necessary to explain this by the imbalance of discharge volumes because discharge is a function of catchment area. By equating the recharge volumes for both the Miles and Old Furnace Levels with the mine plan catchment areas it is possible to calculate a predicted flow volume (Q_{MP}). If the total discharge from the water budget period (Q_{WB}) is deducted from the predicted flow volume the difference is equal to the volume of flow (Q_{DIFF}) that is 'lost' from the mine plan catchment area ($Q_{MP} - Q_{WB} = Q_{DIFF}$). In the case of the Old Furnace Level the

TABLE 6.2 : Catchment area determination values for both water budget and mine plan methods for the Pennant free-drainage levels.

Free-Drainage Level	Water Budget Catchment Area	Mine Plan Catchment Area	Total Discharge Predicted (Mine Plan x effective rainfall)	Total Discharge measured	Loss or gain of discharge
	km^2	km^2	$x\ 10^6\ m^3$	$x\ 10^6\ m^3$	$x\ 10^6\ m^3$
Old Furnace	3.07	5.14	1.27	0.9	- 0.37
Miles	2.53	3.63	1.02	0.74	- 0.28
Quest Slade	0.57	0.72	0.22	0.18	- 0.22
Scots	0.07	0.68	0.21	0.02	- 0.19
Parkhill	1.03	0.6	0.18	0.38	+ 0.2
Tufts	1.9	0.65	0.2	0.7	+ 0.5

N.B : Data presented in graphical form in Figure 6.16

difference in discharge is equal to 3.7 x 10^5 m^3 and the Miles Level, 2.8 x 10^5 m^3.

However, it is necessary to determine whether the difference in catchment area (and/or difference in discharge) is attributable to :

(i) an error associated with the mine plan catchment area determination method,

(ii) whether there is a hydrogeological explanation for the loss of water from the catchment.

or (iii) an error in the measurements and calculation of the effective recharge volume.

The first two cases will be discussed in detail in the following two sections (sections 6.6 and 6.7). The third can be briefly discussed here. An error in the prediction of the volume of the annual effective recharge would effect the determination of the catchment areas by using the water budget method employed. However, in this case it is considered not to be important because the method of calculation employed underestimates the recharge volume (as stated earlier) and the water balance for the catchment areas in fact has a surplus of recharge (adit discharge < catchment area recharge).

6.6 ERRORS ASSOCIATED WITH CATCHMENT AREA DETERMINATION FROM ABANDONMENT MINE PLANS.

The catchment areas for the Old Furnace and Miles levels have been determined from available abandonment coal mine plans. It is important to note here the method that was used and the general inadequacies of this data source, in an attempt to explain the difference in catchment area mentioned above. Firstly, a brief resume of the historical development of coal mine plan production, with particular reference to the Forest of Dean, and this is followed by a general interpretation of the validity of this data source.

Although coal has been mined for many years, records of the extent of mining were not required to be deposited by law until 1872. Plans do exist prior 1872, but these only reflect a small part of the shallow coal extraction that took place. many plans produced before NCB times have been lost or misplaced. However, various sources are available for the location of existing plans for all the UK coalfields. NCB (now British Coal) abandonment plans follow the pattern described in the Coal Mine Abandonment Plan Act 1954 (Chapter 1), and are generally on a large scale (6" to a mile), classified by the relevant coal seam and do not contain detailed records of outcrop workings. In the case detailed in this chapter (and many others see Chapter 10), more detailed maps are required. For the Forest of Dean these are held by the Deputy Gaveller. These plans are classified under each Gale (see chapter 3). To use the Deputy Gavellers archive it is necessary to determine the correct Gale for the particular area required, this can be done from either the 1909 Royal Commissioners Report (Appendix A) or Sopwiths 1841 Report for the Forest of Dean Coalfield, and then referencing this Gale name in the Gale book to find the correct archive tube number, for the plan. The plans are kept in numbered tubes (1 to 240), in the Deputy Gavellers Office, each tube contains a number of plans for the Gale required or adjacent Gales. More importantly the workings on one plan may either out date or compliment the workings on another, and the user has to be aware of this. These detailed plans are normally on a scale 22 chains to an inch or even 4 chains to an inch, and show areas of mined coal, coal barriers, major roadways, backfilled areas, shafts and adits. Due to this later difference, the joining of one mine plan with another (which is often required) is complicated by differing scales, map dates, and boundary disputes. Although the maps depict the state of underground workings they only represent the state at the time of the survey, and many surveys were incomplete. It is not uncommon to find that coal has been robbed from adjacent collieries were maps overlap. This was generally the robbing of coal from boundary barriers (Aldous et al 1986), unfortunately in many instances this was unrecorded. Areas such as these allow water movement across drainage divides and into deeper workings. This point will be considered in detail with respect to the case outlined in this chapter.

The initial conclusion, in the study above was that the mine plan catchment area is too large. The mine plan catchment area determination has been conducted using proven geological structures and recorded mining activities (mined areas and boundary barrier removal). (It should be noted that boundary barrier removal in the Miles and Old Furnace Level areas is particularly well documented). It is also considered highly unlikely that barriers documented as removed were not removed, the contrary case being more probable, and in any case this would only enlarge the catchment further. For a case of barrier removal to make the Miles or Old Furnace Level catchments smaller the westerly, southerly or northerly boundaries would have to be altered, there is no documentary evidence for this.

Where single roadways cross 'barren' or unmined areas these have also been included as there is evidence that such roadways act as major groundwater flow routes (Plate 6.1). However, large areas of the Horse Fault Washout in the Old

Plate 6.1 : Collapsed roadway which crosses the Horse Fault (washout area) in the Old Furnace Level although access is precluded by the collapse a substantial flow of 27.45 ls^{-1} is still discharged from the roadway.

Furnace Level and Low Faults in the Miles Level catchments are not traversed by roadways and recharge may move vertically through the massive Pennant Sandstone into the deep basin. (Evidence for this flow mechanism is given in Chapter 10). In the case of the Old Furnace Level this area (0.38 km^2) is included in the mine plan catchment area this volume of recharge should be deducted from the net deficit (1.1 x 10^5 m^3) making the difference now 2.6 x 10^5 m^3. Similarly in the case of the Miles Level the are of the Low Faults is 0.12 km^2 equates with a loss of discharge to the deep basin of 0.37 x 10^5 m^3 and an adjusted net deficit of 2.4 x 10^5 m^3. The other catchment boundaries are either outcrop areas or areas of unmined coal. It is also important to note that the difference in catchment areas is identical (water budget catchment area < mine plan catchment areas) in both catchments and the possibility of the deficit in discharge (to make the water budget catchment area equal to the mine plan catchment area) for the Old Furnace level draining to the Miles Level is remote. Furthermore, there are no other discharging adits which drain the outcrop area in this location, and therefore the only other possible flow route for recharge waters is to the deep basin, and thereby bypassing the free-drainage levels.

6.7 HYDROGEOLOGICAL EXPLANATIONS FOR PROBLEMS ASSOCIATED WITH CATCHMENT AREA DETERMINATION IN OUTCROP AREAS.

The second explanation concerns the hydrogeological function of the coal drainage barriers (chapter 3) which maintain the free-drainage level portal discharges, because the mine plan catchment area assumes that no water is lost from the free-drainage level catchment area to the deep basin. There are two possible natural mechanisms by which this may occur, firstly leakage through the underlying seat-earth clay, and secondly, natural leakage through the coal barriers (which form the drainage barriers of the long measure levels) which is a function of the permeability of the coal. The first is highly unlikely considering the low permeability of the seat-earth clays (typically 0.17 - 1.7 x 10^{-3} md^{-1}), but the second does warrant further analysis.

By applying Darcy's Law (Equation 6.2) the amount of discharge lost through the drainage barriers can be calculated. The cross-sectional area of the long-measure drainage barriers are 2615 m^2 for the Old Furnace Level, and 2400 m^2 for Miles Level, and the hydraulic gradient is assumed to be equal to the dip of the coal seam (0.176 for the Old Furnace Level and 0.09 for Miles Level). Now by using the range of permeability values for coal in Chapter 2, it is possible to calculate the possible variation in leakage volume for the water budget period (Table 6.3).

Table 6.3 : Calculated natural and enhanced coal barrier leakage volumes for Old Furnace and Miles Levels for the 334 day water budget period.		
Coal Permeability md^{-1}	Old Furnace Level m^3	Miles level m^3
(natural permeability)		
0.15	2.3×10^4	1.1×10^4
0.65	1.0×10^5	4.6×10^4
(enhanced permeability see section 6.7.2)		
0.93	1.43×10^5	0.6×10^5

These calculated leakage volumes are considerably less than the discharge volume differences which resulted from the two catchment area determination methods. In fact the highest value is a factor of 2 too small. For the leakage to be singularly attributed to this process, and the permeability of the coal barriers would have to be between 2.0 and 4.0 md^{-1}, at least 3 times larger than the highest recorded in chapter 2. It is therefore considered that the primary conclusion can be made that natural leakage does not singularly explain the loss of discharge. But it should be noted that there is no evidence to suggest that this process does not occur.

There are two further processes which may explain the loss of groundwater. These primarily concern :

(i) groundwater flowing over the drainage barriers, and through the Pennant Sandstone.

or (ii) an artificially induced groundwater flow through the drainage barriers, due to an artificially increased permeability.

Both of these processes will be discussed, by considering case histories.

6.7.1 GROUNDWATER FLOW OVER DRAINAGE BARRIERS (LONG MEASURE AND CROSS MEASURE LEVEL COLLAPSE).

Groundwater can bypass the drainage barrier and recharge the deep basin, when failure of the Pennant Sandstone roof causes a blockage in the main long-measure level. Extensive ponding occurs behind the blockage due to sedimentation of coal, seat earth clay and ferric hydroxide deposits behind the collapse, and an elevated hydraulic head is produced in the adjacent aquifer. Therefore the ponded zone that occurs behind the blockage can drain directly through the overlying Pennant Sandstone and into the deep basin (Figure 6.11). Three collapses of this nature are known to occur within the

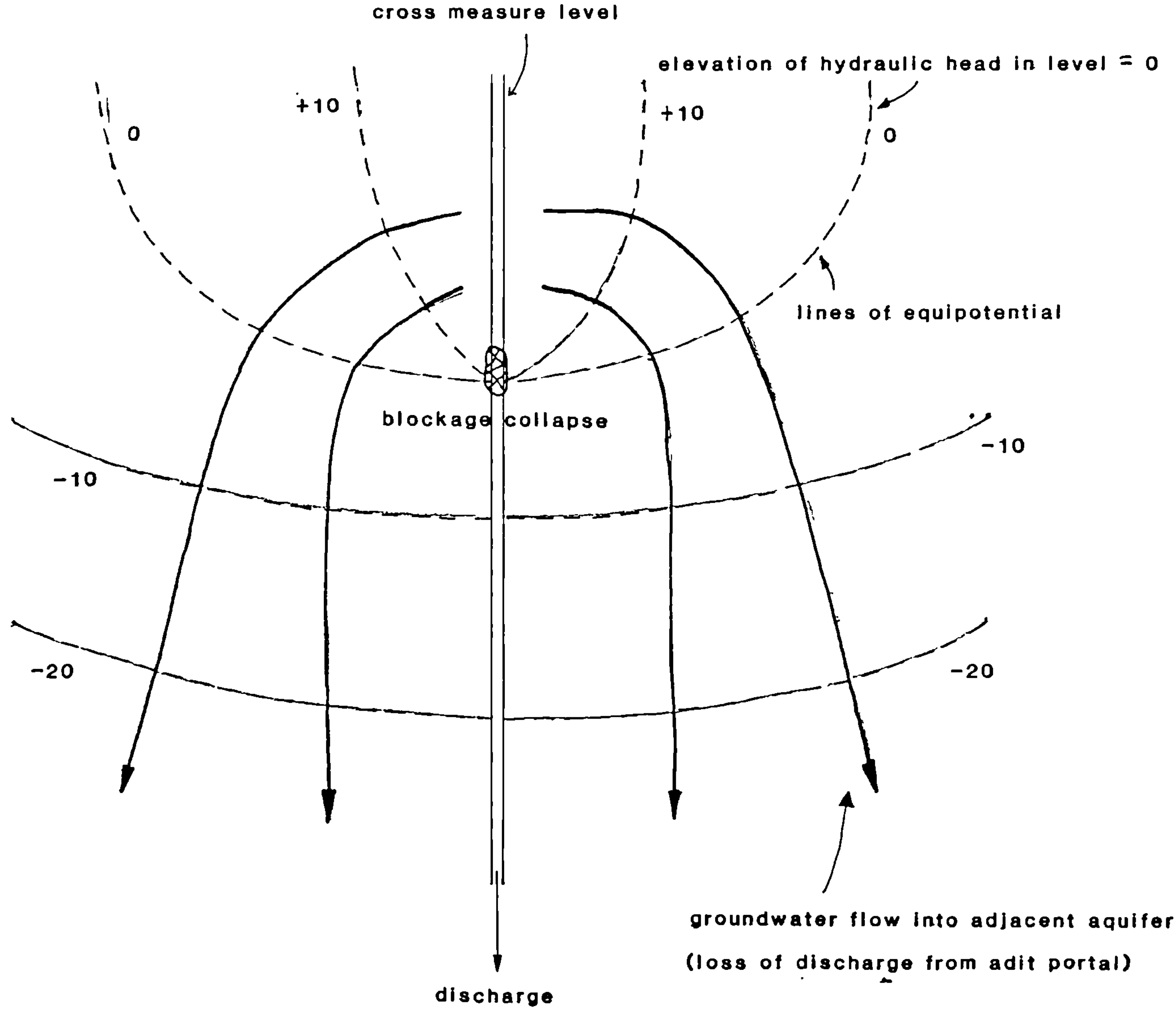
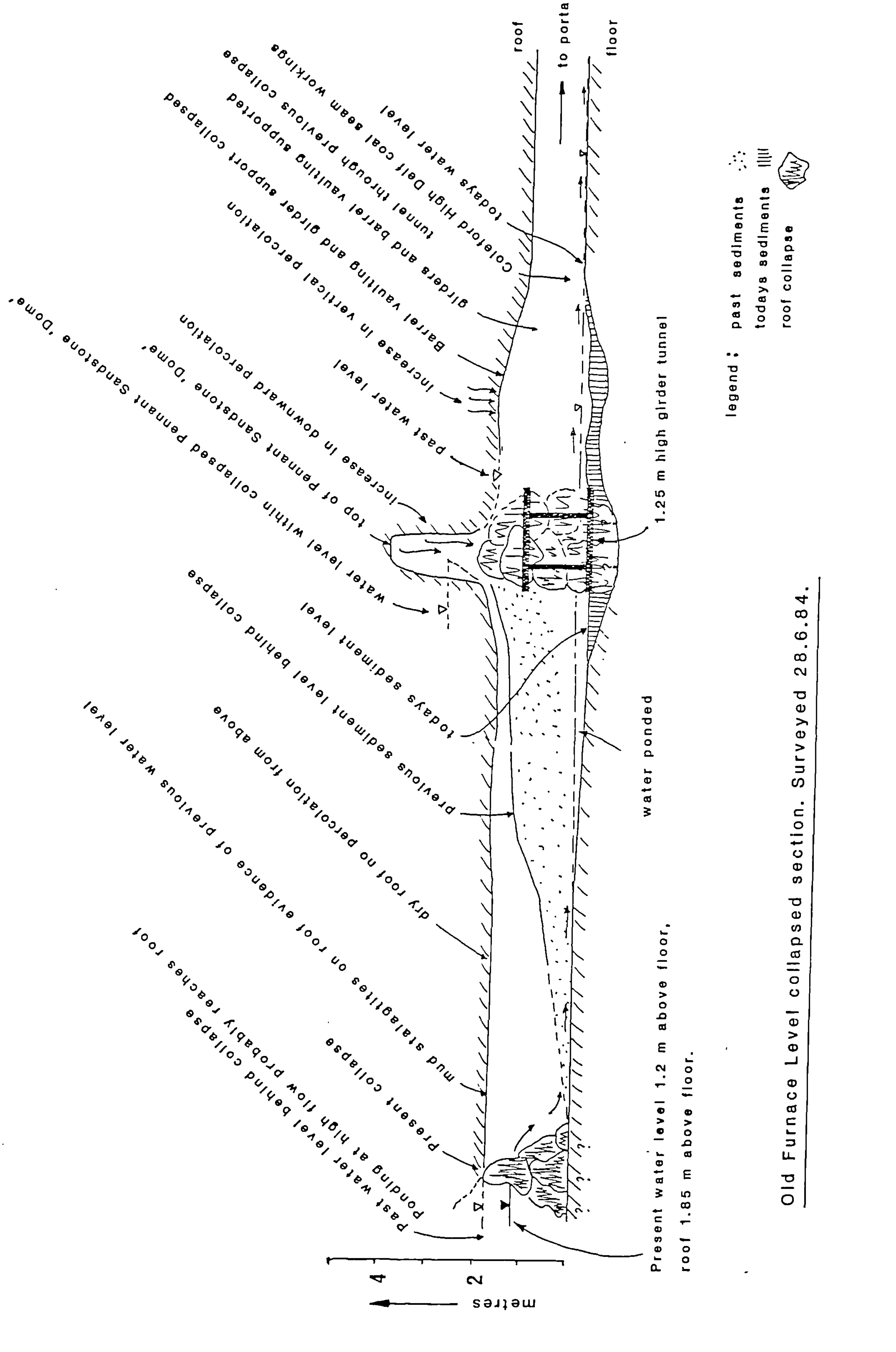


FIGURE 6.11 : Schematic flow net diagram for a blockage collapse in a cross-measure level, showing formation of groundwater 'mound' and discharge of level water into adjacent aquifer.

Figure 6.12 : Long section through blockage collapse in the main drivage roadway of the Old Furnace Level.



Miles Level catchment, but more significantly an historic collapse exists within the cross-measure level of the Old Furnace Level (Figure 6.12). This collapse was removed (by tunnelling, probably because it effected drainage of the local mines) during ~1900. This has allowed the detailed analysis of the effects of the collapse on the level behind the blockage. Plates 6.3 and 6.4 show the extensive laminated sediment deposits that occur (which have been subsequently eroded) and the mud and ferric hydroxide stalagtites on the level roof are a record of the previously elevated hydraulic head. However, the total volume of water lost from the portal discharge by this process is considered to be small under normal conditions. Further hydrological and environmental implications of the 'blockage collapse' will be discussed in chapter 10.

Two fluorescent dye tracer tests were conducted in the Miles Level, Bixslade (Upper and Lower) Level complex of workings to determine storage and residence time for the inaccessible collapsed mine workings (reported in chapter 7). These tests also indicated a loss of discharge occurred at high flow, but no loss occurred at low flow, because the recoveries of the tracer dyes differed under the two flow regimes. The recovery was in excess of 100 % at low flow (108 %)(Figure 6.13), suggesting an overestimate of flow from the Miles Level gauging structure (probable accuracy +/- 10 %), while at high flow the recovery was much lower, being 63 %. This cannot be explained by gauging error, and no other discharges occur in the area (it is impossible for the dye to reach the Old Furnace Level because of a difference in elevation), and therfore a flow distributory must occur (Brown and Ford 1971).

A detailed analysis of the available coal mine plans for the area are shown in Figure 6.14. The dye (as 500 ml solutions containing 5 g of Sulpho Rhodamine B dye (3rd Edition of the Colour Index (1971) C.I. No. 45100) was injected underground in an abandoned mine (~1970) 0.5 km from the Miles Level where a stream (discharge 9.6 ls^{-1} high flow, 2.4 ls^{-1} low flow) disappeared into collapsed workings. No ponding of the water was visible, suggesting free flow continued beyond the collapsed workings. However, there are two possible flow routes the dye may have taken. The first is via a roadway which connects directly to the Miles Level long and cross-measure roadways. The second route is via the modern workings (post 1970) towards the partially removed Miles Level drainage barrier. It is not known which of these routes was taken but the direction of flow at the injection site was towards the partially removed Miles Level drainage barrier. This flow route is more likely to be open than the other due to the difference in age. However, the explanation of the dye

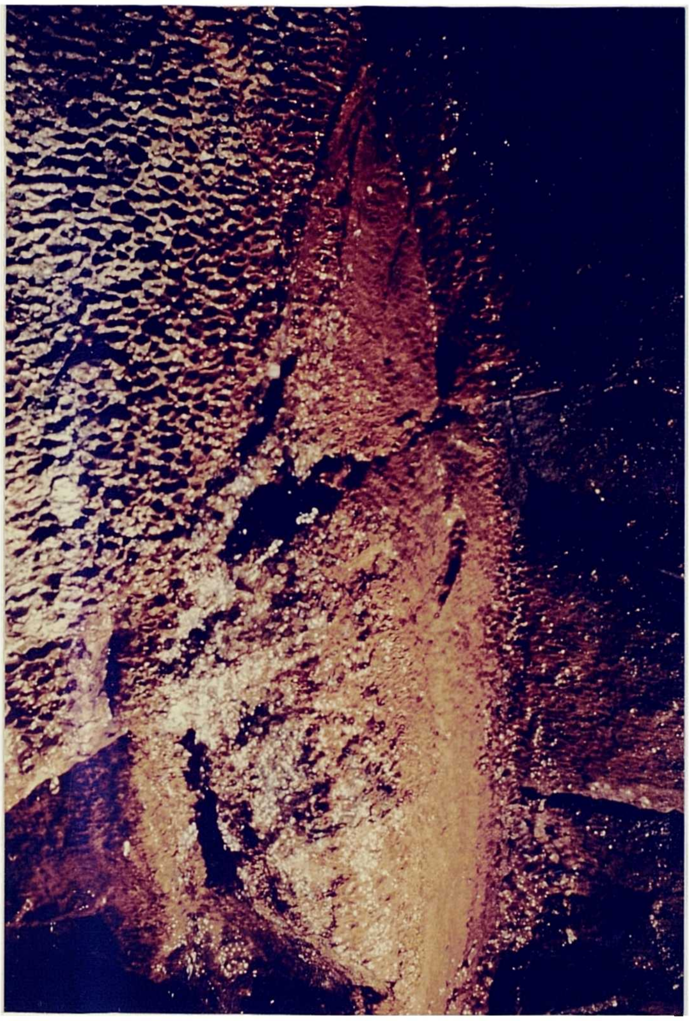


Plate 6.2 : Drainage of rapid recharge, temporarily held within fracture storage (Ch 7). This plate clearly demonstrates the dominant fracture flow within the Pennant Sandstone Aquifer.

Plate 6.5 : Partial barrier removal has occurred in the Yorkley coal seam at an elevation below the Old Furnace Level main cross measure drivage, ponding occurs as the intact coal retards further down dip percolation. However, drainage can occur through the overlying fractured Pennant Sandstone into the deep basin.

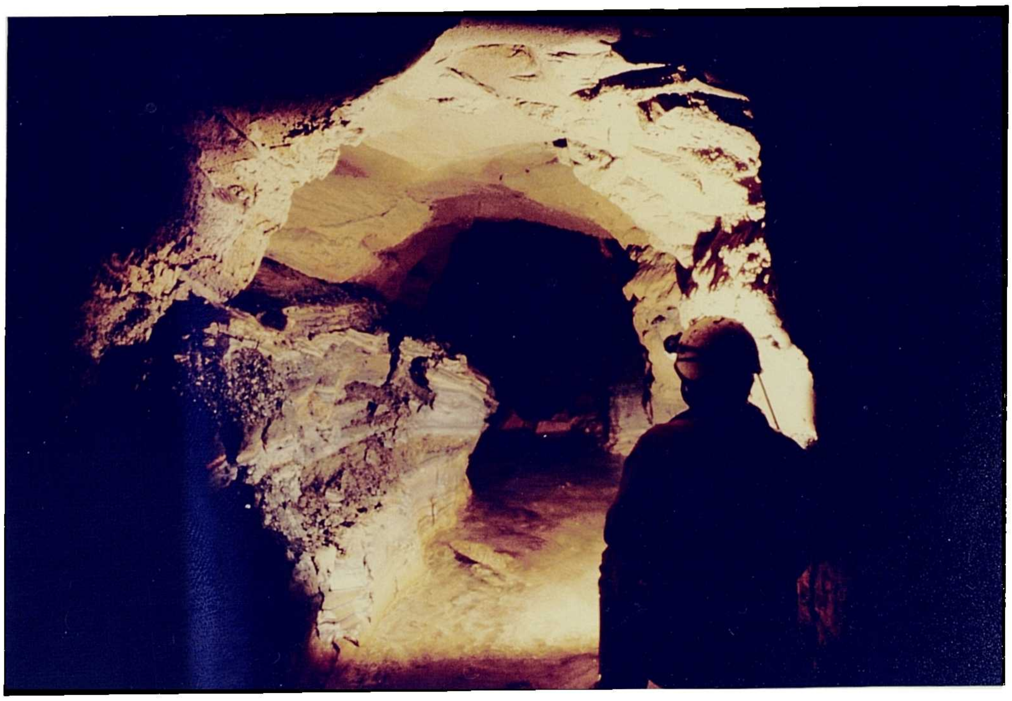


Plate 6.3 : Sediments deposited behind the blockage collapse in the Old Furnace Level.

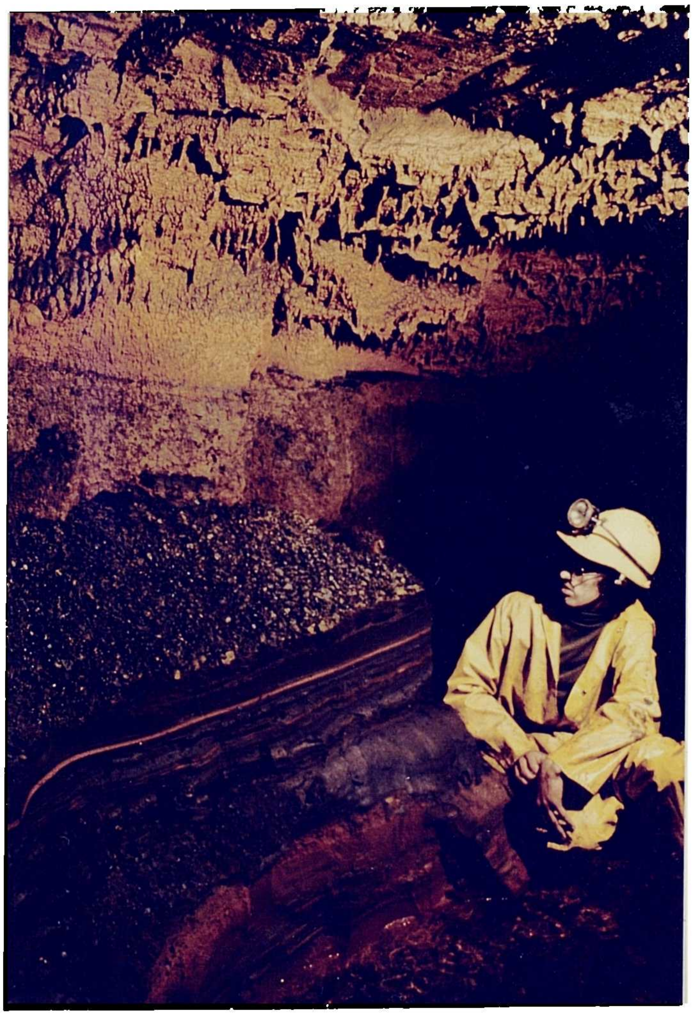


Plate 6.4 : Sediments deposited behind the blockage collapse in the Old Furnace Level.

FIGURE 6.13 : Sulpo Rhodamine B tracer breakthrough curves for high and low flow conditions at the Miles Level.

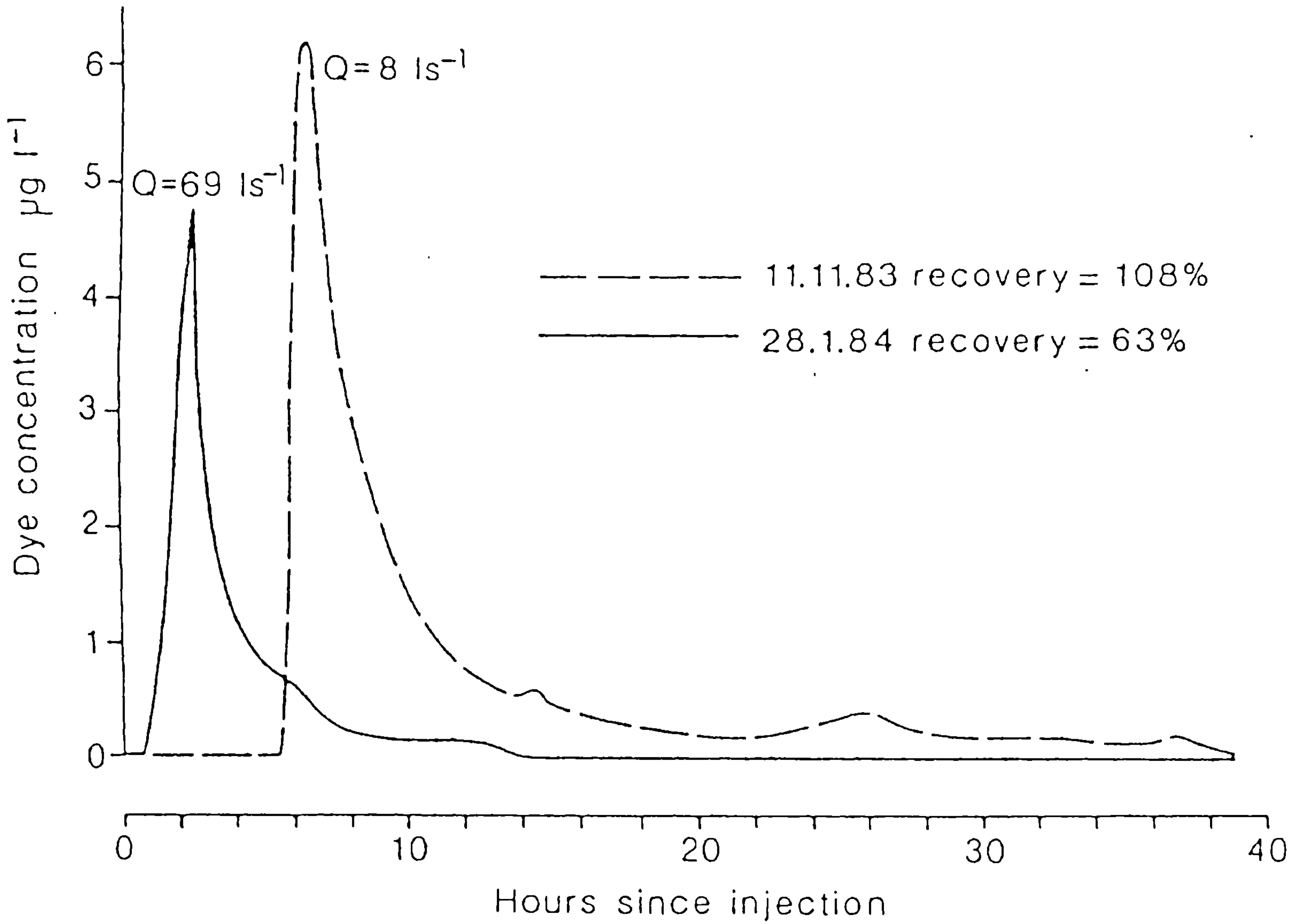
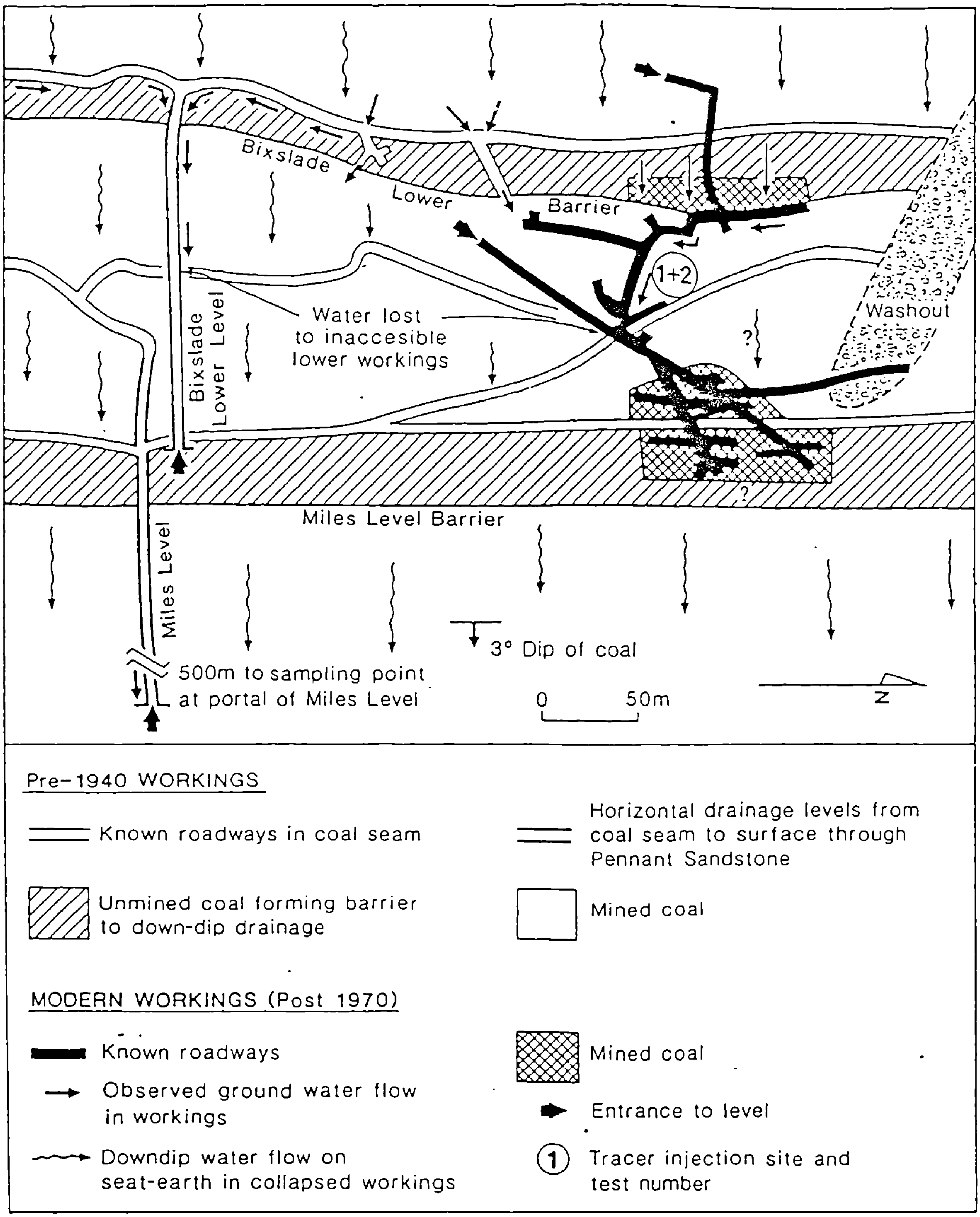


FIGURE 6.14 : Plan showing the extent of coal workings, intact and removed coal barriers and known groundwater flow paths in the Miles and Bixslade Gale areas.



loss is that at high flow substantial ponding occurs in either, the area of the partially extracted drainage barrier connected to the post 1970 wokings or another unrecorded area. This permits water to flow over the drainage barrier in the sandstones above and drain to the deep basin.

6.7.2 ARTIFICIALLY INDUCED GROUNDWATER FLOW THROUGH DRAINAGE BARRIERS. (COAL BARRIER REMOVAL).

There are two methods by which additional groundwater flow can be induced through a coal barrier, these are :

(i) where secondary coal mining decreases coal barrier thickness and (ii) where secondary coal mining totally removes all or part of a coal barrier.

Where secondary coal mining has taken place after the initial mine abandonment and partially removed large areas of the drainage barriers along the long-measure level, this decreases the barrier thickness and may increase the leakage from the long-measure roadway into the deep basin. This has occurred in the Yorkley coal seam workings of the Old Furnace level (Plate 6.5 and Figure 6.15). The barrier of coal has been partially removed allowing a ponded section of groundwater to be formed, when the inflow is greater than the outflow this then overflows into the adjacent long-measure level. The total outflow through the drainage barrier can be either percolation through the remaining coal barrier (probable thickness 4.0 m compared to a previous 10.0 m) or were ponding is substantial, through the Pennant Sandstone above. In the example shown in the Old Furnace Level the measured inflow was 0.2 ls^{-1} and the long-measure outflow 0.03 ls^{-1}, which indicated a loss of 0.17 ls^{-1} over a section of barrier of 30 m in length. By applying Darcy's Law in a similar manner to that above, the permeability of this partially removed coal barrier can be calculated, this is equal to 0.93 md^{-1}. This is still significantly lower than that required to account for the catchment area discharge loss. However, this case only represents the amount lost at one particular location at one particular time.

It is known that roadways punctured coal barriers, to either provide drainage or access into deeper gales. This occurred in both the Miles and Old Furnace Level catchments, and an example from the latter is shown in Plate 6.6. The roadway has completely punctured the barrier of coal and a discrete point loss of discharge occurs. In this case 3 ls^{-1} is lost to the deep basin (28.2.85). A similar situation exists in the Bixslade No.2. Gale in the Miles Level catchment (see below), and the documented sequence of events that occurred when

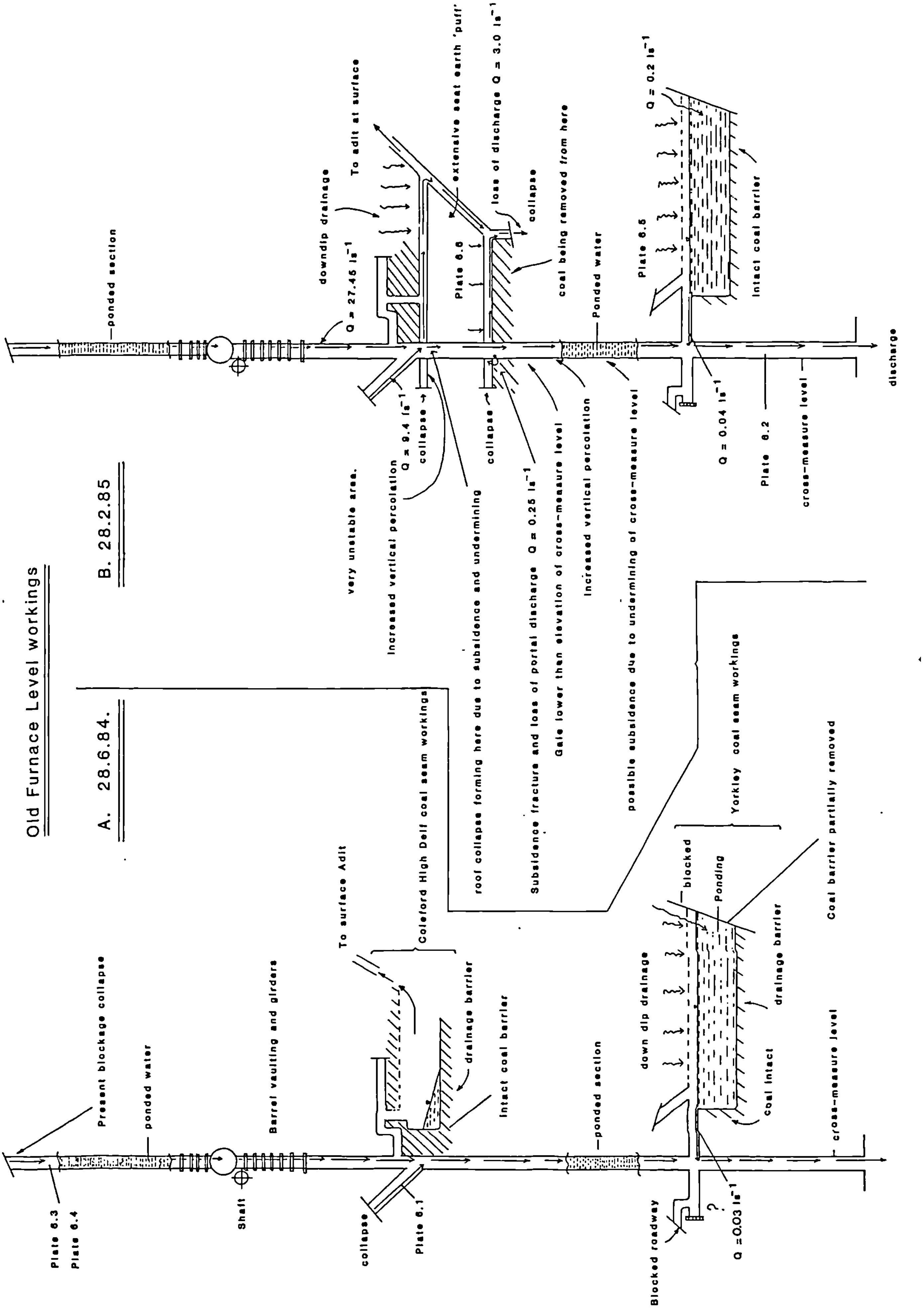


FIGURE 6.15 : Schematic diagrams showing the extent of recent barrier removal in the Old Furnace Level

Plate 6.6 A: Complete coal barrier removal has occurred and a point loss of groundwater flow from the surface portal of the Old Furnace Level discharge results.

Plate 6.6 B : Partial coal barrier removal has occurred (the coal barrier has been pierced), resulting in a loss of portal discharge at the Miles Level.

the Miles Level long-measure drainage barrier was punctured is discussed in chapter 10. More importantly it should be noted that the removal or puncturing of barriers is an activity that is widely used by the remaining free miners who are currently extracting coal from the Yorkley and Coleford High Delf coal seams in both the Miles and Old Furnace Level catchment areas.

The schematic plans (Figure 6.15) of the Old Furnace Level show the extent of present barrier removal in the Coleford High Delf coal seam and the effect on the integrity of the major cross-measure level. The barrier removal not only enhanced down dip loss of discharge, which probably already occurred via diffuse flow routes, but has also affected the cross-measure level, because where the coal has been removed from below the cross-measure level subsidence of the level floor has occurred and collapse of the level roof. The former has resulted in more extensive ponding and at one location subsidence fractures in the Pennant Sandstone are evident and a loss of the portal discharge is visible. The loss is probably in the region of 0.25 ls^{-1}. Furthermore, the area of mined coal below the cross-measure level is typified by extensive roof leakage. One future implication of the recent undermining of the major cross-measure and decrease in the stability and integrity of the cross-measure level roof, is that a blockage collapse could occur within the level. In this particular case the results would be more dramatic as the collapse has started the adit portal side of the long measure levels, which would allow ponded water to flow (contrary to the anticipated direction) down the long measure levels, and where the coal barrier has been removed directly into the deep basin. In the case of the Old Furnace Level the possibility of all the flow being intercepted by this route is high.

The point source loss of discharge of 3 ls^{-1} in the Old Furnace level catchment represents a 0.865 x 10^5 m^3 volume of flow for the water budget period. The unaccounted discharge volumes for the catchment areas (lost discharge - that accounted by natural leakage and washout zones) are equal to between 2.37 x 10^5 and 1.6 x 10^5 m^3 for the Old Furnace Level and 2.46 x 10^5 and 2.11 x 10^5 m^3 for the Miles Level. These figures represent point source losses of between 8.2 and 5.5 ls^{-1} for the Old Furnace Level and 8.0 and 6.8 ls^{-1} for Miles Level (Table 6.3). As mentioned above one point source is already known with a discharge of 3.0 ls^{-1} and the possibility of another existing is highly probable. Furthermore, the values for Miles Level would also not seem unreasonable in view of those observed and predicted from the Old Furnace Level.

TABLE 6.3 : TABULATION, EXPLANATION AND QUANTIFICATION OF THE POSSIBLE SOURCES OF THE LOSS OF PORTAL DISCHARGE AT THE OLD FURNACE AND MILES LEVELS.

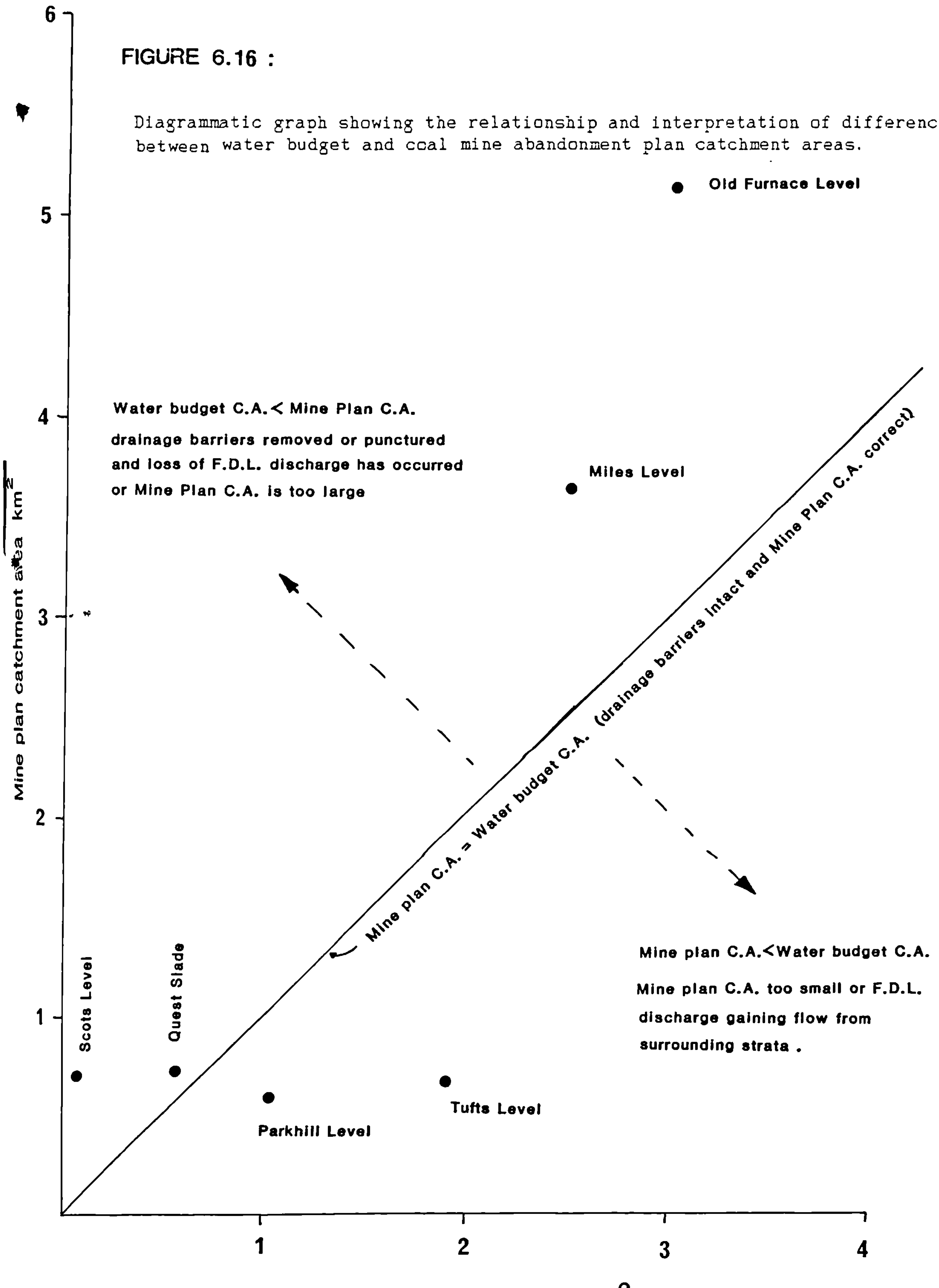
SOURCE OR PROCESS FOR LOSS OF DISCHARGE	OLD FURNACE LEVEL x 10^5 m^3		MILES LEVEL x 10^5 m^3	
TOTAL LOSS OF DISCHARGE BETWEEN MINE PLAN AND WATER BUDGET CATCHMENT AREAS.	3.7		2.8	
LOSS OF DISCHARGE TO THE DEEP BASIN VIA THE HORSE AND LOW FAULTS	1.1 ↓ ↘		0.37 ↙ ↘	
NATURAL LEAKAGE THROUGH COAL DRAINAGE BARRIERS	0.23	1.0	0.11	0.46
POSSIBLE POINT LOSSES OF DISCHARGE DUE TO COAL BARRIER PUNCTURING	2.37	1.6	2.32	1.97

N.B. :- It is not possible to include here the losses of discharge attributed to the increase in permeability of coal barriers associated with partial barrier removal because the extent of this activity in the catchment areas is unknown. However, if the value of 0.93 md^{-1} obtained for the 30 m length of barrier in the Old Furnace Level catchment is used for the total barrier lengths the loses would be 1.43 x 10^5 and 0.6 x 10^5 m^3 for the Old Furnace and Miles Levels respectively. However, there is no evidence that this has actually occurred to this extent.

In conclusion, the difference in portal discharge between that predicted from the mine plan catchment area and that which is recorded can be explained by the occurrence of four processes : natural leakage through intact coal drainage barriers; enhanced leakage through partially removed drainage barriers; leakage via washout zones to the deep basin because the impermeable seat earth clay is absent and; broken or punctured coal drainage barriers. All of these processes permit the loss of groundwater from the free-drainage levels to the deep basin. However, it has not been possible to identify one single process that could account for the losses measured and the most likely situation ia that a combination of two or more occurs. Although the latter process discussed here, the point losses of discharge due to complete drainage barrier removal is the most important because substantial losses of portal discharge can occur and there locations are unpredictable if not documented or accessible by underground exploration. The implications of these processes on the prediction of pollutant pathways for resource management of both ground and surface waters will be discussed in chapter 10.

FIGURE 6.16 :

Diagrammatic graph showing the relationship and interpretation of differences between water budget and coal mine abandonment plan catchment areas.



Legend : C.A. – Catchment Area. F.D.L. – Free Drainage Level

Finally, in the general case, if the processes identified above are not present and no other losses of discharge occur by any further unknown process, the catchment area determined by the water budget should equal that determined by the mine plan method, and if a number of sites are studied a relationship between catchment area determination method exists (Figure 6.16). Therefore any deviation from this should indicate whether the processes identified above are actually present and whether the losses are sig nificant. Catchment areas were determined by both methods (water budgets and mine plans) for four further adits (Scots Level, Quest Slade, Parkhill Level and Tufts Level) and these results are presented in Figure 6.16. Scots Level plots remarkably distant from the 45° mine plan = water budget catchment area line, and this would indicate that substantial drainage barrier coal removal has occurred; however, there are no records to support this. The Quest Slade Adit also plots similarly to Scots Level but is significantly closer to a correct catchment area. More remarkable is the situation for both the Parkhill and Tufts Levels. The water budget catchment areas are much larger than those associated with the analysis of mine plans. In these two cases, this is attributed to additional groundwater being discharged from the adjacent Carboniferous Limestone Aquifer because the main cross measure levels were driven through the Coal Measures to also mine iron ore from the Carboniferous Limestone. However, this does demonstrate another aspect of the general model depicted in Figure 6.16. Furthermore, a case could exist whereby the mine plan catchment area was too small in comparison to the water budget catchment area and measured discharge because the amalgamation of adjacent gales by the removal of boundary barriers had not been recorded on the mine plans.

6.8 A CONCEPTUAL MODEL OF GROUNDWATER FLOW IN AN OUTCROP AREA DRAINED BY A FREE DRAINAGE LEVEL AND DOMINATED BY THE PRESENCE OF A RIVER LEVEL DRAINAGE BARRIER.

The conceptual model outlined here summarises the processes that control groundwater movement in shallow abandoned coal mines drained by free drainage levels.

In the unsaturated zone (Figure 6.17) above the elevation of the drainage barrier, percolation is predominantly vertical in the fractured sandstone, but this is impeded by the seat earth clays underlying the coal seams, which have very low permeabilities (Table 2.1). Whilst these may be excavated in the major haulage roadways to provide adequate roof clearance, they remain undisturbed in the extensive galleries from which coal extraction occurs. Thus

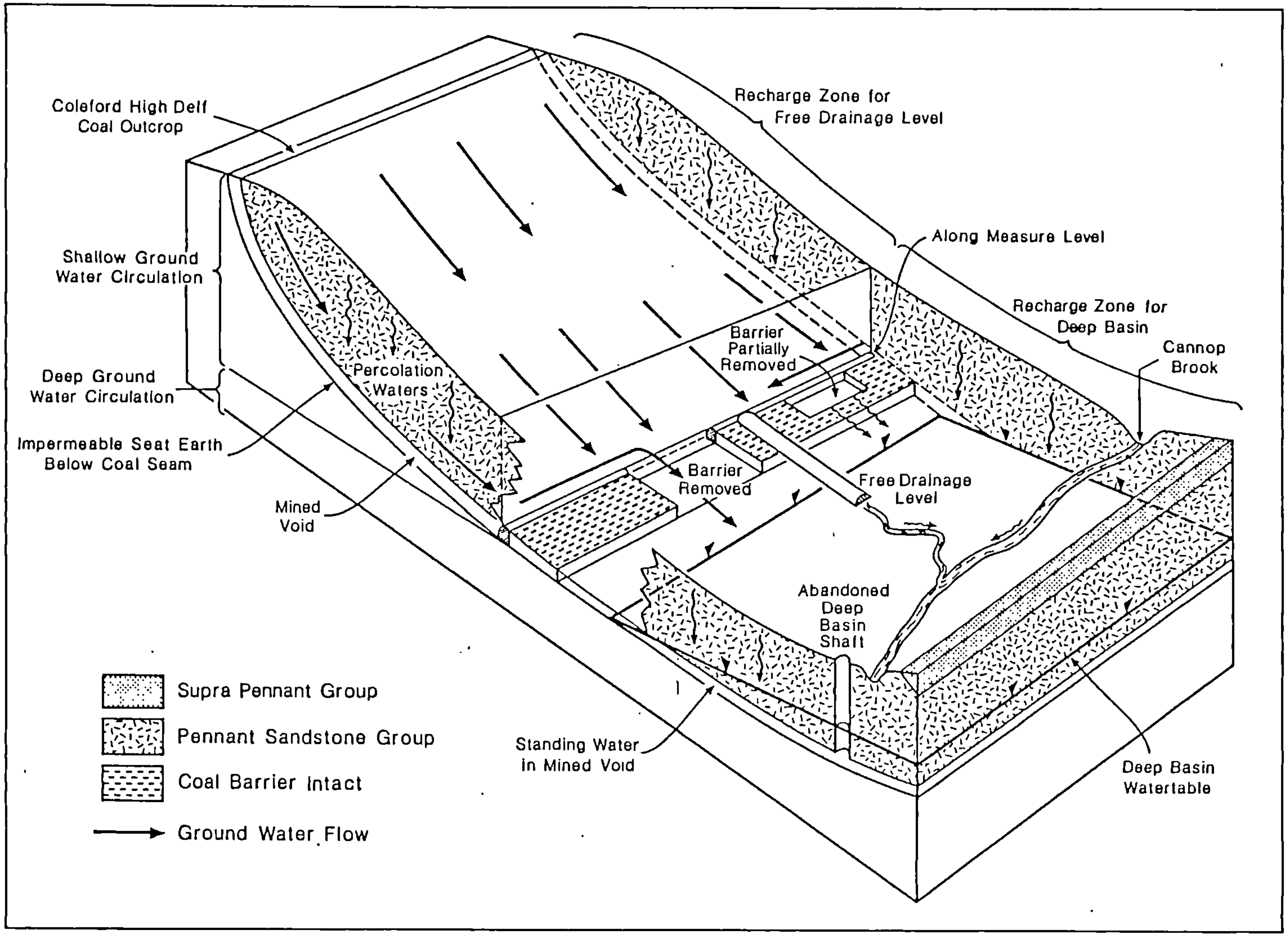


FIGURE 6.17 : Conceptual model illustrating the hydrological function of shallow coal barriers, and the effects of their removal

groundwater flow is directed downdip on the surface of the seat earth, and is concentrated by the network of abandoned roadways into small streams (Plate 2.1). The downdip flow is however diverted laterally by the barriers of unmined coal remaining in the floors of the long measure levels leading to the free-drainage levels. This water, therefore discharges to the surface rather than penetrating further downdip into the deep basin below river level. Present day abstraction of coal from these barriers has necessitated their piercing to facilitate mine drainage, and in some cases they have been totally removed resulting in loss of portal discharge and the production of another potential pollutant pathway. Furthermore removal of coal from beneath the free-drainage level causes subsidence enhanced fracturing and further loss of portal discharge.

6.8 DISCUSSION AND SUMMARY

In summary, this chapter has shown further the utility of traditional hydrological methods (water budgets) in determining groundwater catchment areas, the validity of catchment area determination from coal mine abandonment plans, coal barrier integrity and the behaviour and role of free-drainage levels in determining groundwater flow paths and patterns.

In the case of the Supra Pennant Series the catchment areas for specific discharges (or groups of discharges) have been determined, by analysis of both geological structures and coal mine plans (but primaril y the former), the leakage rate of a regional aquitard and the integrity of an inaccessible coal barrier has been suggested. Collectively this has enabled the development of a conceptual model of the role and behaviour of the free-drainage levels in determining groundwater conditions in an isolated coal basin for use as a future groundwater management tool.

In comparison, the Pennant Series free-drainage level study was more detailed, because within the Pennant Aquifer a two component groundwater flow system exists. An upper component, the shallow groundwater circulation (Figure 6.17) and a lower component, the deep groundwater circulation. The two components are separated at river level by a coal drainage barrier which maintains a groundwater discharge from the upper component to the nearest water course. The catchment area for the upper component draining to a specific free-drainage level can be determined primaril y by the analysis of coal mine abandonment plans and secondly the geological structure (outcrop areas, washout zones, synclines and anticlines). In the cases analysed, results from the catchment areas determined from the mine plans and from the water budgets differed considerably. This indicated that a loss of discharge from the free-drainage level portal had occurred. In fact, the difference was a loss of discharge of 29 % (3.7×10^5 m^3) of the expected discharge at the Old Furnace Level and 27 % (2.8×10^5 m^3) for the Miles Level (Table 6.2). This difference could not be explained by an incorrect analysis of the catchment area from the coal mine plans.

Present day abstraction of coal from intact drainage barriers occurs, and the processes that result directly and indirectly from this activity, explained the loss of discharge, and the erronous catchment area determination from the water budget method. Where piercing of coal barriers or total removal was present in the catchments understudy, substantial point losses of discharge from the upper component to the lower component occurred (this could be seen by direct exploration of the workings). In addition, where coal drainage barriers are partially removed, the natural leakage due to the permeability of the coal barrier was enhanced and substantial ponding occurs. Also where coal has been removed from barriers close to either long or cross measure levels, blockage collapses occur producing substantial saturated groundwater mounds, permitting leakage from the upper level component to the lower component through the fractures of the adjacent sandstone. Losses of discharge due to these processes were significant enough at high flow (winter conditions) to be detectable by the use of quantitative fluorescent dye tracer techniques and could sufficiently explain the loss of discharge within the expected error of the use of the water budget method (+/- 10%).

Although small scale, mining continues in many coalfields after abandonment of the major mines. Until recently the possible hydrological effects of this activity had not been considered, however it has been demonstrated that substantial reduction and diversion of flow in free-drainage levels can occur as a result of this continued coal extraction from coal barriers. The environmental, implications of this loss of discharge will be discussed in Chapter 10. Also two general case models have been developed, firstly a conceptual model of groundwater flow in a free-drainage level dominated by the presence of barrier (Figure 6.17), and secondly, a graphical representation technique to determine whether coal barriers are intact or have been removed for any free-drainage level discharge. Both of these models form the basis for the implementation of a groundwater management policy.

Finally, although in Britain there is a statutory obligation to survey the extent of mine workings, these coal mine plans form an essential though imperfect basis for the interpretation of the hydrological functions of the abandoned workings However, many mine plans are incomplete and some times erronous. Because interpretation of the flow routes in mine voids depends largely on the nature of any coal barriers remaining, a single unrecorded roadway may substantially alter the flow conditions underground. Other difficulties in the use of coal mine plans relate to blockage and ponding of the roadways and drainage lines which can substantially divert flow, but for which the location, extent and response cannot be predicted.

CHAPTER 7.

THE QUANTIFICATION OF THE HYDROGEOLOGICAL CHARACTERISTICS OF ABANDONED COAL MINED AQUIFERS.

7.1 INTRODUCTION.

The previous two chapters have determined groundwater flow paths, patterns and catchment areas in the abandoned coal mined aquifers. This chapter quantifies the hydrogeological characteristics of these aquifers, in terms of flow velocities, transmissivity, storativity, and storage volumes. These parameters are determined primarily using recession curve techniques (for both groundwater discharges and groundwater levels), but this is supplemented by the analysis of available pumping test data for the STWA boreholes, and quantitative fluorescent dye tracer tests (Table 7.1). The results presented quantify the hydrogeological parameter transmissivity for the major aquifers (Coleford High Delf, Yorkley, Brazilly and Serridge Aquifers) as areal average values for the whole aquifer. Total storage volumes for these aquifers are also calculated. In some cases the total storage can be subdivided into temporary fracture and fissure storage in the vadose or unsaturated zone and flooded or ponded storage in the phreatic or saturated zone for the Pennant Sandstone Aquifer. It has been possible to determine the hydrogeological parameters for three sub-categories. Firstly for the Coleford High Delf Aquifer as a whole (Pennant Sandstone and coal mined voids) from recession curve analysis for the Norchard Drift discharge, secondly for the Pennant Sandstone from pumping test data at the Cannop Cross Borehole, and thirdly for the coal mined voids from artificial tracer tests. This later category has been sub-divided into shallow (essentially free-flowing) and deep (saturated) groundwater circulation mined voids. The analysis of the Brazilly and Serridge Aquifers has been confined to areal aquifer parameter estimates only (Table 7.1) due to the limited data available.

7.2 THE USE OF RECESSION CURVE ANALYSIS TECHNIQUES TO IDENTIFY STORAGE ZONES.

The two forms of recession curve analysis used here involves discharge and groundwater level recessions. Discharge recession curves are the decline in discharge with respect to time, as a result of the decline in groundwater storage. Normally, it is necessary to construct the recession curve (which contains both surface runoff and groundwater baseflow) by the addition of different segments of the rece ding groundwater discharge, a process known as superposition (Fetter 1980). In the examples used here the construction of the recession curve was much simpler because all the adits that were monitored

TABLE 7.1

HYDROGEOLOGICAL CHARACTERISTICS DETERMINED FOR COAL MINED AQUIFERS OF THE FOREST OF DEAN COALFIELD. THIS TABLES INDICATES THE HYDROGELOGICAL PARAMETERS DETERMINED AND THE METHOD USED.

AQUIFER / TECHNIQUE USED	PENNANT		SUPRA PENNANT	
	DEEP GROUNDWATER CIRCULATION COLEFORD HIGH DELF AQUIFER	SHALLOW GROUNDWATER CIRCULATION COLEFORD HIGH DELF	BRAZILLY AQUIFER	SERRIDGE AQUIFER
BASEFLOW RECESSION	TOTAL STORAGE AND STORAGE ZONES	TOTAL STORAGE AND STORAGE ZONES	TOTAL STORAGE AND STORAGE ZONES	TOTAL STORAGE AND STORAGE ZONES
	T AREAL AVERAGE FOR WHOLE AQUIFER	T AREAL AVERAGE FOR WHOLE AQUIFER	T AREAL AVERAGE FOR WHOLE AQUIFER	T AREAL AVERAGE FOR WHOLE AQUIFER
GROUNDWATER RECESSION	T AREAL AVERAGE FOR WHOLE AQUIFER	T AREAL AVERAGE FOR WHOLE AQUIFER	-------	-------
GROUNDWATER LEVELS	T WHOLE AQUIFER *	-------	-------	-------
PUMPING TESTS	T and S PENNANT SANDSTONE	-------	-------	-------
DYE TRACING TECHNIQUES	STORAGE FLOODED MINED VOID	STORAGE FLOODED MINED VOID	-------	-------
	FLOW VELOCITY	FLOW VELOCITY	------	-------

Legend :-

T - Transmissivity, S - Storativity.
* - Also determined for the deep groundwater circulation of the Yorkley Aquifer.

showed no response to short term rainfall events, and only where discharge slightly increased or maintained was any adjustment to the natural recorded decline in the groundwater discharge recession curve necessary.

It has been widely reported (Fetter 1980, Martin 1973, Karanjac and Altug 1980, and Nutbrown and Downing 1976) that the recession curve can be represented by the equation :-

$$Q = Q_o e^{-kt} \text{..............................Equation 7.1}$$

Where Q = the flow at time (t) after the recession started

Q_o = the flow at the start of the recession

k = the recession constant for the catchment area or aquifer drained.

t = the time since the recession began.

As this equation is of an exponential form, it can also be expressed in logarithmic notation.

$$\ln Q = Q_o - kt \quad \text{.....................Equation 7.2}$$

When the recession curve is constructed as a log-normal graph this later equation allows the rapid determination of the recession constant (k), because the graphical plot is a straight line and the recession constant is analogous to the gradient, (because equation 7.2 has the same form as y = mx + c where m is the gradient of the straightline). The results of determining the recession curve equations and recession constants are shown in Table 7.2.

A similar equation is also used for the recession of groundwater levels:

$$H = H_o e^{-kt} \text{ ....Equation 7.3}$$

Where H = the level of ground water at time t

H_o = the level of groundwater at time t=0

t = time (in days)

and k = the recession constant

The recession constants are shown in Table 7.3.

When plotted on a log/normal graph sometimes recession curves show distinctive changes in slope (compound curves), this is interpreted as the draining of different linear stores (Figure 7.1). Where this is the case for the recession plots (Figures 7.2, 7.4 and 7.6), recession equations have been calculated for both segments.

7.2.2 STORAGE IN THE PENNANT AQUIFER.

The shallow groundwater circulation adits, Miles and Old Furnace Levels have compound recession curves (two components), while those for Scotts, Bixslade

FIGURE 7.1 : Construction and general interpretation of a compound recession curve.

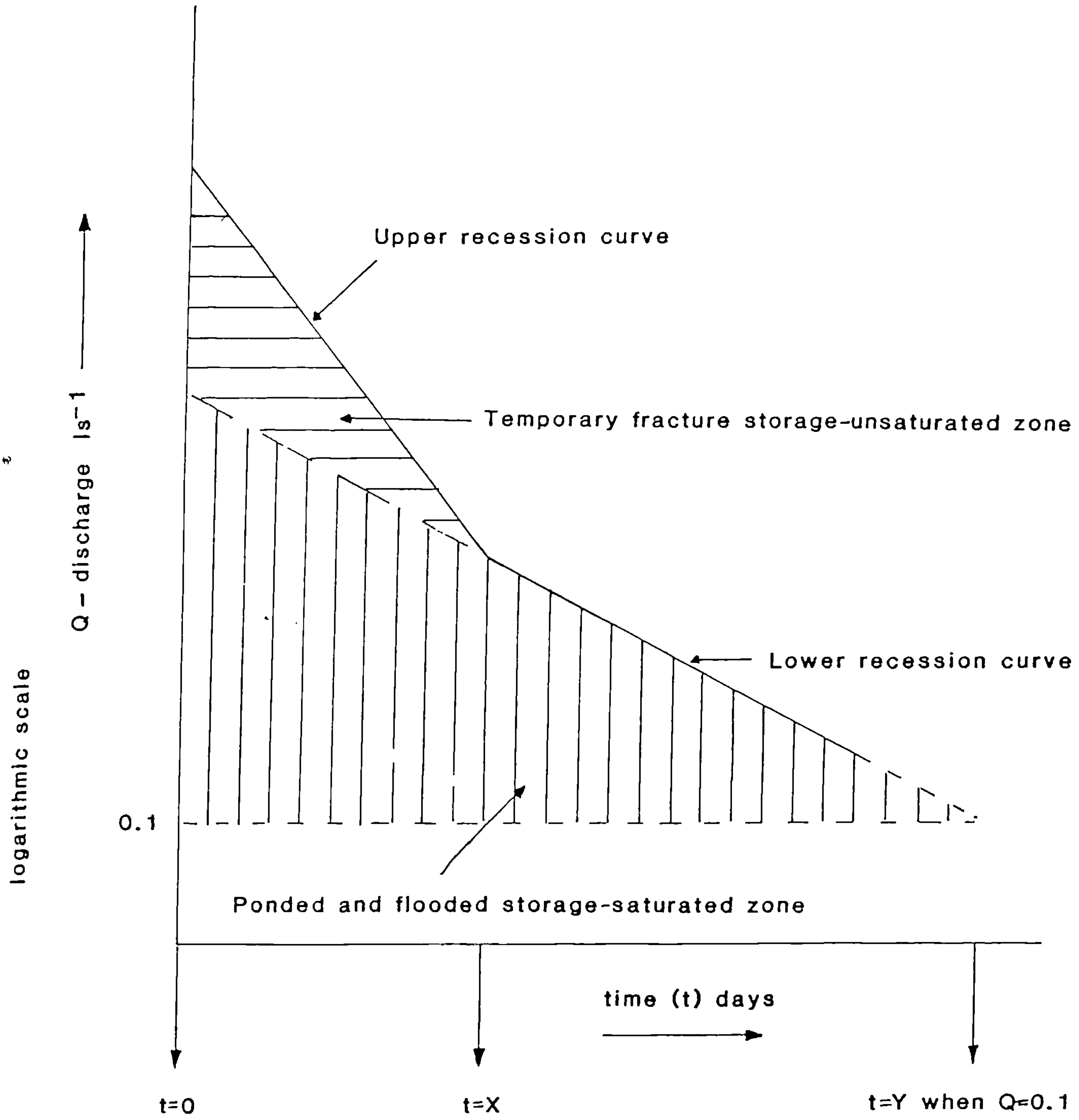


TABLE 7.2

RECESSION CURVE EQUATIONS AND RECESSION CONSTANTS FOR DISCHARGE SITES.

Site		Equation	r^2	n
PENNANT GROUP (COLEFORD HIGH DELF AND YORKLEY AQUIFER UNITS)				
DEEP GROUNDWATER CIRCULATION				
NORCHARD DRIFT	1.	$Q= 436e^{-0.009\,t}$	$r^2=0.995$	n=12
	2.	$Q= 336e^{-0.006\,t}$	$r^2=0.993$	n=15
SHALLOW GROUNDWATER CIRCULATION				
OLD FURNACE LEVEL	1.	$Q=122.0e^{-0.0538t}$	$r^2=0.998$	n=6
	2.	$Q= 66.7e^{-0.0147t}$	$r^2=0.994$	n=19
MILES LEVEL	1.	$Q=105.0e^{-0.0276t}$	$r^2=0.975$	n=10
	2.	$Q= 59.0e^{-0.0133t}$	$r^2=0.993$	n=20
BIXSLADE LOWER LEVEL		$Q= 4.3e^{-0.0124t}$	$r^2=0.979$	n=8
BIXSLADE UPPER LEVEL		$Q= 14.6e^{-0.0161t}$	$r^2=0.987$	n=15
SCOTTS LEVEL		$Q= 2.2e^{-0.0155t}$	$r^2=0.89$	n=5
QUEST SLADE		$Q= 43.6e^{-0.0713t}$	$r^2=0.98$	n=11
SUPRA PENNANT GROUP (BRAZILLY AQUIFER UNIT)				
INDEPENDENT LEVEL	1.	$Q= 46.5e^{-0.0186t}$	$r^2=0.991$	n=11
	2.	$Q= 24.5e^{-0.0085t}$	$r^2=0.987$	n=11
CANNOP LEVEL		$Q= 14.3e^{-0.0164t}$	$r^2=0.974$	n=10
PARKEND COLLIERY SPRING		$Q= 18.6e^{-0.0072t}$	$r^2=0.93$	n=6
SPECULATION COLLIERY SPRING		$Q= 2.2e^{-0.0127t}$	$r^2=0.755$	n=5
SUPRA PENNANT GROUP (SERRIDGE AQUIFER UNIT)				
KENSLEY LODGE STREAM		$Q= 1.5e^{-0.0345t}$	$r^2=0.979$	n=14

TABLE 7.3

RECESSION CURVE EQUATIONS FOR GROUNDWATER LEVEL SITES.

Site	Year		Equation	r^2	n
PENNANT GROUP (COLEFORD HIGH DELF AQUIFER UNIT)					
CANNOP COLLIERY	1984		$H=41.7e^{-0.00128t}$	$r^2=0.995$	n=28
FLOURMILL COLLIERY	1984		$H= 30e^{-0.00109t}$	$r^2=0.983$	n=29
	1984	1.	$H=31.2e^{-0.00223t}$	$r^2=0.911$	n=8
	1984	2.	$H=29.1e^{-0.00085t}$	$r^2=0.972$	n=21
SALLOWVALLETS BOREHOLE	1980		$H=48.9e^{-0.00252t}$	$r^2=0.965$	n=10
	1981		$H=50.9e^{-0.00305t}$	$r^2=0.985$	n=9
	1984		$H=43.4e^{-0.00164t}$	$r^2=0.983$	n=23
CANNOP CROSS BOREHOLE	1979		$H=29.6e^{-0.0016\,t}$	$r^2=0.983$	n-9
PENNANT GROUP (YORKLEY AQUIFER UNIT)					
CANNOP CROSS BOREHOLE	1980		$H=57.4e^{-0.00028t}$	$r^2=0.897$	n=11
	1981		$H=58.5e^{-0.00031t}$	$r^2=0.988$	n=7
	1982		$H=59.7e^{-0.0002\,t}$	$r^2=0.917$	n=6
	1984		$H=59.7e^{-0.0003\,t}$	$r^2=0.925$	n=13

Legend :- Regression equations prefixed with a number refer to upper (1) and lower (2) recession curves. All other equations refer to total data sets.

FIGURE 7.2 : Recession curves for the major Pennant adit discharges.

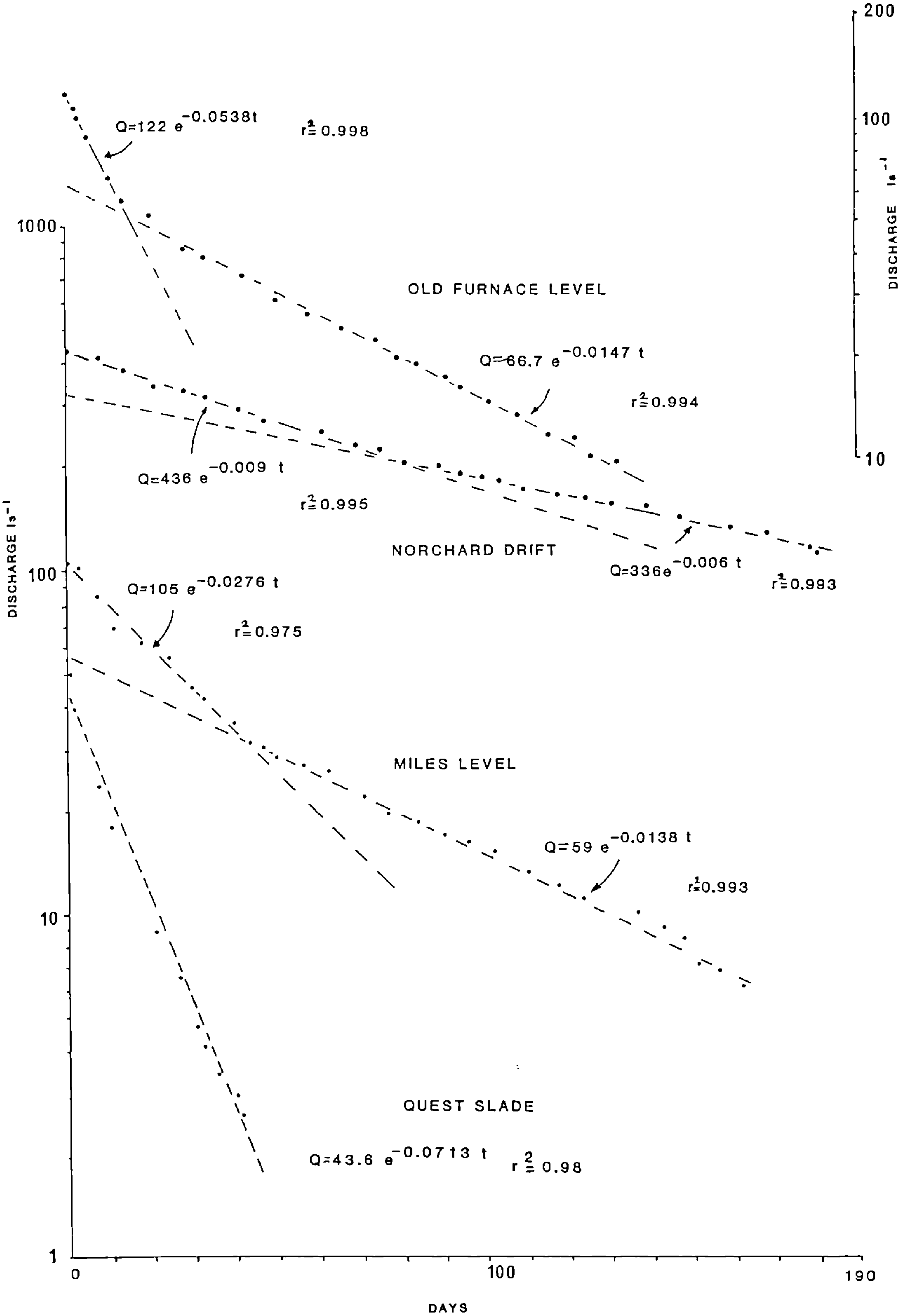
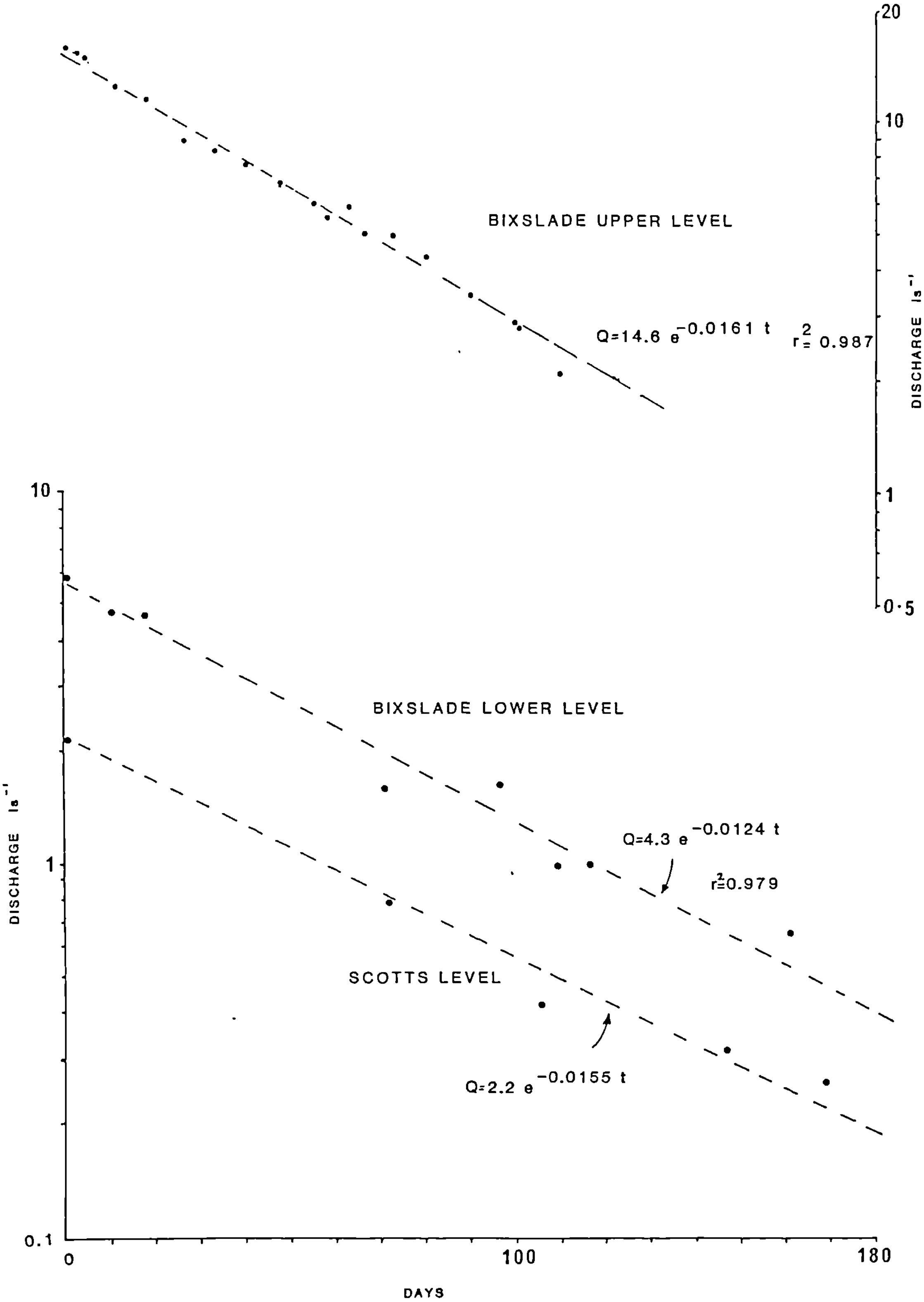
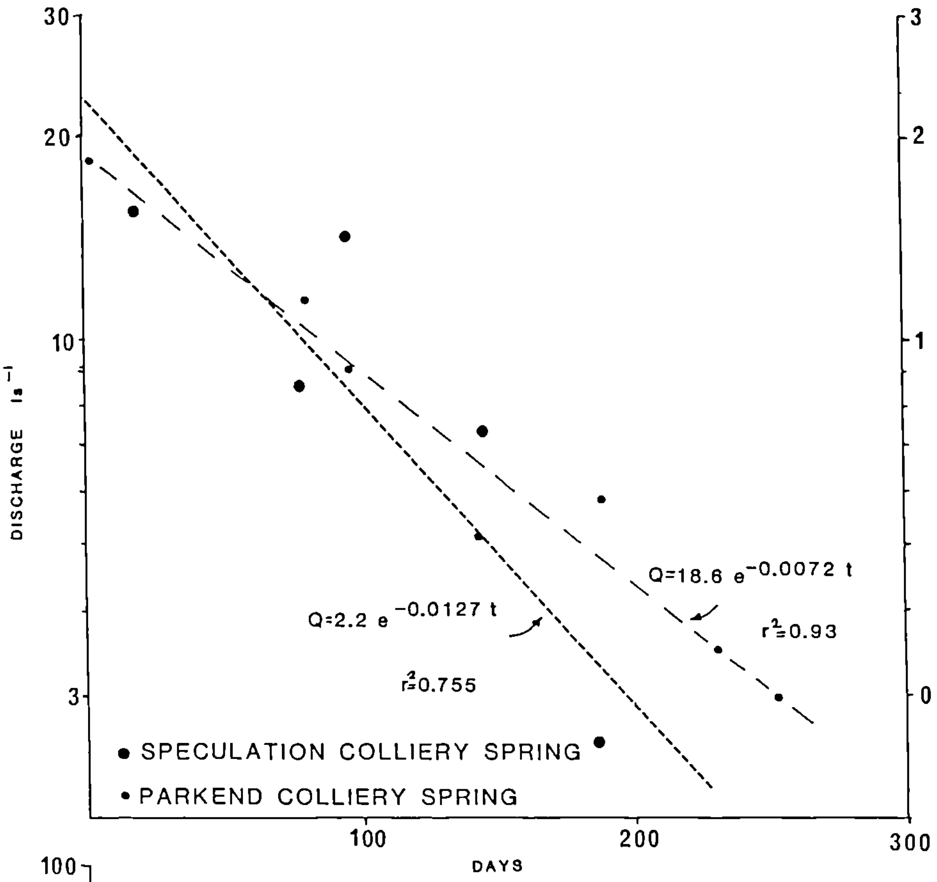


FIGURE 7.3 : Recession curves for the smaller Pennant adit discharges.





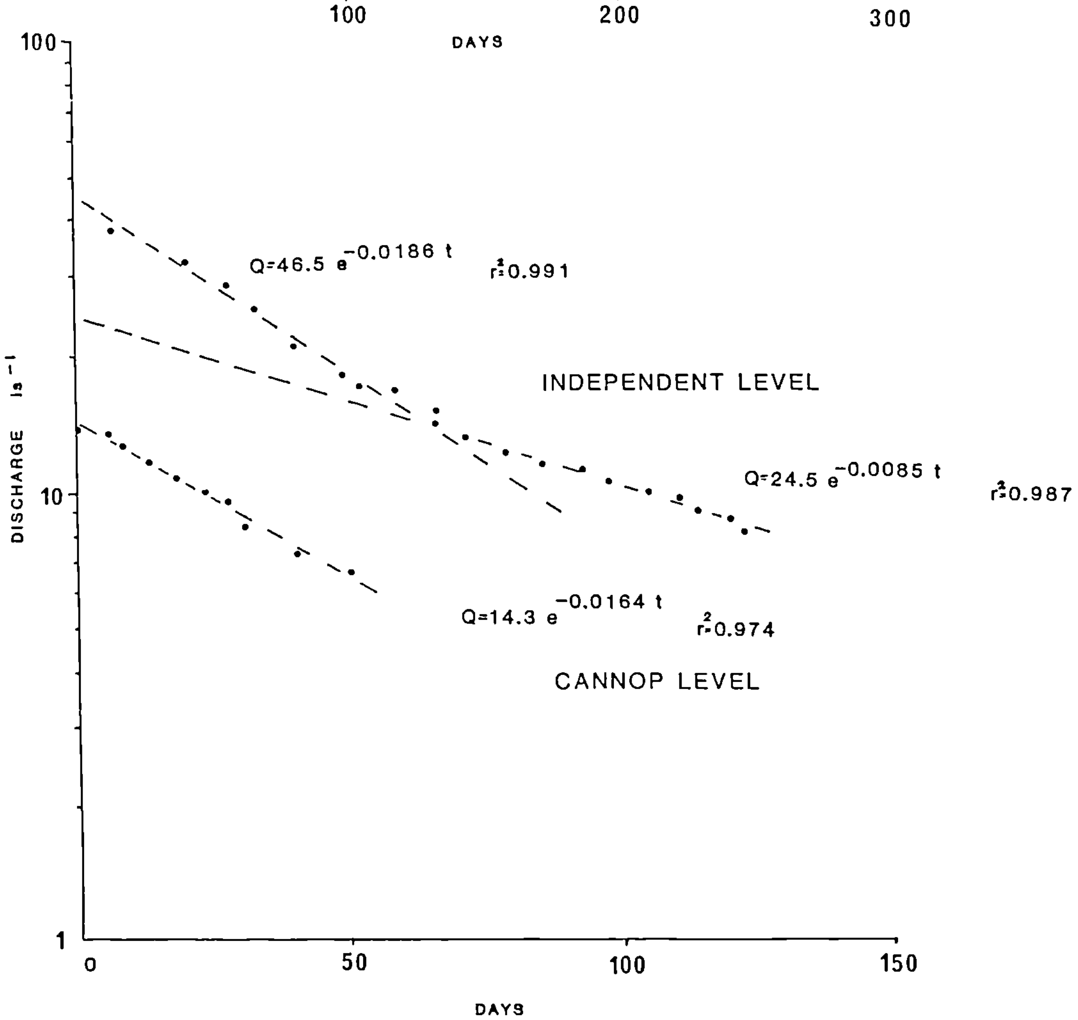


Figure 7.4 : Recession curves for the Supra Pennant adit and mine drainage spring discharges.

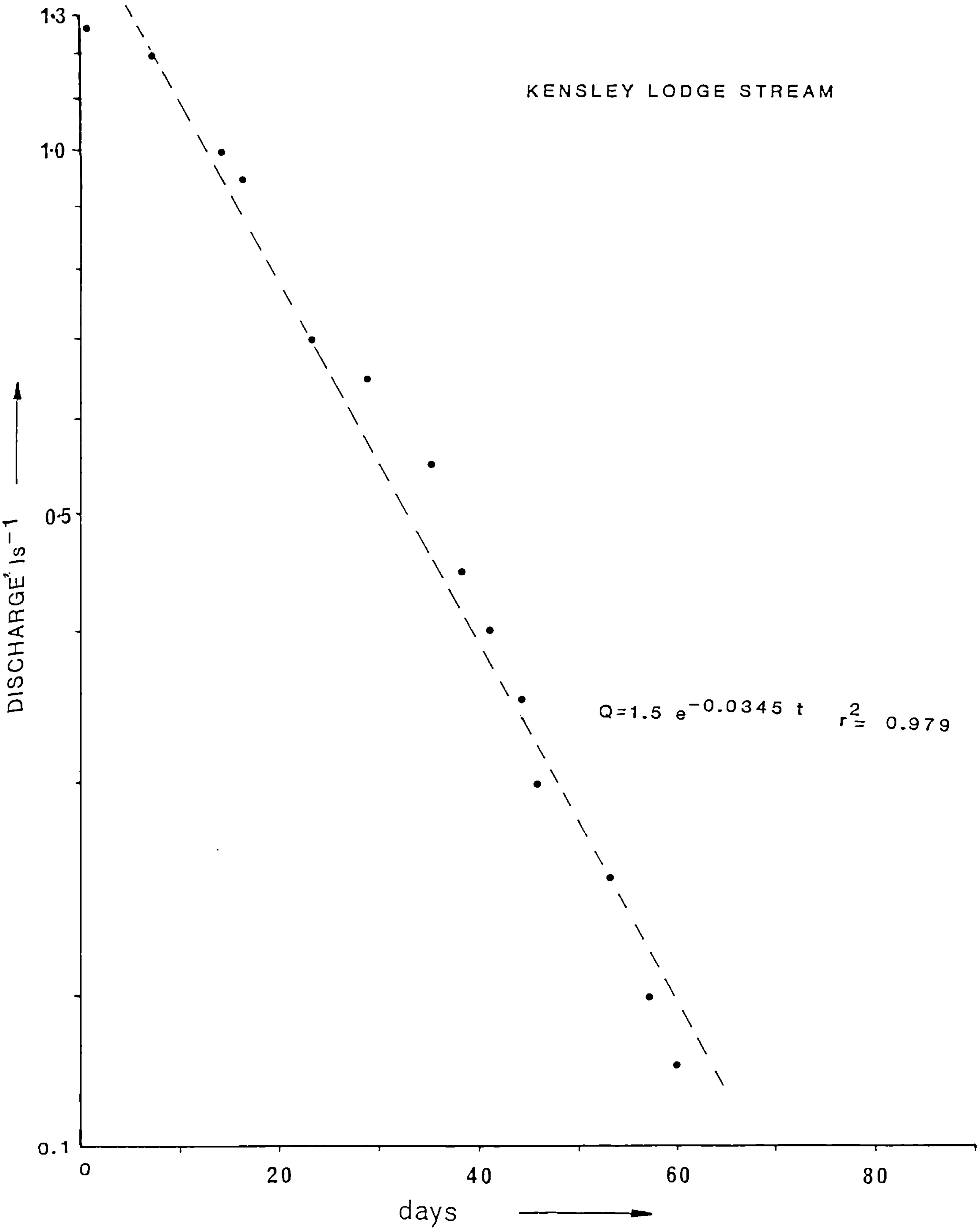


FIGURE 7.5 : Recession curves for the Kensley Lodge Stream which drains the Serridge Aquifer.

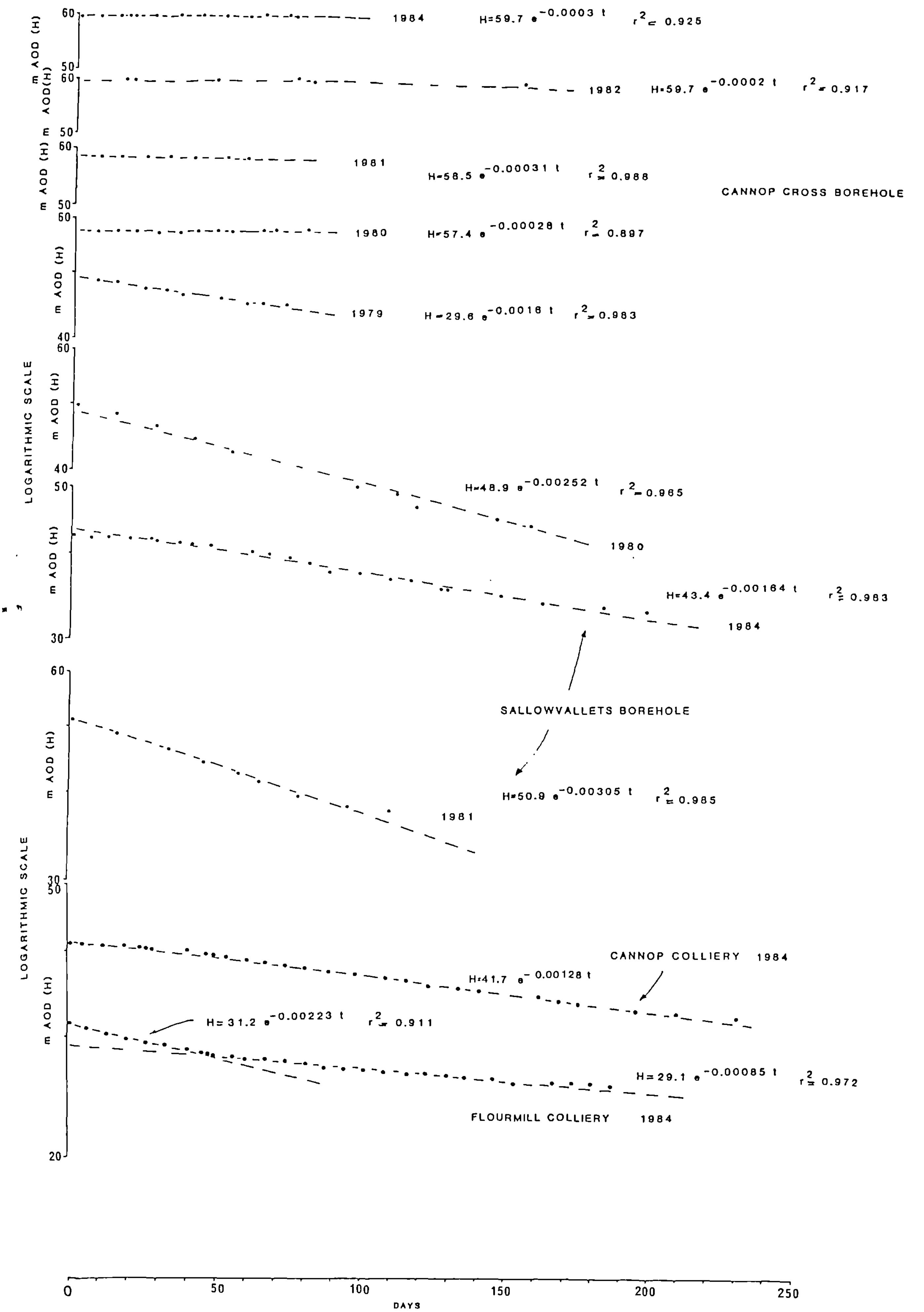


Figure 7.6 : Groundwater level recession curves for the Pennant Aquifer.

Upper and Lower and Quest Slade Levels are single component curves. The single component curves have differing recession coefficients. Those of the Bixslade Upper (0.0161) and Lower (0.0124) Levels and Scotts Level (0.0155) are similar to the lower components of the Miles (0.0138) and Old Furnace (0.0147) Levels, while that of the Quest Slade (0.0713) is similar to the upper component from the Miles (0.0275) and Old Furnace (0.0538) Levels. The upper component of the recession curve is interpreted as rapid drainage from temporarily flooded fractures and fissures (fracture flow) in the vadose zone (Plate 6.2). This theory is supported by winter peak flows corresponding to maximum recharge periods, which would indicate that recharge is rapidly transmitted through the open fractures and fissures (Figure 6.9 and 6.10). While the lower component represents slower drainage of a flooded or ponded storage zone. This drainage is from saturated storage in both flooded mined voids and the adjacent sandstone. The summer baseflow is the slower drainage of the flooded or ponded zone.

The temporary fracture storage recessions from Miles and Old Furnace Level are 0.0538 and 0.0276, and the value for the Quest Slade adit is 0.0713. These represent pure fracture flow drainage, and is supported by the short length of the recession curve, 40 days for the Quest Slade adit, 43 days at Miles Level, and 11 days at the Old Furnace Level. The shorter length of time for the Old Furnace Level is a function of the integration of the fracture flow drainage with the ponded or flooded storage zone. In the case of the Miles Level it is known that the volume of flooded mined void is small (see below). In the case of the Old Furnace Level it is known that a substantial flooded and ponded section exists beyond the terminal collapse on the main cross measure roadway (chapter 6). Drainage of rapid fracture flow into the ponded section caused by the reversal of dip by the Ridge Anticline (Figure 4.1) would not be transmitted directly to the adit discharge but in fact be redistributed to further flooded storage (ponded fracture/fissure storage) within the ponded section.

In comparison the monitoring sites at Scotts Level, Bixslade Lower and Upper Levels all have recession constants (0.0155, 0.0124 and 0.0161 respectively) which are much lower and are comparable to those of the lower portions of Miles and Old Furnace Level recessions curves (which were 0.0138 and 0.0147 respectively). The lower section of these recession curves represents drainage from storage in the flooded or ponded zone (in the case of the shallow groundwater circulation adits). Therefore it would appear that at Scotts Level and Bixslade Lower and Upper Levels the discharge is comprised solely of flooded and ponded drainage. This is supported in part by the longer duration of the recession curves 170, 180 and 120 days respectively. It should be stated that this interpretation is based on a minimal data for some of the sites discussed and must be viewed with care. More detailed gauging at such sites may reveal slightly different results, for instance fracture flow may be present at Scotts Level but for a short time period perhaps <20 days and was therefore not measured in this study.

The absence of a second component at the Quest Slade Adit indicates that this level drains only the temporary fracture storage and that no saturated storage occurs. The Quest Slade Adit is considerably higher in elevation compared with that of Miles Level (90.8 m AOD compared with 76.0 m AOD) and this would indicate that the upper coal barriers have been removed which allows recharge to continue to lower level precluding the formation of a saturated zone at this higher elevation. Although, the drainage barriers (Figure 6.7) have been removed close to the adit portals at both the Upper and Lower Bixslade Levels the presence of a saturated storage zone is explained by the existence of blockage collapses forming saturated groundwater mounds in the major roadways and adjacent sandstones (Figure 6.11).

The Norchard Drift drains the deep groundwater circulation of the Coleford High Delf Aquifer (chapter 6). This also has a two component recession curve, with both the upper and lower curves having small recession constants. In the case of the Norchard Drift the difference between the two recession constants is small, and visual inspection of the recession curve indicates that there is little difference between the two discharge components and that the response by the components is much more delayed than in the case of the shallow adits (Figure 5.13). However, the difference may be attributed to two processes, the drainage of flooded coal workings and the flooded Pennant Sandstone fractures. This would also indicate that a two phase flow system exists in the deep basin. The two deep basin groundwater level monitoring sites Flourmill Colliery and Cannop Colliery shafts have slightly differing recession curves. The curve for the Flourmill Colliery has an upper and lower section while the Cannop Colliery curve forms a single recession curve. However, the recession constant for all of the Flourmill Colliery Shaft data is not significantly different from either of the other constants calculated and is similar to that of the Cannop Colliery Shaft.

The Sallowvallets borehole shows a variable recession constant for the three years for which data is available. As the initial water levels are similar this suggests that the manner in that recharge occurs affects the recession or a major change in the nature of the aquifer has occurred. However, in general the values are similar to the those for the Cannop and Flourmill Collieries. The data for the Cannop Cross Borehole (Yorkley Aquifer see chapter 5) is different (Table 7.3). The recession constants are significantly smaller than those from any other sites for all years except 1979. The values for the years 1980, 1981, 1982 and 1984 all lie between 0.0002 and 0.0003, while that for the year 1979 is 0.0016. This value is similar to those for the deep basin of the Coleford High Delf Aquifer, and is in fact representative of this aquifer because in 1979 the borehole was drilled through the overlying Yorkley Aquifer, but later extrusion of the Yorkley seat earth sealed the lower part of the borehole.

7.2.2 STORAGE IN THE SUPRA PENNANT AQUIFER

The sites from the Supra Pennant Group Brazilly Aquifer fall into two categories; those that drain rapidly, Speculation Colliery Spring (recession coefficient 0.0127) and Cannop Level (0.0164) and the upper portion of the Independent level recession (0.0182) and, those that drain slowly; Parkend Colliery Spring (0.0072) and the lower section of the Independent Level recession (0.0085). But it is not possible to compare the recession constants directly with those of the Pennant Aquifer, because the recession coefficients for the upper component of the curve are similar to those of the lower component of the Pennant Aquifer. The coefficients for the lower component for the Supra Pennant Aquifer are even smaller in magnitude. Although a similar general two component interpretation can be made of the recession curves, the difference in coefficient magnitudes are attributable to differing aquifer properties. The rapidly draining sites again represents drainage from temporary storage in flooded fractures, but in this case it is important to note the locations of the sites, because this indicates the storage zone and drainage transmission behaviour. The sites to the north of the east-west barrier (Figure 6.1) (Cannop Level and Speculation Colliery Spring) all have single recessions with only fracture drainage being present. It is therefore suggested that the slower less rapid drainage of flooded or ponded storage is lost to the deep basin and is not discharged via these locations and passes through the east-west barrier (as hypothesised from the catchment boundary calculations and water budgets) and is discharged to the south via either the Parkend Colliery Spring or Independent Level. The fracture flow component present at the Independent Level would be the direct transmission of recharge from the sandstones outcropping above the Lowery coal seam. The Parkend Colliery Spring recession curve is considerably longer (260 days) than that at the Independent Level and may therefore represent drainage from another aquifer. There are two possibilities, firstly drainage from the ponded aquifers which lie below the Lowery coal seam and Independent Level, or secondly, drainage from the Yorkley Aquifer. This later case is supported by the location of the spring. It is adjacent to the Cannop Fault Belt and within the area where possible outflow from the Yorkley Aquifer to the Cannop Brook could occur.

The other aquifer unit present in the Supra Pennant Group of rocks is the Serridge Aquifer and the recession constant for the small stream (Kensley Lodge Stream) which drains a perched aquifer of the uppermost sandstones of this aquifer unit shows a single recession curve and a large recession constant (0.0345) which suggests that storage is small and drainage of flooded fractures is rapid.

In conclusion the analysis of baseflow recession constants has enabled the differentiation between groundwater storage zones. These storage zones fall into two categories :

(i) a rapidly draining 'quick flow' component which is interpreted as temporary storage in the major fractures and fissures of the sandstones present.

and (ii) a slow draining 'baseflow' component which is interpreted as drainage from flooded or ponded storage in both sandstone and mined voids.

However, it is not possible to determine separate characteristics solely from the recession constants between differing aquifer units due to differing aquifer properties. The next section will determine the volumes stored within the zones identified and quantify their importance in the aquifers understudy.

7.3 TOTAL STORAGE VOLUMES WITHIN COAL MINED AQUIFERS.

If a discharge recession curve is integrated from a particular time t to infinity, the total volume of storage can be equated:-

$$V_{\infty} = \int_{t=0}^{t=\infty} Q \, . \, dt \qquad \text{.................... Equation 7.4}$$

The use of the integral method requires either the integration of the discharge baseflow recession equation between time t= 0 and t= x when the curve is compound or t= 0 (or t= x when stepped) and t= infinity (t= Y Figure 7.1). The latter is a difficult case and a set discharge value is assigned and the relevant t value calculated. Storage volumes were calculated for the lower recession of a compound curve from t= 0 to a time when Q= 0.1 ls^{-1}, and for the upper curve for t= 0 to t= x where x was the curve breakpoint.

The previous section has indicated that storage occurs in two different forms:

(i) temporary fracture and fissure storage in the vadose zone or unsaturated zone

and (ii) ponded or flooded storage in the phreatic or saturated zone.

However, storage also occurs in the primary pores of the host rock, the Pennant Sandstone in the case of the Coleford High Delf and Yorkley Aquifers, the intermediate sandstones of the Brazilly Aquifer and Serridge and Crabtree Hill Sandstones of the Serridge Aquifer. In the case of the former, the primary porosity (intergranular) of the major aquifer, the Pennant Sandstone was calculated as 2 % (Chapter 2), these pores while holding capillary water, will not drain easily under gravity. A similar case is assumed for the other sandstones. Therefore, storage in the primary pores can be neglected.

The results (Table 7.4) indicate that the largest storage volume is within the deep saturated zone draining to the Norchard Drift. This comprises of 94.6 % of the storage discharged from the Norchard Drift. The upper recession provides only 5.4 % of the storage present. In the case of the Miles and Old Furnace Levels saturated storage is 86 % and 93 % respectively. The proportion of temporary fracture storage is remarkably small, the highest total being 0.06 x 10^6 m^3 or 14 %. The saturated storage for the Bixslade (Upper and Lower) and Scotts Levels is considerably smaller than that for the Miles and Old Furnace Levels this may indicate the storage is only associated with groundwater mounds formed by blockage collapses (see chapter 6) or that the majority of ponding occurs close to the head of the cross measure level and the river level drainage barriers which are below the elevation of the Bixslade Levels and above that for the Miles Level adit portal. The flooded fracture storage for the Independent Level is also similar in magnitude 0.044 x 10^6 m^3 or 37.3 % of the total storage, however in the case of this level the saturated storage is considerably less.

As all of the possible drainage outlets draining both the Supra Pennant Group Brazilly Aquifer and the Pennant Group Coleford High Delf Aquifer were monitored it is possible to quantitify the total storage within these aquifers. (This however does not take into account the small portion of storage in the Pennant Sandtone drained by the free-drainage levels which penetrate the Carboniferous Limestone on the western outcrop (Tufts, Parkhill

TABLE 7.4

TOTAL STORAGE VOLUMES (x 10^6 m^3) CALCULATED FROM DISCHARGE RECESSION CURVES FOR THE MAJOR ADITS.

PENNANT GROUP - DEEP GROUNDWATER CIRCULATION (COLEFORD HIGH DELF AQUIFER)			
	SATURATED STORAGE[1]	SATURATED STORAGE[2]	TOTAL STORAGE
NORCHARD DRIFT	0.28	4.9	5.18
PENNANT GROUP - SHALLOW GROUNDWATER CIRCULATION			
	TEMPORARY FRACTURE STORAGE	SATURATED STORAGE	TOTAL STORAGE
OLD FURNACE LEVEL	0.02	0.38	0.40
MILES LEVEL	0.06	0.36	0.42
SCOTTS LEVEL	----	0.07	0.07
QUEST SLADE	0.05	----	0.05
BIXSLADE UPPER LEVEL	----	0.08	0.08
BIXSLADE LOWER LEVEL	----	0.02	0.02
SUPRA PENNANT GROUP (BRAZILLY AQUIFER)			
INDEPENDENT LEVEL	0.044	0.074	0.118
CANNOP LEVEL	0.013	----	0.013
SPECULATION COLLIERY SPRING	0.01	----	0.01
PARKEND COLLIERY SPRING	----	0.02	0.02
SUPRA PENNANT GROUP (SERRIDGE AQUIFER)			
KENSLEY LODGE STREAM	----	0.0034	0.0034

Legend :- [1] Upper recession component. [2] Lower recession component.

and Oakwood levels). The results of these calculations are shown in Figure 7.4.

These calculations confirm the conclusions above that the dominant storage zone is in the saturated region of the aquifer and indicates the minor role played by the temporary fracture storage in the unsaturated zone. More importantly figure 7.4 shows the differences in storage characteristics between the Pennant Coleford High Delf and Supra Pennant Brazilly Aquifers. In the latter the percentage of flooded storage is considerably smaller. This is due to and complicated by two factors :

(i) The recession curve for drainage of the ponded storage zone for the major discharge the Independent Level is short (direct recharge), total length 125 days (Figure 7.4), and that after this time the discharge is completely composed of another component (indirect recharge) (chapter 6) referred to as a constant leakage component. The total storage in the flooded zone in this case is therefore only calculated for the 125 days it is present. This probably gives a more accurate estimate of the storage as an extrapolation to an assumed 0.1 ls^{-1} is not required.

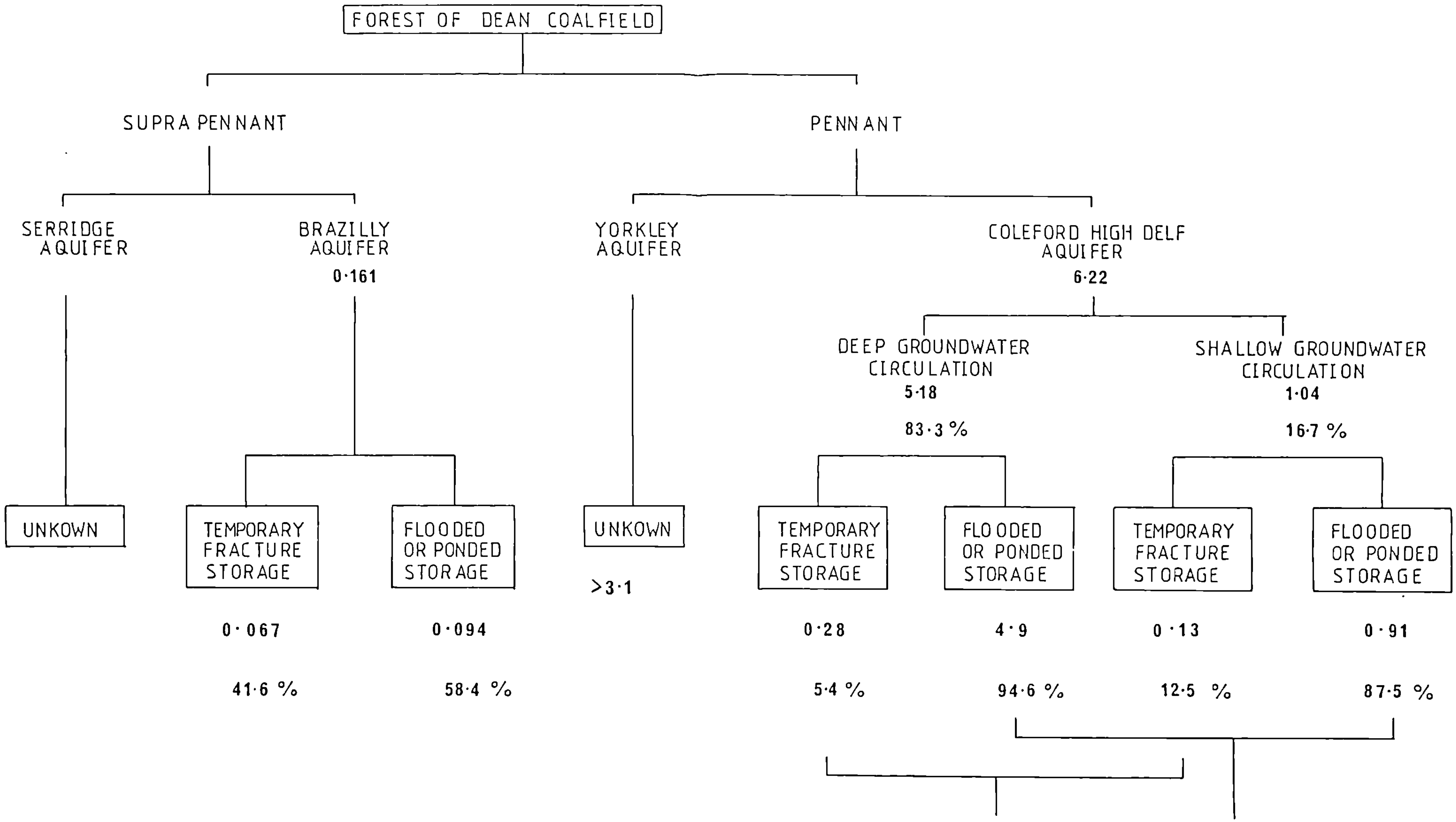
(ii) However, the constant leakage drainage which represents 8 ls^{-1} throughout the year must drain from a source. This was explained in chapter 6 as the drainage from ponded or saturated perched aquifers above that of the Lowery coal seam in which the Independent Level is driven. This therefore adds complication because as the constant leakage does not detectably recede in value over the maximum possible monitoring period it does not possess a recession curve. The minimum storage volume is therefore (8 ls^{-1} x 334 days) 0.23 x 10^6 m^3.

It has not been possible to quantify the total aquifer storage volumes for the Serridge or Yorkley Aquifers, but it can be speculated that in the case of the former the total storage is small as the majority of rainfall does not infiltrate and during prolonged dry summers many of the small springs dry up. The contrary is probably the case for the Yorkley Aquifer, because this aquifer has a diffuse groundwater outflow which drains to the south by the Cannop Brook. The volume discharged to the Cannop Brook (calculated from data in chapter 5) is the only estimate of storage available, this is 3.1 x 10^6 m^3.

7.4 STORAGE IN FLOODED COAL MINE WORKINGS.

The previous section has quantified the storage volumes present within the rapidly draining temporary fracture storage of the vadose zone and the flooded and ponded storage of the saturated zone of the major aquifers of the Forest

FIGURE 7.7 : Tree diagram showing the calculatable storage volumes held within the major aquifers of the Forest of Dean.



All values x 10^6 m^3

of Dean. This section quantifies the storage volumes present within the major saturated mine roadways present in both the shallow and deep groundwater circulations of the Pennant Group. The mine roadways are important because the volume of storage within the mine roadway is the last source of dilution for any pollutant matter before being discharged to the surface and they are also directly linked to possible unauthorised waste disposal sites such as collapsed shafts, or adit entrances.

7.4.1 SHALLOW GROUNDWATER CIRCULATION (COLEFORD HIGH DELF AQUIFER).

By analysing the travel times and the discharge volumes for the two tracer tests conducted in the shallow abandoned coal workings of the Miles Level (see chapter 6 for details) during low flow (discharge 8.0 ls^{-1}) and high flow (discharge 69 ls^{-1}) it is possible to compute a value for the likely storage volume of the flooded mine roadways and mined voids. In the case of the Miles Level many of the upper level workings remain open and are within the vadose zone of the Pennant Sandstone Aquifer. However, ponded storage zones do occur, for instance behind blockage collapses and where adit floor collapse causes ponding (referred to in chapter 6). These ponded sections are predominantly contained within the old haulage roadways, because the mined void where coal extraction has taken place has been filled by the seat earth clay (Plate 2.4) and the available space for ponded storage in the mined void is therefore very small in comparison. These calculations indicate the haulage roadway storage volumes.

By using the principles outlined by Stanton and Smart (1981), the roadway between the injection and recovery points must be predominantly water filled because the additional discharge between low and high flow (8.0 to 69 ls^{-1}) is wholly accommodated by an increase in velocity, (assuming the width (w) and depth of water (d) in a submerged roadway are constrained, because $Q = w.d.v$). The volume of the flooded or saturated roadway can be calculated by using the volume of water discharged from the adit between the time of injection and tracer centroid (time at which 50 % of the injected tracer passed the sample point) (Figure 7.8). However, an increase in discharge occurs between the injection and recovery sites (in this case 9.6 to 69.0 high flow and 2.4 to 8.0 ls^{-1} low flow), therefore the true volume lies between the value calculated using the minimum (input) and maximum (output) discharges. The calculated storage volumes lie between 500 and 70 m^3 for high flow conditions and 285 and 86 m^3 for low flow conditions.

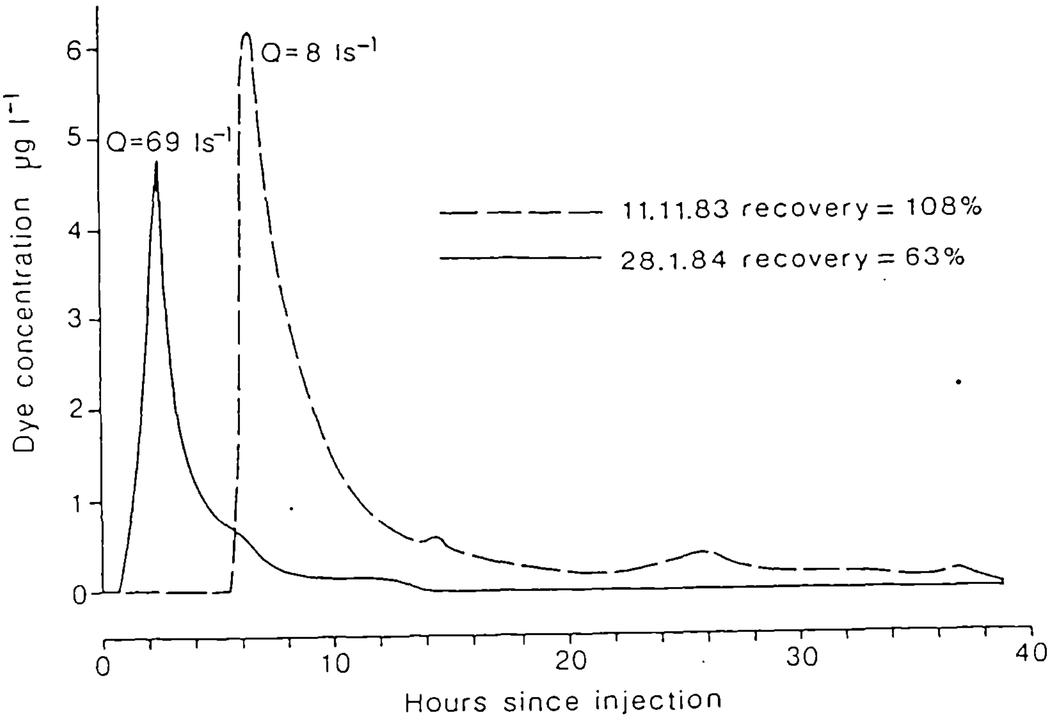


FIGURE 7.8 : Sulpho Rhodamine B tracer breakthrough curves for the Miles Level from tracer tests conducted at low and high flow conditions.

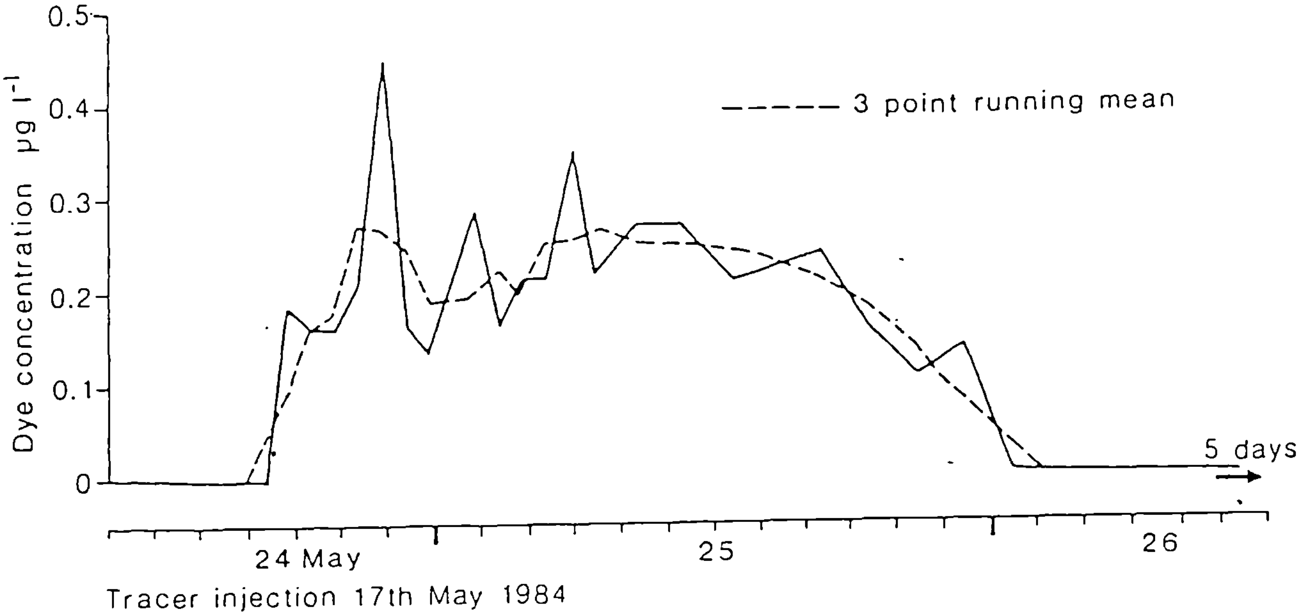
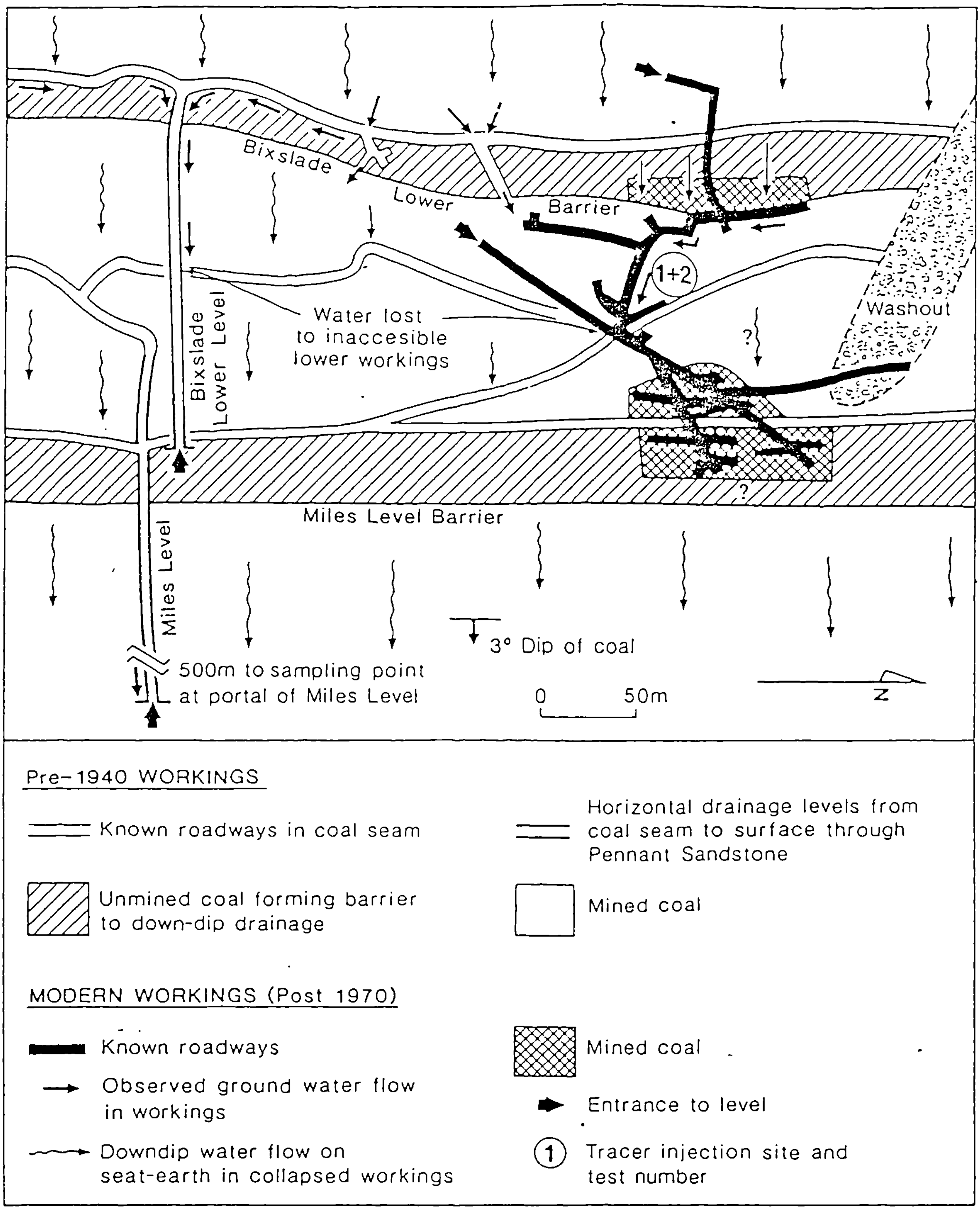


FIGURE 7.11 : Sulpho Rhodamine B tracer breakthrough curve for the Norchard Drift discharge.

FIGURE 7.9 : Plan showing groundwater flow directions, extent of mining and role of intact free drainage coal barriers in the Miles Level catchment area.



The strike roadways which are tributary to the head of the Miles Level contribute the majority of the portal discharge, the section cut through the Pennant Sandstone yielding relatively little additional flow. Of the total 0.85 km flow path (Figure 7.9), 0.6 km is downstream of the level head tributaries. Thus the portal discharge is the most appropriate to use in this volume calculation. The average for the two tests using this discharge is 390 m^3. For the 0.6 km flow path, this suggests a passage cross sectional area of 0.65 m^2 compared with the portal value of 0.4 m^2. This indicates that the major roadway is open in the Pennant Sandstone. The significant parts of the remaining flow path must contribute to the roadway volume. One possibility is that the traced water follows the post 1970 roadways down dip (Figure 7.9) into a ponded section cut into the Miles Level barrier. The difference between high and low flow volume estimates may therefore represent a seasonal change in this ponded volume.

7.4.2 DEEP GROUNDWATER CIRCULATION (COLEFORD HIGH DELF AQUIFER)

A third fluorescent dye tracer test was conducted in the deep saturated workings of the Coleford High Delf Aquifer (Pennant Group). This test also used the fluorescent dye Sulpho Rhodamine B and was injected into the base of the abandoned deep mine colliery shaft at Flourmill Colliery (Figure 7.10). The injection of the tracer and problems associated with the use of fluorescent dyes as quantitative tracers in abandoned coal mines due to adsorption is discussed in Aldous and Smart (1987) and is not of relevance here. However, a small amount of the the tracer (1 %) was detected at the Norchard Drift outfall. This was first detected after 7 days and remained detectable for only 32 hours (Figure 7.11) at the sampling point. This rapid transmission indicates confined flow within a master conduit system, furthermore, the flow velocity is much slower than for the shallow tests (described above). This is not surprising considering the much lower hydraulic gradient, in this part of the aquifer. However, the velocities are comparable to other values reported in the literature (Table 7.5). The rapid clearance of the dye indicates remarkably little longitudinal dispersion during transmission through the workings, which suggests roadways with relatively uniform dimensions, few dead zones and a high discharge (see discussion in Stanton and Smart 1981). Therefore it can be concluded that only the major roadways remain open as groundwater flow routes, and the adjacent mined areas, which were unsupported longwall, are now largely collapsed, and contribute little to water transmission.

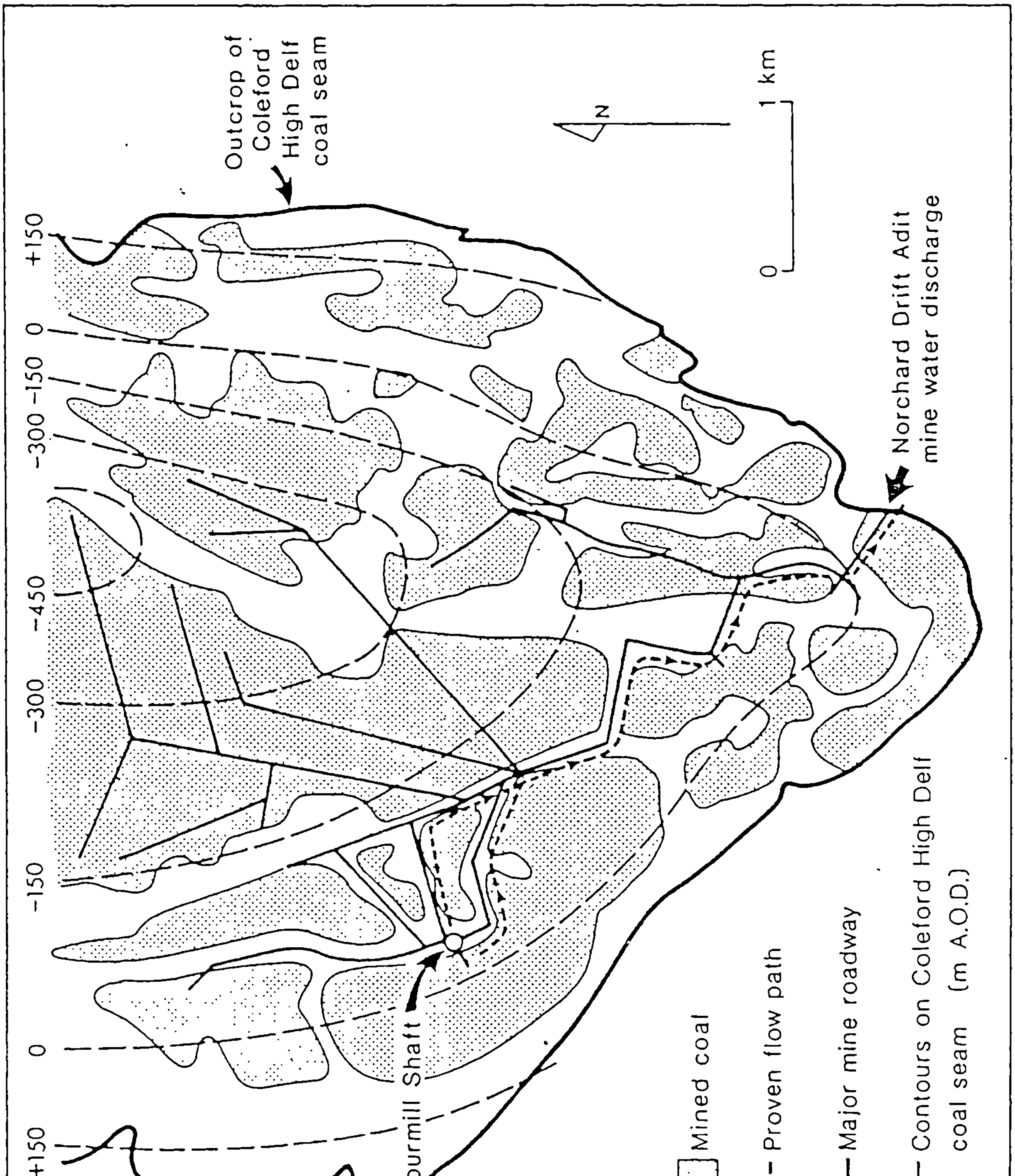


FIGURE 7.10 : Plan showing groundwater flow directions, extent of mining and major haulage roadways for the deep basin in the Coleford High Delf coal seam.

It is possible to calculate the storage volume of this master conduit roadway by using the same method outlined above. The conduit volume is equal to 1.2 x 10^5 m^3 using the centroid of the tracer breakthrough curve. If the conduit roadway storage volume is calculated by using the distance determined from the abandonment plans and a cross sectional area of 6.25 m^2 (width 2.5 m and depth 2.5 m) the value is 2.8 x 10^4 m^3. This does assume that the conduit roadway is completely waterfilled, and this is assumed to be correct due to the elevation of the roadway and the elevation of the discharging adit at the Norchard Drift. In fact access beyond a distance of 30 m below ground at the Norchard Drift is precluded by the rest water level reaching the roof of the roadway as it declines in elevation into the basin structure of the coalfield. There is a significant difference between the two values that are calculated. This means that either one or a combination of the following cases occurs. Firstly, there is a difference in travel velocities between the tracer moving from the region of the bottom of the shaft and the conduit roadway which connects to the discharge outlet and that the velocity within the conduit roadway is considerably faster. Secondly, that significant parts of the discharge volume originate from other sources and these connect with the conduit roadway. Three possible sources exist, firstly, discharge from the shorter roadway which drains from the north on the eastern side of the basin (Figure 7.10), secondly, discharge from the longer roadway which connects with the conduit roadway (through which the tracer had pass) which is to the north of the Flourmill Colliery Shaft and finally, an addition of discharge which enters the conduit roadway from the lower Trenchard coal seam workings which are below the Coleford High Delf coal seam workings. This discharge would join the conduit roadway close to the adit portal where the roadways form a T structure (Figure 7.10).

7.4.3 GROUNDWATER FLOW VELOCITIES IN ABANDONED COAL MINE AQUIFERS.

As well as providing unequivoca l evidence of potential pollutant pathways artificial tracer tests also provide data on the groundwater flow velocities for the aquifer through which the tracer has travelled. The groundwater flow parameter is an important value in the design or implementation of an aquifer pollution protection policy. However, relatively few previous tracer tests have been conducted in Coal Measure Aquifers (Aldous and Smart 1987) those available are listed in Table 7.5. The values reported by both Parsons and Hunter (1972) and Mather (1969) represent saturated or confined flow conditions and compare favourably with the value determined in the deep basin for the Forest of Dean. It is also important to note that the values quoted by Mather (1969) represent velocities for groundwater flowing in both mined void and the subsidence enhanced fracture zone in the sandstone above the mined coal. The values for the shallow groundwater circulation are much faster than those of the deep basin.

In conclusion the field tests reported above have demonstrated that concentrated conduit flow can occur through mined voids in Coal Measure Aquifers. The characteristics of these voids are similar to the natural cave conduits observed in karstified limestone aquifers, which have similarly high flow velocities. For instance Smith and Atkinson (1972) report average values of 3500 md^{-1} for 40 tracer test from the White Limestone of Jamaica and 7400 md^{-1} for the 23 tests reported from the Central Mendip Hills, England. Therefore it is suggested that in view of these comparisons, similar aquifer protection and management policies are employed in these aquifers as are suggested for Limestone Aquifers (Atkinson 1971).

TABLE 7.5 GROUNDWATER FLOW VELOCITIES FROM TRACER TESTS CONDUCTED IN COAL MEASURE AQUIFERS.

LOCATION	TRACER	INJECTION SITE	TRAVEL VELOCITY md^{-1}
Forest of Dean Coalfield U.K. (this study)	Sulpho Rhodamine B Sulpho Rhodamine B Sulpho Rhodamine B	Underground Stream[1] Underground Stream[2] Shaft[3]	1840 16000 460
South Wales Coalfield U.K. (Parsons and Hunter 1972)	Tritium	Shaft	363-162
South Wales Coalfield U.K. (Mather et al 1969)	Fluorescein Sodium Chloride Sodium Chloride	Borehole Borehole Borehole	921 570 88
Legend : 1 - Shallow groundwater circulation low flow conditions. 2 - Shallow groundwater circulation high flow conditions. 3 - Deep groundwater circulation.			

7.5 DETERMINATION OF AQUIFER CHARACTERISTICS.

The previous sections have determined, in a general context the storage volumes and zones that are present within the aquifers of the Forest of Dean and quantified and highlighted major groundwater flow pathways in the aquifers. This section will quantify the aquifer parameters transmissivity (T) and storativity (S).

7.5.1 QUANTIFICATION OF AREAL AVERAGES OF TRANSMISSIVITY.

The recession curve of baseflow can also be used to determine the aquifer diffusivity (Trainer and Watkins 1974) for a particular discharge outlet. The aquifer diffusivity is defined as the ratio of transmissivity to storativity (Equation 7.5). The equation used by Trainer and Watkins (developed by Rorabaugh and Simons 1966) is :-

$$\frac{T}{a^2 S} = \frac{0.933}{\Delta t/\text{Cycle}} \quad \text{..................Equation 7.5}$$

Where T = is the Transmissivity of the aquifer,

S = the Storativity

a = the distance from the discharge outlet to the hydrological divide. In the examples calculated in Table 7.6 a is taken as the distance from the outcrop of the aquifer to the discharge outlet for that particular aquifer).

Δt = the time taken for the discharge to decline through one logarithmic cycle

The aquifer diffusivity was also used by Jacob (1944) to determine aquifer parameters from groundwater level recession curves in a similar manner (Equation 7.6)

$$H = H_o e^{(-\pi T t / 4 a S)} \quad \text{............Equation 7.6}$$

Where H = the height of the water table after a given time t

H_o = the initial height of the water table above sea level

a = is the width between the drainage divide and the discharge outlet for any water. (In the examples calculated in Table 7.6 a is taken as the distance from the outcrop of the aquifer or the limit of saturation near to the outcrop and the discharge outlet for that particular aquifer).

T = Transmissivity

S = Storativity

The two equations are identical except that the former has been subject to a limited mathematical manipulation for easier use and data analysis (Trainer and Watkins 1974). However, in both cases it is possible to estimate the transmissivity (T) or storativity (S) from the aquifer diffusivity ratio if a value of transmissivity or storativity is known. The analysis undertaken here has concentrated on those recession curves or parts of recession curves which represent drainage of flooded or ponded saturated zones. The results of these

TABLE 7.6

VALUES OF AQUIFER DIFFUSIVITY, AND TRANSMISSIVITY CALCULATED FOR THE MAJOR AQUIFERS FROM RECFSSION CURVES.

SITE	ΔT/cycle days	T/a^2S	a km	T:S	T^1 m^2d^{-1}	T^2 m^2d^{-1}
DEEP GROUNDWATER CIRCULATION (COLEFORD HIGH DELF AQUIFER)						
NORCHARD DRIFT	523	0.0018	12.85	297000	2750	
FLOURMILL COLLIERY SHAFT 1984	3110	0.0003	5.1	7800		200
CANNOP COLLIERY SHAFT 1984	2577	0.0004	10.5	44100		400
CANNOP CROSS BOREHOLE 1979	1439	0.0006	9.0	52550		480
SALLOW VALLETS BOREHOLE 1984	1330	0.0007	11.0	84700		780
1981	755	0.0012	11.0	150000		1375
1980	903	0.0010	11.0	125000		1150
DEEP GROUNDWATER CIRCULATION (YORKLEY AQUIFER)						
CANNOP CROSS BOREHOLE 1984	5580	0.0002	6.5	8450		80
1982	10700	0.0001	6.5	3720		34
1981	6840	0.0001	6.5	5770		53
1980	8640	0.0001	6.5	4790		44
SHALLOW GROUNDWATER CIRCULATION (COLEFORD HIGH DELF AND YORKLEY AQUIFER)						
OLD FURNACE LEVEL	158	0.0059	2.7	43000	400	
MILES LEVEL	168	0.0056	2.2	27100	250	
SCOTTS LEVEL	173	0.0054	1.0	5400	50	
BIXSLADE UPPER LEVEL	170	0.0055	1.4	10750	100	
BIXSLADE LOWER LEVEL	156	0.0060	1.7	17300	160	
SUPRA PENNANT (BRAZILLY AQUIFER)						
INDEPENDENT LEVEL	274	0.0034	3.8	49000	450	
PARKEND COLLIERY SPRING	320	0.0029	2.6	19000	175	
SUPRA PENNANT (SERRIDGE AQUIFER)						
KENSLEY LODGE STREAM	80	0.0117	0.5	2900	27	

Legend :- values of Transmissivity are quoted as T^1 for groundwater discharges and T^2 refers to groundwater level observation. Transmissivity calculations are described in text. If not specified data refers to the year 1984.

calculations are shown in Table 7.6. The transmissivity values which were determined assumed a storativity of 0.09. This value is the specific yield value that was calculated for the saturated deep basin (coal mined void and Pennant Sandstone (predominantly the latter) in chapter 4. (The term storativity and specific yield are synonymous, the former term is generally applied to confined aquifers while the later refers to unconfined aquifers. Both terms define the volume of water released from a unit volume of saturated aquifer by a unit reduction in hydraulic head (in the former case a unit reduction in peizometric head and the latter in rest water level)). This value, is thought to be more reliable than that determined from the pumping test (see below).

The transmissivities calculated for the Coleford High Delf Aquifer deep groundwater circulation vary considerably, with a range between 2750 and 200 m^2d^{-1}. The highest value is for the Norchard Drift while the lower ones are from the abandoned shafts. In the case of the former, the higher value probably reflects the increased permeability caused by the presence of the open haulage roadways (as proven in the Flourmill Colliery Shaft tracer test), while those for the groundwater level monitoring sites are not directly connected to this zone of high permeability. However, the higher values for the Sallowvallets Borehole may be caused by the extra tensional flexing and fracturing caused by the closeness to the apex of the Ridge Anticline. Also the Sallowvallets borehole is located and drilled only to a superficial depth within the Pennant Sandstone while the deep basin shafts fully penetrate the Pennant Sandstone to the Coleford High Delf coal seam, at such depths natural fractures would not be as wide because of the effect of the increased overburden, while those present near the surface would be more transmissive, this case may be that reflected in these results. The values for the shallow groundwater circulation are generally similar and compare with those of the deep basin shafts. The Serridge Sandstone of the Serridge Aquifer and Pennant Sandstone of the Yorkley Aquifer are similar in transmissivity values. The former is slightly lower being 27 m^2d^{-1} while the latter ranges between 34 and 80 m^2d^{-1}. In the case of the Serridge Aquifer the sandstones are less fractured and intermediate and not massive, and the lower value would accord with this. However, in the case of the Yorkley Aquifer Pennant Sandstone, the lower values can only be explained by a lack of fracturing. This may be due to the Yorkley coal seam having not been mined at depth in the central basin, while in the case of the Coleford High Delf Aquifer Pennant Sandstone the effects of increased fracturing due to mining induced subsidence fracturing may be present.

As these transmissivity values are areal averages, they cannot be used in estimating potential yields from pumping wells. They however are useful where regional estimates of transmissivity are required, for instance in the first stage of modelling groundwater flow. However there is still a need to determine the range of transmissivity within the aquifer, and this will be discussed below.

7.5.2 CALCULATION OF THE AQUIFER CHARACTERISTICS TRANSMISSIVITY AND STORATIVITY OF THE COLEFORD HIGH DELF AQUIFER (PENNANT GROUP) FROM PUMPING TEST DATA.

When the boreholes at Sallowvallets and Cannop Cross were drilled in 1979 it was planned to pump test both and develop either as a possible further potable water supply source for the Forest of Dean. However, the Sallowvallets Borehole was not tested due to the large depth to the rest water level (~70m). Therefore, the only available pump test data relates to the Cannop Cross Borehole. This borehole was tested when the hole was drilled to 100 m and again at 200 m by both constant rate drawdown and recovery methods (Figures 7.12 and 7.13). This data was analysed according to the methods outlined in Kruseman and De Ridder (1970) and is presented in Table 7.7.

The drawdown curves are similar in shape for both 100 and 200 m depths, both having a characteristically rapid initial reductions in rest water levels followed by extended periods of little or no further decline. In fact in both cases a slow rise in level eventually occurs this is most marked with the 200 m curve (Figure 7.12). This situation is generally referred to as a boundary effect, whereby a source of water is available which equals that of the pumping rate, and only a limited cone of depression is formed.

The rapid drawdown represents the removal of water from a poorly jointed or fractured section of aquifer, which is hydraulically poorly connected to the flow system. When the drawdown reaches a particular level which differs in both pump tests, a major fracture system is intersected. The flow from the fracture system is equal to that of the pump (23.5 ls^{-1}). As pumping continues the rest water level in the borehole slowly rises until the pumping finishes. This rise in water level is interpreted as the development of a fracture system, with the fracture slowly yielding a larger volume of water. This development could simply be the removal of sediment from the fractures or drilling debris from the borehole walls. However, it is recorded in the available documents that after pumping had continued for a period of time the water became coloured with deposits of iron precipitate (presumably ferric

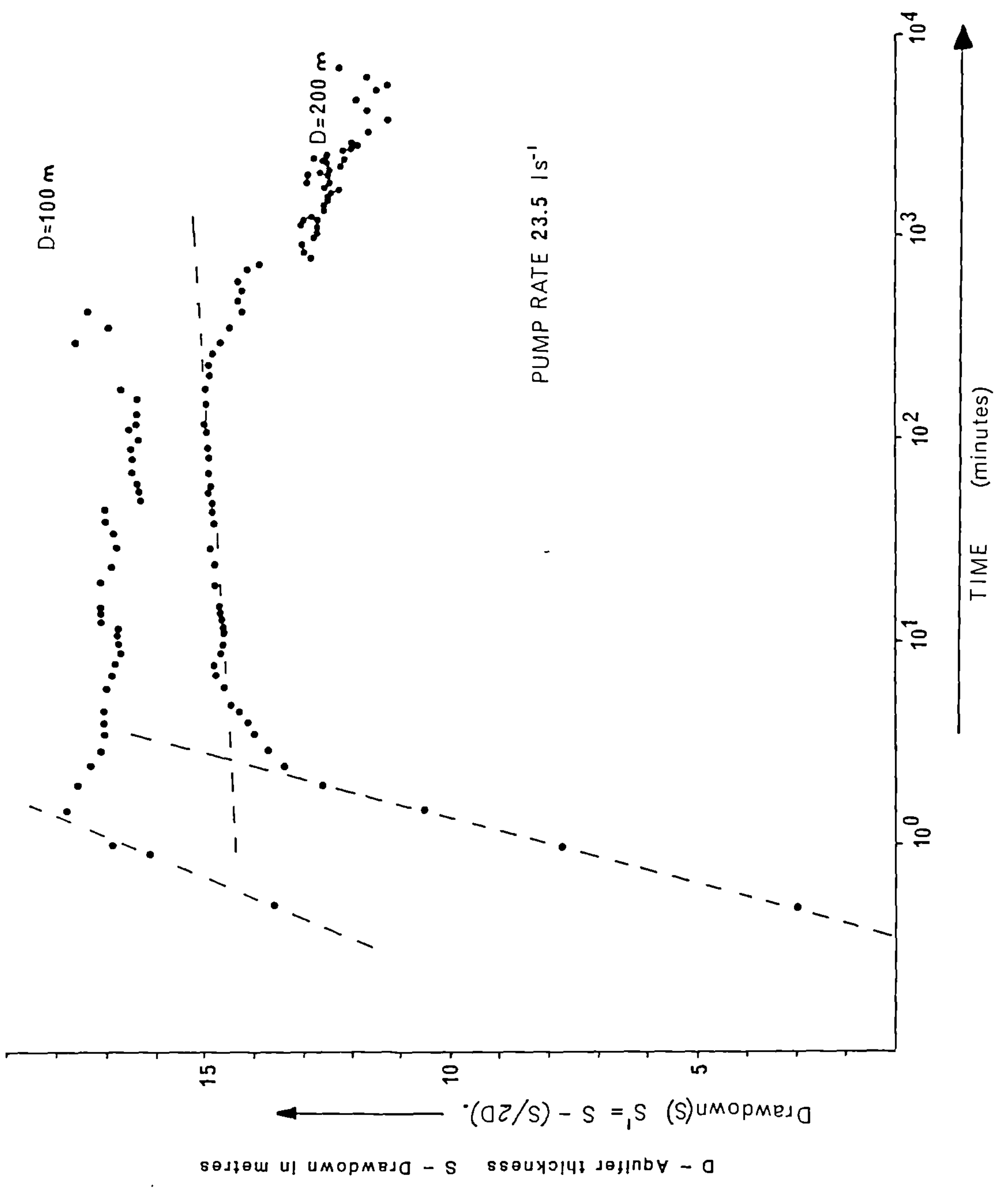
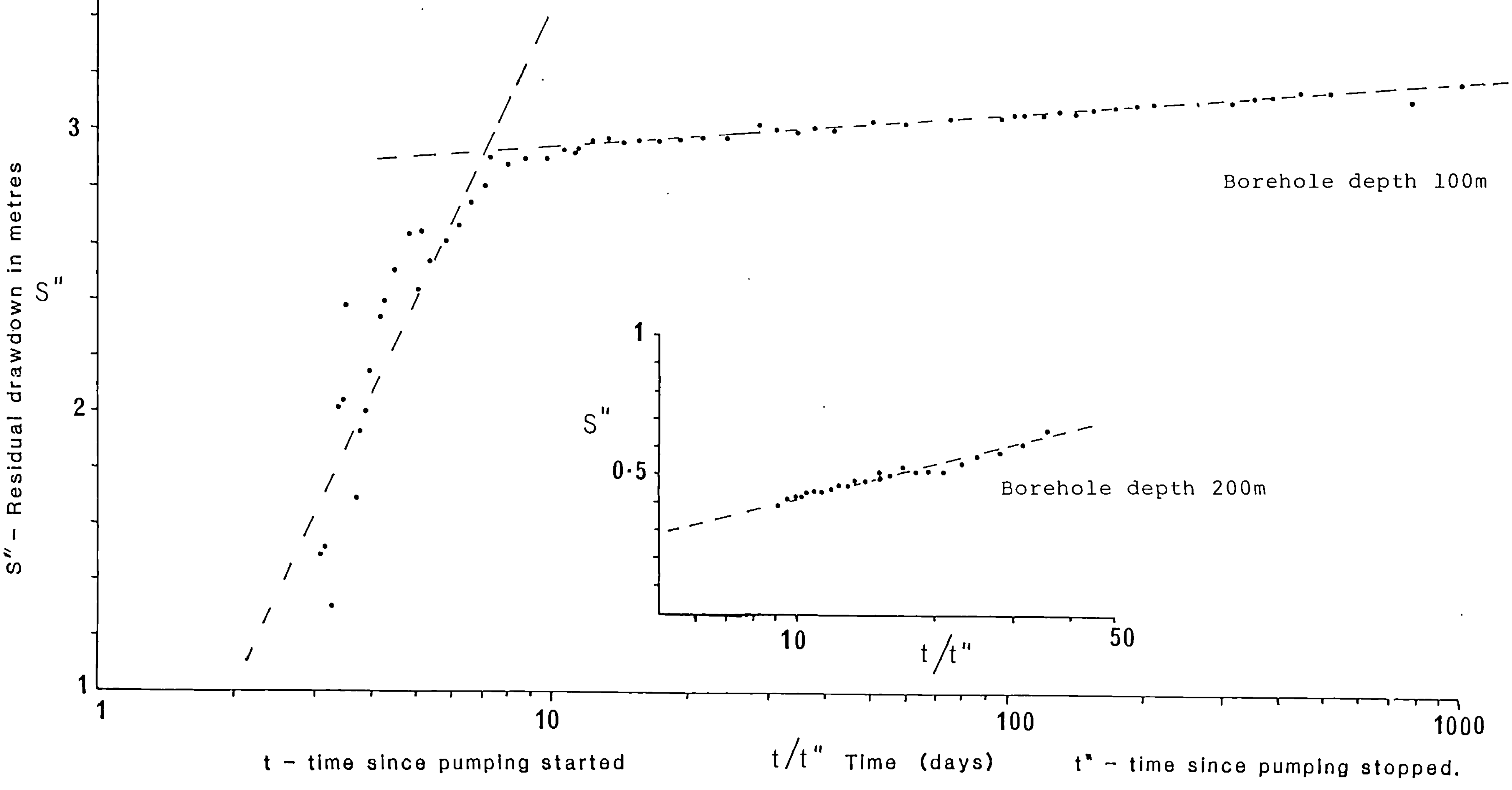


FIGURE 7.12 : Pumping test drawdown curves from the Cannop Cross Borehole 1979.

FIGURE 7.12 : Pumping test recovery curves from the Cannop Cross Borehole 1979.



hydroxide). This may have originated from the Coleford High Delf coal seam workings which lie directly below the base of the borehole. Chemical analyses also indicated that the water contained high sulphate levels, typically 800-900 mgl^{-1}, which further substantiates this theory. The boreholes were abandoned and not developed as a water supply source because of this later reason.

The values for the storativity and transmissivity calculated from the pump test data are in Table 7.7, these values represent those of the Pennant Sandstone. But more importantly are those of the Pennant Sandstone within the highly faulted Cannop Fault Belt. The Transmissivity values vary considerably ranging between 26 and 885 m^2d^{-1}. The higher values are those associated with the recovery method. Similarly the strorativity values are extremely variable. These problems can be attributed to the influence of the hydrogeological regime present, because the pump test analysis method is based upon an homogenous aquifer system, and that present most certainly is not, and is dominated by concentrated fracture flow systems. Such situations and problems are commom in the analysis of pump test data from fracture flow aquifers. The validity of the results presented here is therefore in doubt.

7.5.3 TRANSMISSIVITY OF THE PENNANT SANDSTONE AND DEEP BASIN MINED VOIDS FROM REST WATER LEVEL AND DISCHARGE DATA.

Generally groundwater flow in fractured and granular aquifers is assumed to conform to Dary's Law (Todd 1959). However, workers have proven that in extensive voids (typically cavernous Limestone Aquifers) Darcy's Law is invalid (Swartzendruber 1962). This is because the velocity is not linearily related to hydraulic gradient. Therefore, the flow in abandoned coal mined aquifers which contain extensively fractured rocks caused by subsidence and cavities (mined voids) from coal extraction, through which groundwater flow is known to occur is unlikely to conform to Darcy's Law. However, Darcy's Law is used here, and is considered justifiable because the voids are filled by extensive collapse and the hydraulic heads involved are small, furthermore at depth in the deep basin the flow is predominantly within the Pennant Sandstone and not in the mined void.

The rest water level data for the two accessible abandoned shafts at Cannop Colliery and Flourmill Colliery and Sallowvallets Borehole was used in conjunction with the discharge data for the Norchard Drift Adit. It was assumed that the flow between the monitoring sites and the Norchard Drift was constrained within a width of aquifer 2 km wide. Using the hydraulic gradient

TABLE 7.7

AQUIFER CHARACTERISTICS DETERMINED FROM PUMPING TESTS CONDUCTED AT THE CANNOP CROSS BOREHOLE BETWEEN FEBRUARY AND APRIL 1979.

BOREHOLE DEPTH	TEST	TRANSMISSIVITY	STORATIVITY
100 m	CONSTANT RATE DRAWDOWN	39.1 m^2d^{-1}	0.19
100 m	RECOVERY	108.7 m^2d^{-1}	----
200 m	CONSTANT RATE DRAWDOWN	26.0 m^2d^{-1}	0.0125
	(Fracture)	106.2 m^2d^{-1}	(2.5)
200 m	RECOVERY	885 m^2d^{-1}	-----

TABLE 7.8

TRANSMISSIVITY VALUES DETERMINED FROM THE APPLICATION OF REST WATER LEVEL DATA AND DARCY'S LAW FOR THE PENNANT SANDSTONE AND SATURATED MINED VOIDS IN THE DEEP BASIN.

SHAFT LOCATION	MEAN TRANSMISSIVITY m^2d^{-1}	S.D.	N
FLOURMILL COLLIERY	2475	319	50
CANNOP COLLIERY	2566	679	41
SALLOW VALLETS BOREHOLE	710	273	37

between the Norchard Drift and the ground water level site and Darcy's Law the transmissivity was recalculated using the aquifer thickness between rest water level and the discharge outlet elevation. Furthermore, because of a continuous record of discharge and weekly rest water level data it was possible to calculate a range of values from the data (Table 7.8).

The transmissivity values are considerably higher than those calculated from the pump test data but compare favourably with those from the recession analysis method. The higher values 2475 and 2566 m^2d^{-1} for the deep basin shafts which drain to the Norchard Drift is very similar to that of 2750 m^2d^{-1} from the recession curve analysis for the Norchard Drift. These higher values probably reflect the influence of the open haulage roadways (as proven by the fluorescent dye tracer test) and increased subsidence fracturing associated with the longwall mining method employed in the deep basin. The lower value of 710 m^2d^{-1} for the Sallowvallets Borehole probably reflects the increased influence of the uneffected transmissivity of the Pennant Sandstone, and is similar in magnitude to the values determined from the pumping test data.

7.6 CONCLUSIONS AND SUMMARY.

The use of recession curve analysis techniques has demonstrated that two drainage processes occur within in all the aquifers studied. Although the differentiation of these two components is not possible by direct comparison between differing aquifer units (inter aquifer differentiation) due to differing aquifer properties, intra aquifer differentiation is possible. Of the two storage components identified, temporary fracture storage is present for only short periods, while recharge occurs, and drainage of the second component, saturated storage is present for long periods of time and this maintains summer baseflow volumes. The total storage volumes held within these two components differs considerably, with the saturated zone storage being larger by many magnitudes.

The quantitative fluorescent dye tracer tests indicate that the storage volumes held within the open haulage roadways is small, however these primary flow routes are highly transmissive. This indicates that the majority of the storage occurs within the adjacent flooded mine galleries and Pennant Sandstone. The latter of these two is most important as the majority of the mine galleries are filled by seat earth extrusions (Plate 2.4). The groundwater flow velocities determined for the haulage roadways in the deep basin are considerably slower than those for the shallow groundwater circulation. However, the velocities for the shallow groundwater circulation compare with those of limestone conduits and caves and similar pollution risks must therefore be assumed to exist and similar aquifer protection policies initiated. Especially when considering that the storage volumes are small and little attenuation or further dilution is likely to occur to any pollutant once having entered the confined flow regimes within the open haulage roadways (Plate 2.4).

The determination of the transmissivity and storativity for the Pennant Sandstone Aquifer provided variable values, depending upon the technique used (areal averages from recession curve techniques or point determinations from pump tests). This variation was explained by the particular area of the Pennant Sandstone Aquifer understudy and whether this included the influence of major fracture systems or abandoned mine voids. The areal average values are probably the more representative as these are not influenced by unpredictable borehole locations intersecting or not intersecting major fracture systems or mine voids. It is suggested that these later techniques (boreholes and pump tests) for determing aquifer properties must be considered with doubt, and any further computer modelling should use the areal average values as initial data. Particularly as these values agree well with those obtained from the crude 'model' application of predicted groundwater flow by the use of rest water level data and Darcy's Law.

However in the case of providing data for use in conjunction with an aquifer management policy, logistics, economics, and viability of data production requires discussion. Although, recession curve techniques initially appear to be superior by providing representative data and a cheap alternative to a costly pump test borehole drilling option, they do however require substantially longer time periods for data collection before providing valuable answers especially if the intial raw data is unavailable from archive sources.

The results produced have indicated that as aquifer parameters appear to be spatially variable the alternative to the recession curve methods may be an extensive prolonged and costly borehole/pump test survey. However, there are some additional advantages with this approach, which have not been included in this study. Extensive borehole also permit precise determination of hydraulic gradients and peizometric levels, the use of down-hole geophysical logging equipment or tracer dilution studies. All of these techniques would provide useful additional hydrogeological information for the aquifer understudy.

Finally, the success of the fluorescent dye tracer tests conducted in both the shallow and deep abandoned workings indicates the utility of this technique for determining potential pollutant pathways, dilution factors, storage volumes, catchment areas, and mined void integrity, for direct site appraisal studies in the implementation of a regional aquifer management policy.

CHAPTER 8

A REVIEW OF TEMPORAL HYDROCHEMICAL CHANGES ASSOCIATED WITH MINE ABANDONMENT: A CASE STUDY FROM THE FOPEST OF DEAN.

8.1 INTRODUCTION.

The production of acidic, ferruginous and ochreous mine discharges (acid mine drainage (AMD)) from pyrite oxidation has previously been widely reported (Table 8.1 . The-e studies have concentrated on explaining the complex mineralogical, chemical kineti-, bacterialogical and thermodynamic ontrcls on pvrite ox.ca+i-n, the modelling of neutralisation prodedures and effect on receiving stream waters; the control of production by mine sealing to limit oxygen availability; and environmental both ecological and water quality) effects of such drainage discharges on receiving waters. In addition there are numerous regional and local water quality surveys that have reported field evidence of the detrimental effect of such discharges on water quality. These later reports are not included in Table 8.1, as they present only site specific water quality data with little or no original contribution. It is remarkable that no previous work has examined the temporal hydrochemical changes associated with coal mine abandonment, as reported here.

The changes associated with mining and mine abandonment are first considered for the deep basin mines, and then a detailed analysis is made of the available archive data on the temporal changes in outflow chemistry of the deep basin drainage outlet at the Norchard Drift for the period from when flow commenced in 1966 until the present.

8.2 A SUMMARY OF THE PROCESSES OF PYRITE OXIDATION.

The production of ferruginous waters involves the oxidation of the mineral pyrite (FeS_2), which is present within coal seams and shale layers. Pyrite remains stable as long as anoxic conditions are maintained, this is generally the case before any coal extraction has taken place. At a neutral pH of 7, the requirement for pyrite stability is a redox potential (Eh) of - 200 mv (Figure 8.1). Prior to mining this situation occurs because excess organic matter is present in the coal seam and would consume the naturally occuring dissolved oxygen present in recharge waters. Furthermore anoxic or reducing conditions are likely to be maintained prior to mining because groundwater flow within the coal is restricted by the presence of an impermeable seat earth clay below and shale roof above.

TABLE 8.1

A REVIEW OF PPEVIOUS ACID MINE DRAINAGE LITERATURE INDICATING PREVIOUSLY REPORTED SUBJECT AREAS.

	GEOLOGICAL EFFECTS	MINERALOGICAL EFFECTS	CHEMICAL KINETICS	CONTROL	BACTERIAL EFFECTS	MODELLING	ENVIRONMENTAL EFFECTS
Holliday and Mackenzie 1973	*						
Carrucio and Ferm 1974	*	*					
Brant 1971	*						
Carruccio et al 1981			*				
Ahmad 19"4			*				
Geidel and Caruccio 1978			*				
Carruccio 19 8			*				
Lorenz 1962				*			
Braley 1954				*			
Ferguson 1985				*			
Woodley and Moore 196				*			
McWhorter et al 1974				*			
Atkins and Pooley 198?					*		
Atkins and Singh 1982					*		
Rawat and Singh 1982					*		
Singer and Stumm 1968					*		
Chadderton 1979						*	
Hill 1971						*	
Merkel 1972						*	
Greenfield and Ireland 1978							*
Chadwick and Canton 1983							*
Herricks and Cairns 1974							*
Parsons 1977							*
H ghe and Edwards 1 77							*
Letterman and M.+sch 1979							*
Wirres and McD nneil 1 3			*				*
Emri h and Thompson 19			*				*

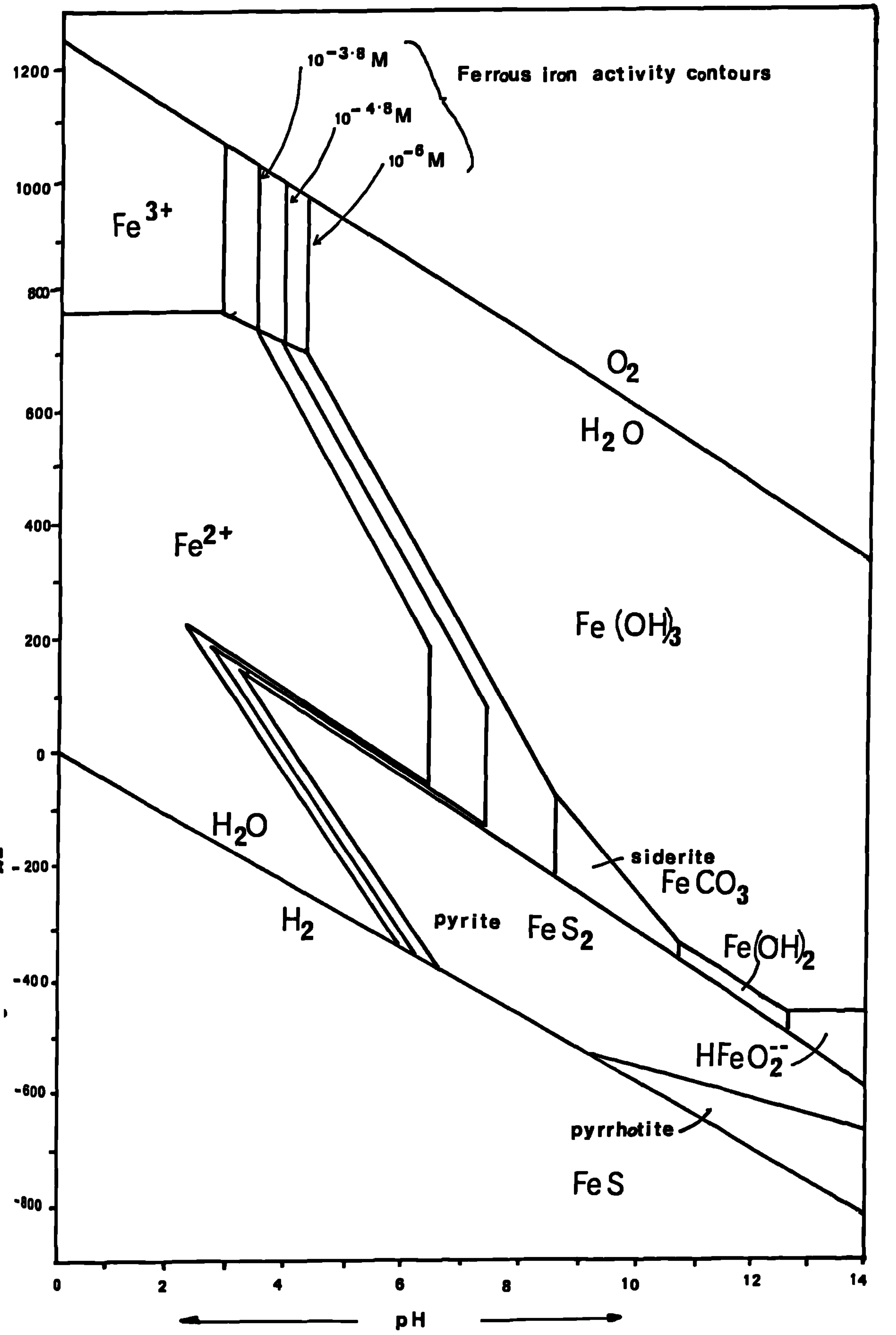


Figure 8.1 · Stability relationship of the iron sulphides, carbonates and metastable hydroxide at 25 °C 1 atmosphere total pressure.

Groundwater flow is therefore controlled exclusively by the in situ permeability of the coal and shale, and substantial rapid groundwater movement is unlikely.

Prior to mining the only source of oxygen at depth is that dissolved in recharge waters. However, during mining there is both a supply of gaseous oxygen in the open workings and a more rapid movement of groundwater induced by pumping. The result is that the pyrite present in the coal or adjacent shales is oxidised (Table 8.2 Eq 1). It has been reported (Atkins and Pooley 1982, Atkins and Singh 1982, Rawat and Singh 1982 and Singer and Stumm 1968) that this reduction involved bacteria such as *Thiobaccillus ferroxidans* (for a pH 5.0 . The ferrous ion produced is then oxidised (Table 8.2 Eq 2) and finally hydroly ed Table .2 Eq 3) producing a red-orange-brown precipitate of ferric hydroxide Plate 1.1 A and B). However in the presence of calcite the acidity produced from equations 1 and 3 dissolves the calcite cement of sandstones producing calcium ions and a weaker carbonic acid. If the pH is above 4.5 this will dissociate and dissolve further calcium carbonate (Table 8.2 Eq 5). This neutralising process is important where waters come into contact with the sandstones of the Forest of Dean all of which contain calcite. Thus all mine drainage outflows in the Forest of Dean are less acidic than pH 6.2 (Table 8.3). However, where contact with sandstones is not possible discharges can have extremely low pH values and many as low as 3.5 are reported in the US. The acidity of the water is particularly important because this determines the solubility of the waters to metals, which can be toxic in receiving waters.

The ferrous ion produced is oxidised (Table 8.2 Eq 2) and finally hydrolysed (Table 8.2 Eq 3) producing a red-orange brown precipitate of ferric hydroxide and further acidity. However, in the presence of calcite and dissolved oxygen the oxidation equation takes the form as Table 8.2 Eq 4. This latter equation shows that no further free hydrogen ions are liberated, having been combined in the dissolution of the calcite.

8.3 THE HYDROCHEMISTRY OF PRE-ABANDONMENT AND ABANDONMENT MINE WATERS.

The historic water quality data for the time periods during mining and at abandonment for both deep and shallow mines is limited. The available data i expressed on a Durov diagram (Figure 8.2 and 8.3 A and B). (The Durov-Zaporovec plot (Durov 1948, Chilingar 1956) is a method of graphical repre entation of water quality data, this can be used to depict the chemical evolution and discrimination of water types). The few samples that were taken, were taken for

TABLE 8.2

Chemical Equations Summarising The Oxidation Of Pyrite $[FeS_2]$ And Formation Of Ferruginous Mine Waters

$$2FeS_2[s] + 7O_2 + 2H_2O \rightleftharpoons 2Fe^{2+} + 4SO_4 + 4H^+ \quad \cdots\cdots 1$$

$$2Fe^{2+} + \tfrac{1}{2}O_2 + 2H^+ \longrightarrow 2Fe^{3+} + H_2O \quad \cdots\cdots 2$$

$$Fe^{3+} + 3H_2O \longrightarrow Fe(OH)_3[s] + 3H^+ \quad \cdots\cdots 3$$

and

$$2H^+ + CaCO_3[s] \longrightarrow Ca^{2+} + H_2CO_3 \quad \cdots\cdots 4$$

$$CaCO_3[s] + H_2CO_3 \longrightarrow Ca^{2+} + 2HCO_3 \quad \cdots\cdots 5$$

Legend: [s] - Solid

FIGURE .2 . General interpretation of the Durov-[illegible] diagram for changes in water chemistry due [illegible] in [illegible] and increased residence time.

A DUROV DIAGRAM.

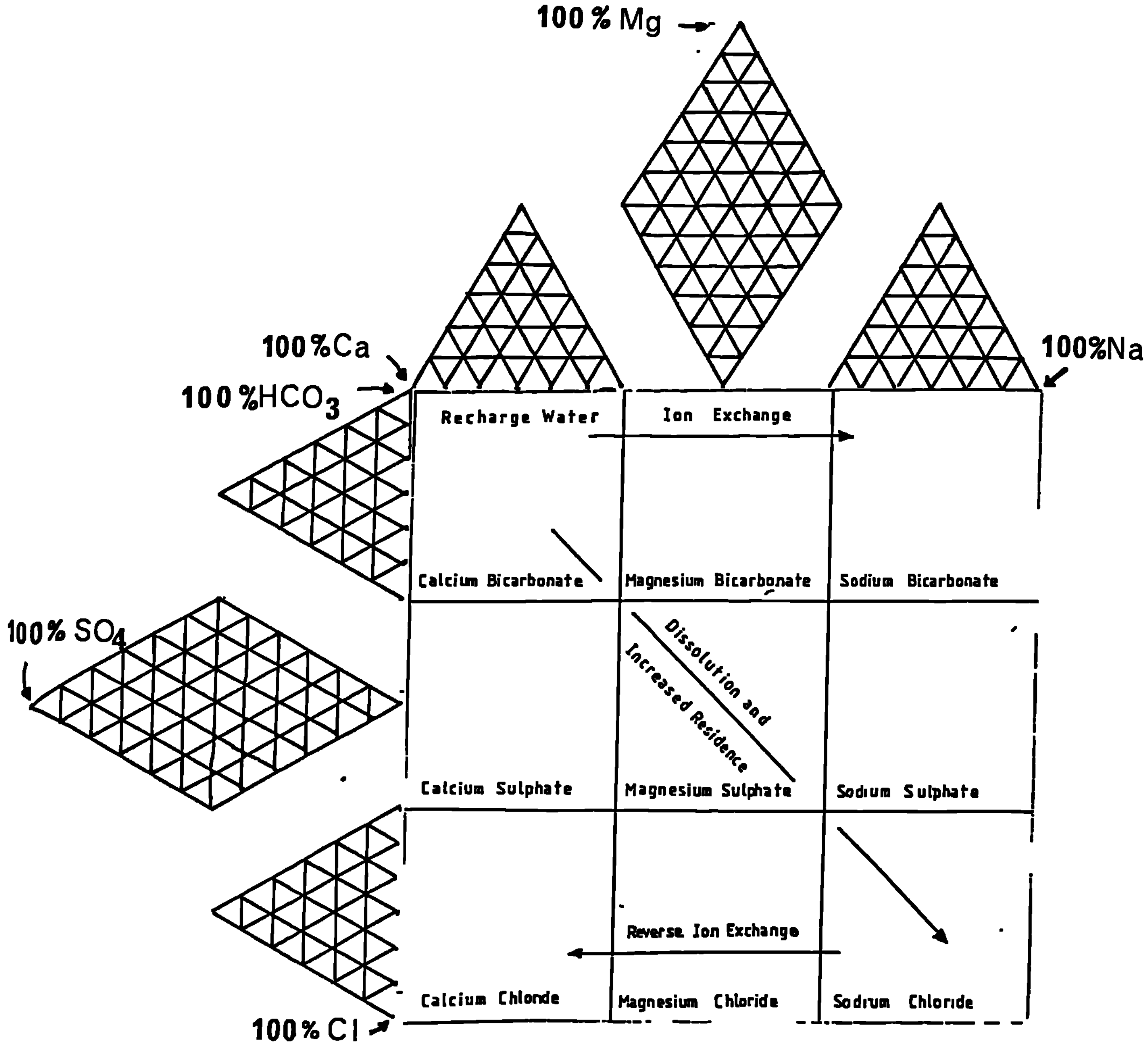
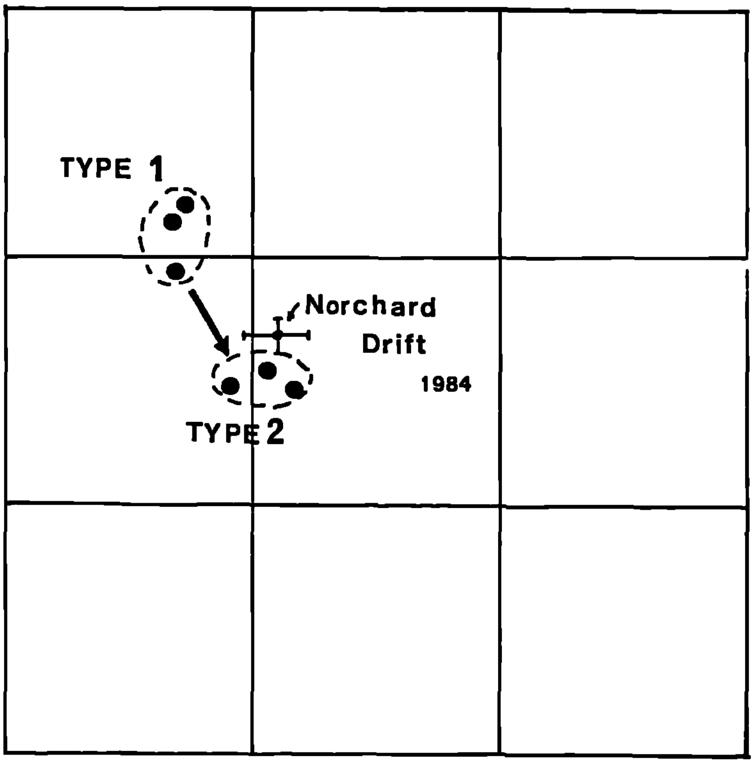


FIGURE 8.3 : A : DUROV DIAGRAM SHOWING THE ABANDONMENT AND ABANDONMENT WATERLOGGED WATER SAMPLES FOR THE DEEP BASIN.

A

1984 Data plot with ± one standard deviation



TYPE 1 - Pumped water samples pre-abandonment from deep basin 1963.

TYPE 2 - Stagnant waterlogged water samples from deep basin 1965.

B

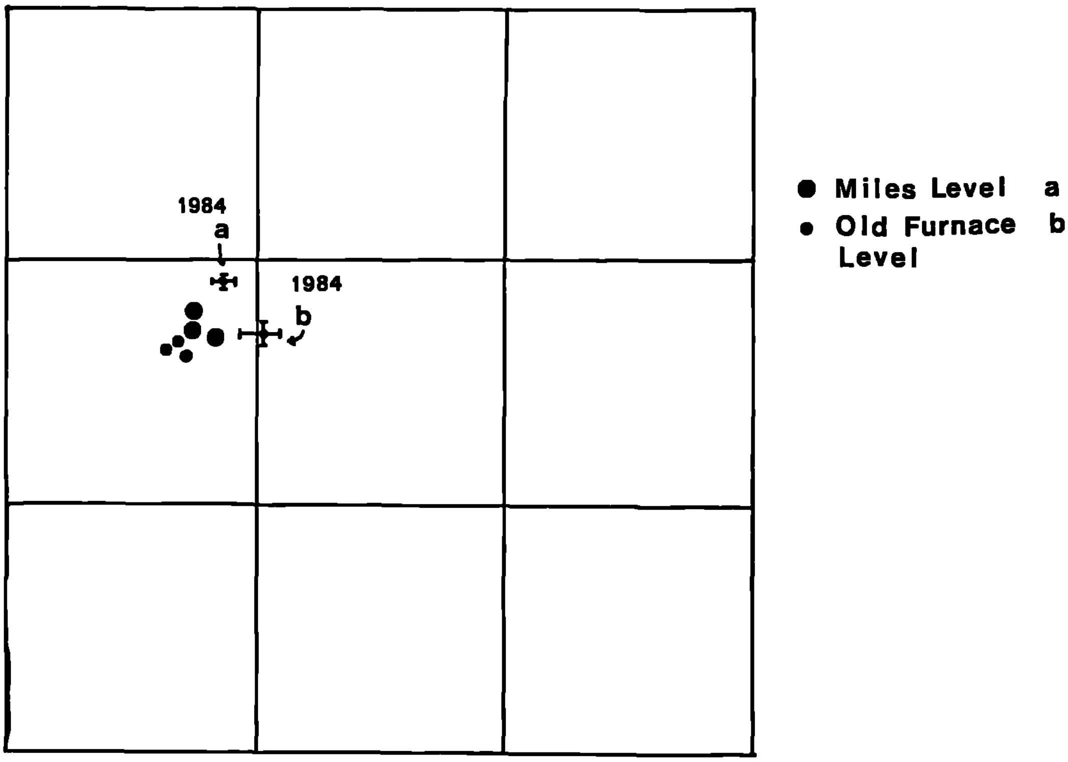


FIGURE 8.3 : B: DUROV DIAGRAM SHOWING FREE- RAINAGE LEVEL WATER SAMPLES (MILES AND OLD FURNACE LEVELS FOR 19 4 1 AND 1 84.

an environmental health reason, concentrating on bacterialogical counts (primarily E. Coli) because the water was used in pit head baths. Because the Durov diagram requires all major cation and anion analyses few samples can be plotted.

TABLE 8.3 : Summary table of pH values for the mine water discharges in the Forest of Dean.

Location	mean pH value	standard deviation	range of values Max	Min	number of observations
Pennant Group					
Norchard Drift	6.8	0.23	7.2	6.3	47
Old Furnace Level	7.4	0.25	8.0	6.6	43
Miles Level	6.8	0.32	7.7	6.2	43
Quest Slade	7.6	0.15	7.8	7.3	9
Scots Level	7.1	0.12	7.3	7.0	6
Supra Pennant Group					
Independent Level	6.8	0.27	7.2	6.4	42
Cannop Level	7.0	0.1	7.2	6.9	8
Old Bobs Colliery Spring	6.9	-	-	-	2
Parkend Colliery Spring	7.2	0.16	7.5	7.0	5
Speculation Colliery Spring	6.9	-	7.0	6.9	2

The three samples available during mining (prior to 1965) from the deep mines at Princess Royal and Norchard Drift Collieries plot as calcium bicarbonate and calcium sulphate waters (Type 1) (Figure 8.3 A). The major anion is either bicarbonate or sulphate and the dominant cation calcium. This dominant calcium cation indicates that this water has originated either directly from the Pennant Sandstone or by interaction of mine water with the sandstone. The slightly elevated sulphate concentrations are attributed to the oxidation of pyrite. However, the dominant proportion of the anion component is bicarbonate, this originates from the dissolution of the Pennant Sandstone calcite matrix by unsaturated (aggressive) recharge water. However, the residence time of the water is short as no ponding occurs and the water is immediately removed by pumping when vertical percolation reaches the mine level.

After the cessation of pumping the old workings become flooded. Water samples collected from this ponded saturated zone have an increased residence time, with the dominant classification being that of magnesium sulphate or calcium sulphate waters (Type 2) (Figure 8.3 A). The change in dominant cation from calcium to magnesium reflects a change in source of the water or the chemical evolution processes present. The calcium originates from dissolution of the calcite matrix of the Pennant Sandstone but when ponding occurs this permits longer contact with the seat earth clays and cation exchange can occur with calcium ions being adsorbed and the calcium magnesium ratio changing accordingly. Also plotted on Figure 8.1 B, is the 1984 data for the Norchard Drift, this shows little compostional difference in comparison to the waterlogged samples taken on abandonment.

There are only minor compostional changes in the free drainage level waters over this same time period (1963/1965-1984) (Figure 8.3 B). Unfortunatley again the amount of data is limited. Over this period the water classification of calcium sulphate remains unchanged. Although the 1984 data for the Miles and Old Furnace Levels does differ slightly. This can be tentatively be explained by upper barrier removel in the case of the Miles Level, which has permitted a larger and more rapid flow of Pennant Sandstone waters to the Miles Level and dilution of the sulphate dominated coal void water. While in the case of the Old Furnace Level, there has been no change in the anion component of the water but a change in cation composition with respect to proportions of calcium and magnesium. One possible explanation is random collapse and vertical subsidence which has disrupted the seat earth aquiclude of the Yorkely coal seam and associated shales above and permitted vertical capture of upper drainage. The increased contact with the seat earth clays associated with the increased ponding and collapse permits cation exchange and a relative increased in magnesium levels in comparison to those of calcium due to selective adsorption.

It is also significant that the Norchard Drift and Old Furnace Level waters are very similar in the proportion of major cation and anions, considering there differences in hydrogeological behaviour (Chapter 5 and 6) and that they drain differing aquifer flow systems (shallow and deep groundwater circulations). This compostional similarity would agree with the explanation given above of the processes through which the chemistry of the groundwaters present has evolved, because in both situations, collapsed and waterlogged conditions exist and although the residence times and extent of mineralisation do differ, the Durov diagram presents the data (percentages) in a comparable form.

8.4 THE INTERPRETATION OF TEMPORAL CHANGES OF ABANDONED DEEP COAL MINE OUTFLOW CHEMISTRY FROM ARCHIVE SOURCES.

This section is concerned with the temporal changes in outflow chemistry at the Norchard Drift that have occured since discharge commenced (during the time period 1966 until 1985). The chemical data has been collated from numerous archive sources (STWA, NCB and the Deputy Gaveller). The data base collated covers the following determinands :
Alkalinity as $CaCO_3$, pH, conductivity, temperature, cadmium, calcium, chloride, chromium, copper, iron, lead, magnesium, manganese, nickel, sulphate, total hardness and zinc.

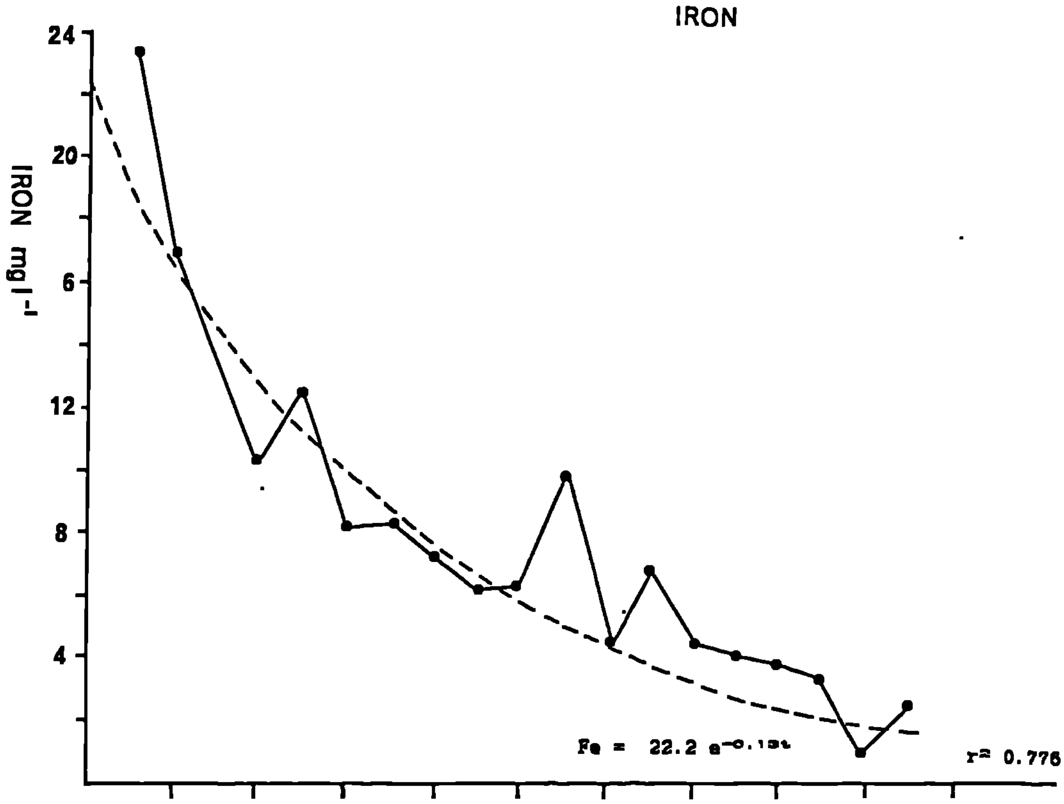
Before detailed analysis, it is necessary to discuss the form and inadequecies of the data. Three major problems were encountered during the data analysis. Firstly it was evident that the chemical changes which were present, followed two differing response forms, sharp changes and gentle trends. Furthermore, neither of the changes were linear over the whole time period of the avaialble data and the fitting of trends or curves would be necessary. Secondly, the data for any particular determinand was often poorly represented at particular time periods (for instance between 1966 and 1974 when sampling was undertaken on an occasional basis by the River Boards and NCB) and well documented for short periods (for instance one particular year would be represented by 24 analyses while the subseqent four years total data would amount to only 4 or 5 analyses). This precluded the use of sophisticated statistical analysis such as fourier or time series analysis to determine long term trend changes, because they require a regular sampling interval. The third problem involved the fitting of trends by regressive techniques or running average curve fitting programs (Becker and Chambers 1984). This was complicated by the presence of seasonal cycles, and again some years would be biased by the irregular sample interval high lighting high peak or low trough concentrations. This was problem was partially overcome by the use of yearly average values to indicate long term trends from such data. The regression techniques were used because these allowed inter determinand comparisons. The fourth and final problem, is due to the length of time period over which the data spans. During this period the reorganisation of the bodies responsible for sampling changed twice, and complications arise through changes in sampling, analytical techniques and results for sensitive parameters like temperature and pH.

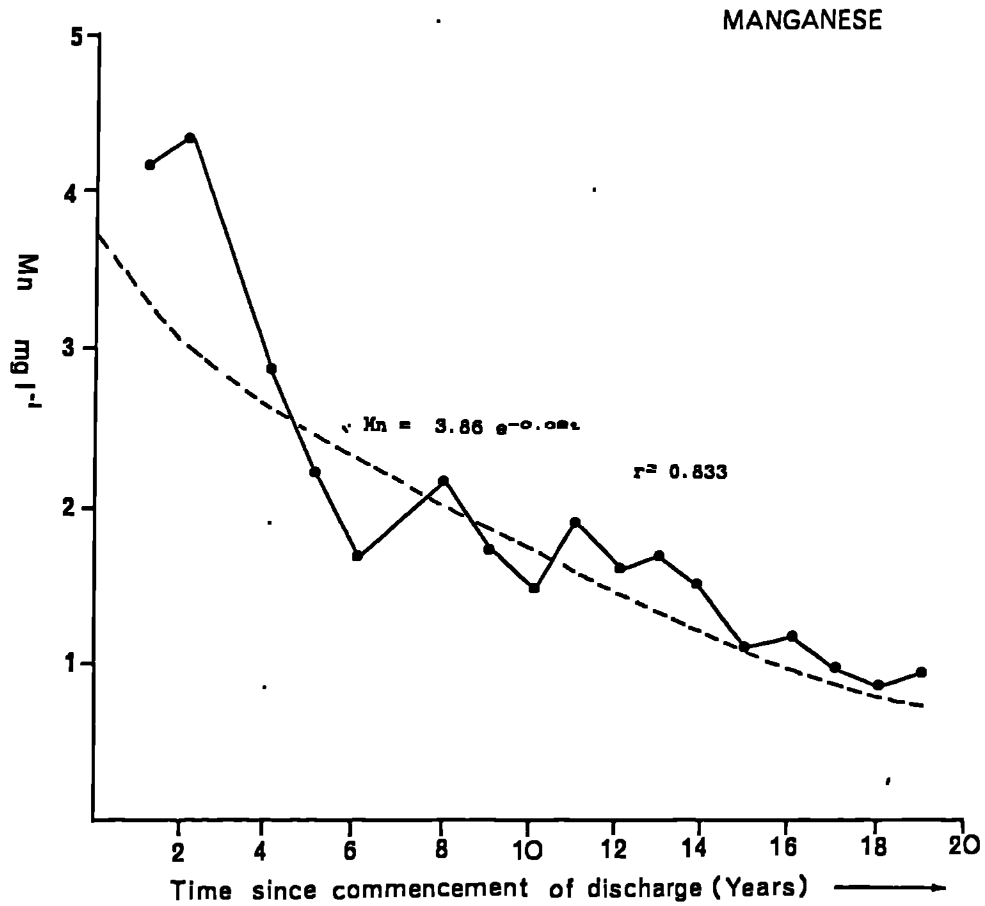
The available data is used to form a schematic model of the response changes in outflow chemistry form mine drainage discharges, and also indicates some of the major groundwater flow patterns and pathways for the deep basin of the Forest of Dean, which have not been previously possible to determine.

8.5 THE INTERPRETATION OF LONG TERM TEMPORAL CHANGES IN CHEMICAL COMPOSITION OF ABANDONED DEEP COAL MINE OUTFLOW WATERS.

The long term changes in chemical composition are more easily detected from year average values for the determinands. These are shown in Figures 8.4, 8.5 and 8.6. All the trace metals (iron, manganese, zinc, and nickel) decline in an exponential form, reaching levels of either detection or background concentrations between 10 and 17 years after peak concentration. The origin of the majority of the metals is from sulphide minerals contained in the coal seams and shales (Carrucio and Ferm 1981). As fresh rock surfaces (especially coal) are revealed during mining, weathering or oxidation of the reactive minerals takes place (as discussed above). The initial discharge waters 'flush' out the products of oxidation and therefore contain extremely high concentrations. But because of the subsequent waterlogging there is a decrease in oxygen availability, and a return to anoxic conditions, the production of further oxidation reaction products is severely reduced. After the initial 'flush' a continuous leaching process becomes dominant, which follows an exponential decay in concentration during subsequent years. In the case of lead, initial concentrations are lower than subsequent values, but this interpretation is based on only three analyses, and cannot be considered reliable.

Analysis of the decay rates ($t_{1/2}$ - time taken for the concentration to decrease by 50 %) for the calculated regression equations indicate that iron concentrations decay more rapidly than manganese, zinc and nickel, taking 5.5 years in comparison to 10 years for a 50 % reduction. This indicates that the improvement in water quality is more rapid with the respect to iron than the other metals. This difference is not considered to be due to the control on the solubility of the metal ions in solution, because the pH values remain constant through out this period. Data was avaliable for the metals copper, chromium and cadmium but these show no temporal changes and concentrations remained at or below detection for the 19 year period. This may be due to either/or both of the following cases. The near neutral pH, limiting the solubility of the ions or the capacity of the ferric hydroxide (which lines the walls, and floors of abandoned coal mined voids) (Plate 1.1 A and B) to adsorb and co-precipitate free metal


IRON
IRON mg l⁻¹
24
20
6
12
8
4
Fe = 22.2 e^-0.13t
r² 0.776


MANGANESE
Mn mg l⁻¹
5
4
3
2
1
Mn = 3.86 e^-0.08t
r² 0.833
2
4
6
8
10
12
14
16
18
20
Time since commencement of discharge (Years)

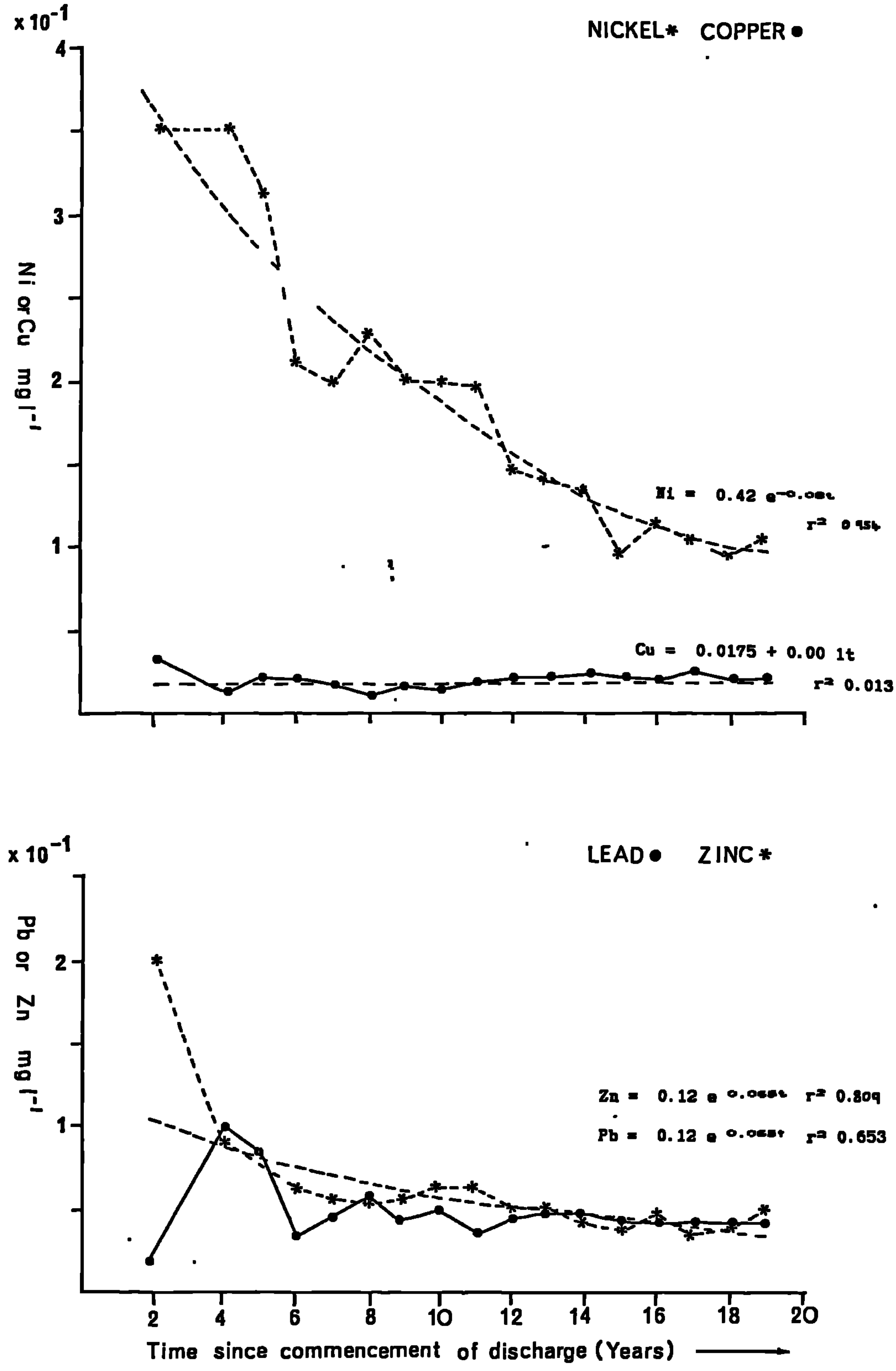
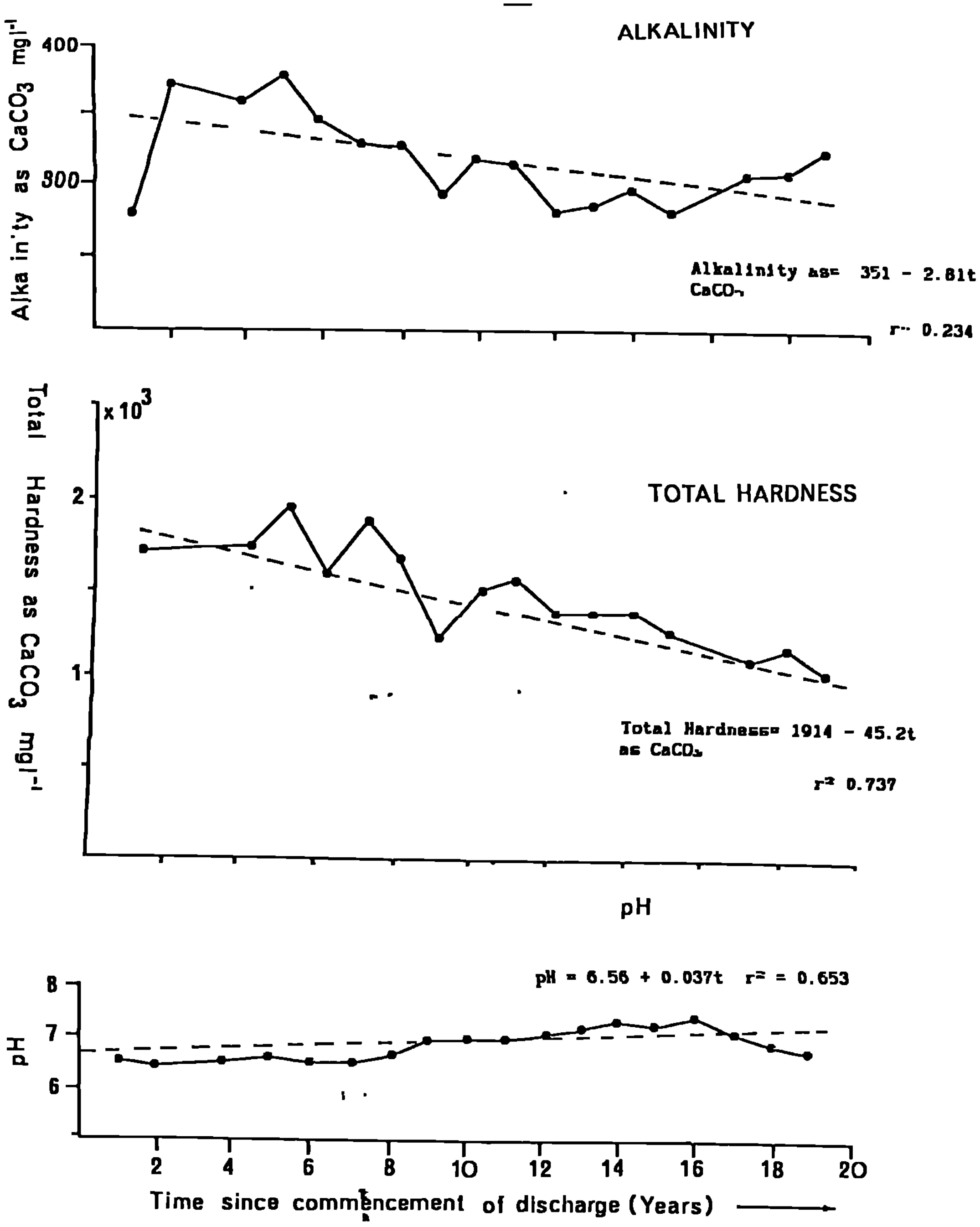
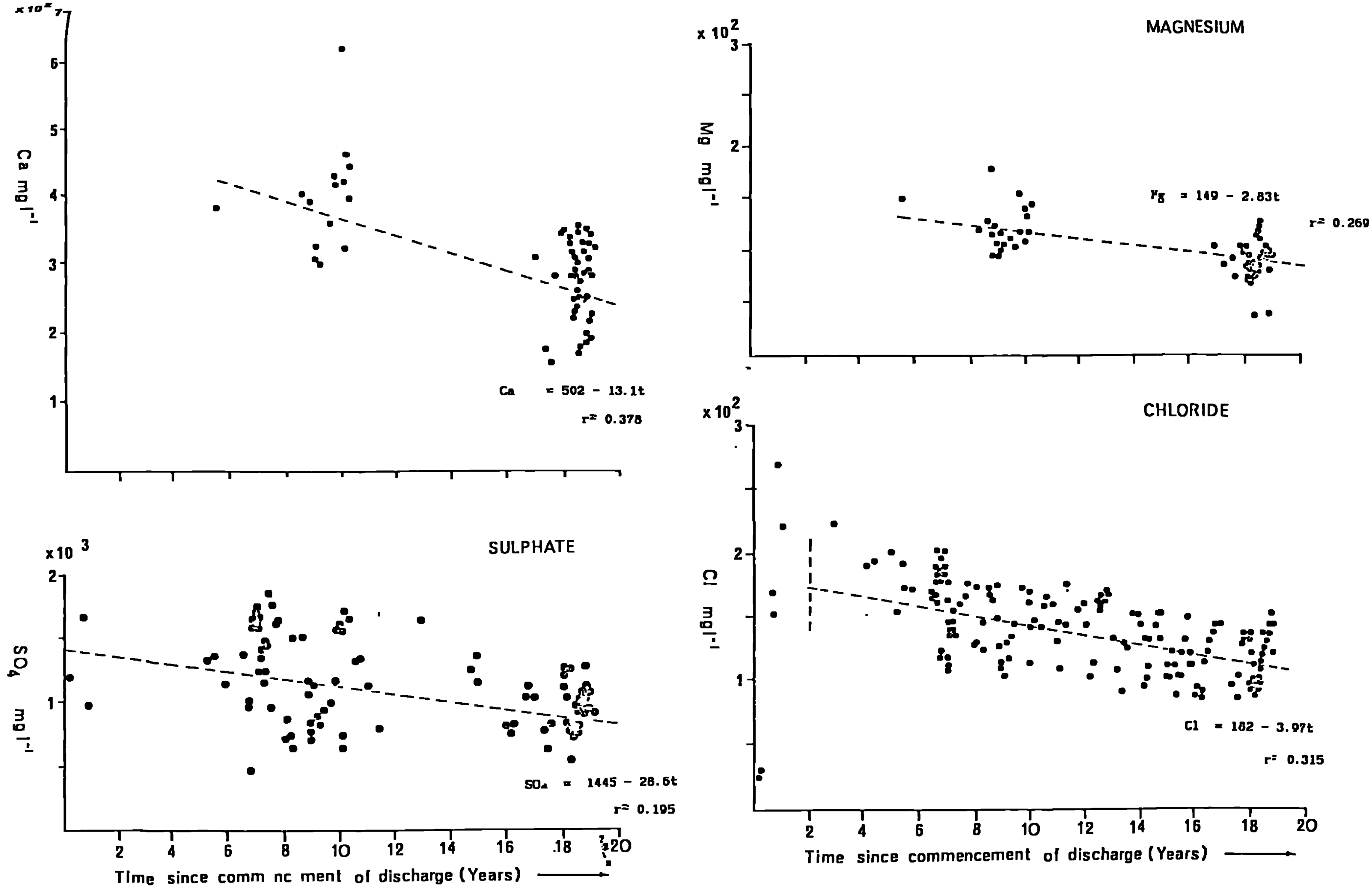


Figure 8.5 : Long term temporal changes in groundwater chemistry at the Norchard Drift : Metal ions yearly average data.


ALKALINITY
Alka lin'ty as CaCO3 mgl-1
400
300
Alkalinity as= 351 - 2.81t
CaCO3
r= 0.234
TOTAL HARDNESS
Total Hardness as CaCO3 mgl-1
x 10^3
2
1
Total Hardness= 1914 - 45.2t
as CaCO3
r2 0.737
pH
pH = 6.56 + 0.037t r2 = 0.653
8
7
6
2
4
6
8
10
12
14
16
18
20
Time since commencement of discharge (Years)



x 10² 7
Ca mg l⁻¹
Ca = 502 - 13.1t
r² 0.378
MAGNESIUM
x 10² 3
Mg mgl⁻¹
Mg = 149 - 2.83t
r² 0.269
SULPHATE
x 10 3
SO4 mg l⁻¹
SO4 = 1445 - 28.6t
r² 0.195
Time since comm nc ment of discharge (Years)
CHLORIDE
x 10² 3
Cl mgl⁻¹
Cl = 182 - 3.97t
r² 0.315
Time since commencement of discharge (Years)

ions (in particular cadmium, copper, nickel and lead) and therefore lower the relative concentration present (Laxen 1984 and 1985). This may also be the process that occurs which lowers the initial concentrations of the metals (manganese, zinc and nickel) and has subsequently effected the t ½ decay rates.

The second type of response, is shown in the figures for total hardness, pH, alkalinity and chloride (Figure 8.4 and 8.6). The graphs for chloride and total hardness all show lower concentrations for the initial year after commencement of flow. This is particularly marked in the case of chloride, where concentrations where 16 mgl ¹ in the first year and between 220 and 120 mgl ¹ in subsequent years. Chloride concentrations are typically 15-25 mgl^{-1} in normal recharge waters (similar to concentrations in the shallow groundwater flow from the upper levels at the Old Furnace and Miles Levels), this would indicate that the initial water has had a short residence time. These values are also similar to those from pumped water from working collieries at similar depths in the South Wales Coalfield (Ineson 1967). Alkalinity concentrations are also signifi antly lower in the first year, subsequent concentrations rise and then fall slowly. The bicarbonate species (the dominant alkalinity anion at a pH of 6.5 are directly related to the volume and residence time of recharge waters passing through the Pennant Sandstone). The bicarbonate is a product from the dissolution of the calcite matrix of the Pennant Sandstone. The initial lower values are a direct response to a shorter residence and contact time of the water with the Pennant Sandstone.

Unfortunately there is little total hardness data (combined calcium and magnesium hardness), and no data exists for calcium and magnesium concentrations during this initial period (year 1). The total hardness value for year 1 on Figure 8.4 is an average of the only two values available. There was no data for years 2 and 3. It would have been expected that a decrease in calcium concentration also occurs as this is also dependent on an identical mechanism to that of alkalinity for its presence. However this remains as speculation.

The initial flush of water (discharge year 1), is recharge water that has originated from the Pennant Sandstone Aquifer, filled the remaining open mine galleries and voids and haulage roadways but is transported quickly within the major mine roadways to the discharge outlet. The major chemical composition (cations and anions) remains unchanged, being in contact with the relatively inert bricklined haulage roadways, and mined void. The residence time in the mined void is small and as the waterlogged zone increases in size, the rest water level continues to move and rise. This later movement in the mined void puts into solution the products of pyrite oxidation (iron and associted metals) and forms the highly mineralised initial 'metal flush'. The chloride, bicarbonate and total hardness remains low as the proportion of flow that has had further contact with the Pennant Sandstone aquifer is small. The hydraulics associated with the discharge of this initial water are that when the mined void and haulage roadways are initially filled this water is subsequently displaced by further recharge. (Analogous to a queue system whereby the queue (in this case the storage volume of the mined void and haulage roadways) only changes due to an addition to the back of the queue which displaces an equal amount from the front of the queue).

After this initial flush of water, generally concentrations rise to their maximum levels followed by either a period of constant concentration or slow decline. In the case of chloride concentrations rise dramatically from ~ 25 mgl^{-1} to ~ 250 mgl^{-1} in the first 12 months. The elevated levels are a result of the two possible processes. Firstly mixing and dilution of brine and connate waters having high chloride concentrations. This is because, the seat earth below (and in some cases the shale roof above) but in the case of the Coleford High Delf coal seam probably the Yorkley coal seam and associated seat earth clay above, act as a semi permeable membrane, which has allowed little leaching or dilution by natural groundwater movement to take place, and a concentrated brine to form. Downing and Howitt (1969) report concentrations averaging around 10,000 mgl^{-1} in Coal Measure rocks in the East Midlands. This theory is also supported by Russell (1933) and Glover (1983). However, if this process was significant it would be expected that chemical analyses during mining and mine development to contain extremely high concentrations of chloride as the brine waters are dewatered from the mine. Unfortunately there is little data to substantiate this but the mining samples plotted earlier on the Durov diagram do show that chloride is not the dominant anion. The second explanation for the incresed chloride levels involves the sedimentary origin of the rocks in which the recharge waters are in contact. The increased concentrations could be due to leaching and dissolution of chloride salts from shales, clays and coals of a marine or brackish water sedimentary origin. This later process combined with the dilution of saline connate waters is more probable. Another possible reason for the decline is a change in groundwater flow source area. Early discharge contains a larger proportion of coal mine water Pennant Sandstone water, and later discharges contain a higher proportion of

Pennant Sandstone water and a decline in coal mine water volume. This would accord with the subsidence and closure of the mined voids at depth.

Unlike chloride the sulphate does not show the initial low concentration associated with the first flush of recharge water. Initial concentrations are the highest recorded, being ~ 1300 mgl^{-1}. This initial high concentration is due to the origin of the sulphate. Sulphate is a product of the oxidation of pyrite, and is therefore transported in solution by the same processes that removes the iron and metals from the mined voids. Concentrations do not decline rapidly in a similar manner to that of the iron and metals, but decline in a gradual manner like chloride. In the case of chloride this was explained by a continued leaching proceses and the dissolution of chloride salts. A similar case may be present for sulphate, as another origin of sulphate other than pyrite oxidation is the oxidation of other sulphide minerals from the coal seams and marine shales. (It should be noted that the high value for year 13 is an artifact of a seasonal cycle and the yearly averaging process).

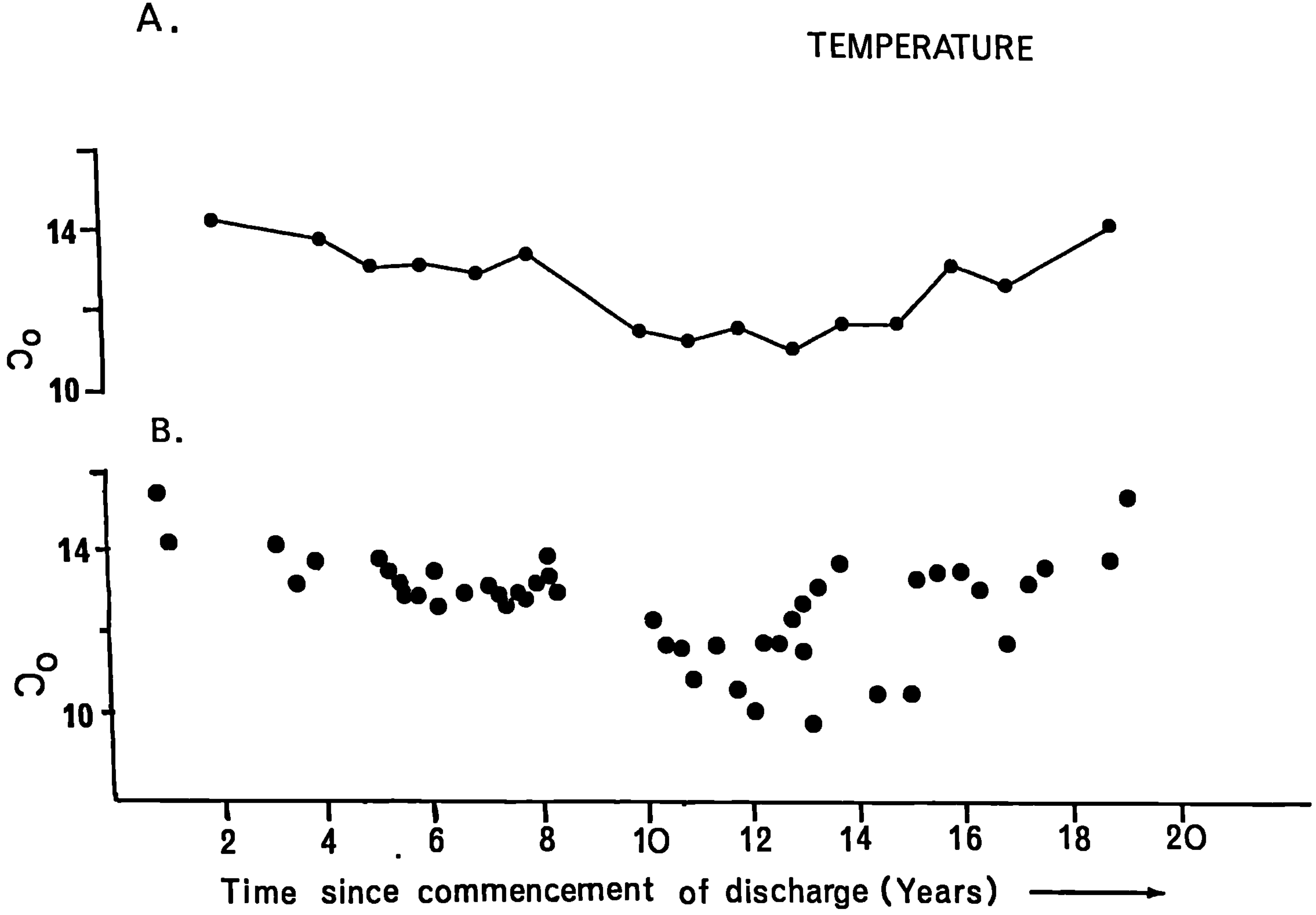
Unfortunately there is little data for calcium and magnesium (Figure 8.4 and 8.6), although substantially more exists for total hardness data (Figure 8.4). There has been a gradual decrease over the 19 year period. I could be tentatively suggested that the initial water from the mine void was more acidic came into contact with the Pennant Sandstone and reacted with the calcite matrix producing calcium and bicarbonate, the later acting as a buffering system to compensate for the additional acidity produced from pyrite oxidation. The magnesium is primarily derived from contact with the marine shale layers and cation exchange with clays.

The graph for temperature (Figure 8.7 A and B) shows a parabolic shape, initial high groundwater temperatures (14.5 °C) slowly decline over the first ten years (to 11.75°C) followed by a rise over the next nine years (to 14.5°C), which is equal to the initial temperature. The higher than normal groundwater temperature is attributed to the geothermal heating as the groundwater has circulated through the Coleford High Delf Coal Seam workings and the Pennant Sandstone Aquifer, possibly reaching depths of -400m, before being discharged. The commonly expressed geothermal gradient is 1°C for every 35 m (Rodda et al 1976 and Freeze and Cherry 1979). If this is the case applied here, an initial recharge water of 10°C (the free drainage level discharges range between 9 and 10°C) would be warmed to between 20 and 23°C. This assumes that no cooling by conduction takes place when the water rises when discharged at the ground surface and that the

FIGURE 8·7

Temperature graphs for the Norchard Drift Adit discharge since commencement of flow.

A. Yearly average values and B. all data values.



discharged water is not cooled by mixing with another shallow source. Both of these cases may occur, and could account for a cooling of between 6 and 9°C. By applying a two component mixing model, and assuming that the cooling process is the mixing of a colder recharge water with a temperature of 10°C. With an initial temperature of 20°C, a mixing of 55% : 45% (Shallow to Deep Ratio) is required to obtain 14.5°C and 82.5% : 17.5% for 11.75°C. These values are significantly different to those determined in section 8.6 see below. This may be due to the natural geothermal gradient and potential at depth being altered by the mining of the coal, and it is not unreasonable to suggest that the aquifer may have cooled considerably at depth from this process and the geothermal gradient is less than the 1°C per 30 or 40 m suggested in general texts. By applying the same two component mixing model in another form, and using an average 55% baseflow to recharge volume (calculated in 8.6 see below) it is possible to back calculate the initial deep water temperature and therefore the geothermal gradient present. These indicate an initial temperature of 18.2°C for an outflow temperature of 14.5°C and 13.2°C for an outflow of 11.75°C. To obtain 18.2°C the geothermal gradient would have to be 0.82°C per 40 m and for 13.2°C, 0.32°C per 40 m. The former seems most reasonable in comparison to those normally quoted.

Another case worthy of consideration is that suggested in Figure 3.4 and Figure 5.14, that the barrier breaks which are at -210 m and the major roadways which circumnavigate the basin at this depth control the movement of groundwater and the depth to which annual recharge waters move. If this is the case a geothermal gradient of 1° C for every 35 m would produce an outflow temperature of 16.7° C for a recharge water of 10° C, if similar conditions are assumed to apply as described above. Again if a two component mixing model is applied, for an outflow temperature of 14.5° C the proportions of baseflow (deep basin water) and recharge water are 65 % : 35 % or for 11.75 ° C 27 % : 73 %. The former case 65 % : 35 %) is the best result when compared with those suggested in section 8.6 and Figure 8.9, and this provides further evidence that the roadways and breached barriers which circumnavigate the basin do control the movement of groundwater.

The decrease in temperature after initial discharge can be explained by a continued cooling effect of the introduction of the colder Pennant Sandstone recharge waters or an increase in the proportion of colder recharge waters being discharged. However, the increase is more difficult to explain. One possibility is that a barrier at depth gave way releasing a large volume of stagnant warmer water into the circulation or contrary to earlier time periods the flow proportion of warmer deep water in comparison to the colder Pennant Sandstone recharge water has increased. However, the calculations undertaken here are based upon a limited knowledge concerning the behaviour of the geothermal gradient at depths in mined coal seams.

Unfortunately there is insufficient data to comprehensively assess changes in mineral saturation indices for calcite and dolomite. However those calculated using the WATSPEC computer program (Wigley 1977) are in Table 8.4. A seasonal cycle is present, which shows positive (super saturation) occurs during the recessive discharge months April to October, while during the winter months of November to March when discharge increases the saturation indices are under saturated. This would indicate that the amount of water that is in contact with the Pennant Sandstone that is discharged from the Norchard Drift is relatively constant and that this volume is diluted by aggressive recharge waters which have moved rapidly via the major roadways within the coal seams or fracture systems in the Pennant Sandstone during winter months.

8.6 AN ANALYSIS OF SHORT TERM TEMPORAL CHANGES IN CHEMICAL COMPOSITION OF ABANDONED DEEP COAL MINE OUTFLOW WATERS.

The data available for chloride, iron and total hardness is sufficient to be able to determine that a strong seasonal cycle is present (Figure 8.8). Maximum concentrations occur generally in the August and minimum concentrations in the January or February of each year.

In the case of chloride concentrations have declined, from an annual average of 165 to 120 mgl^{-1}, but over this period the amplitude of the seasonal cycle remains constant. Although the mean value for any particular year varies the standard deviation of the values remains constant. This is the general case, except for the years 1975/1976. There was a lack of winter rainfall in 1975 and the chloride concentration is thus not diluted by recharge water. However the peak concentration for the summer of 1976 remains similar to other years and is not elevated. This indicates that the peak concentrations represent baseflow conditions (water from the deep basin) which has a chloride composition, ranging between 190 and 158 mgl^{-1}, for the thirteen years. A similar pattern is also evident in the total hardness and iron data, except that in the case of the iron data the magnitude of the seasonal cycle is not constant but varies, with peak concentrations (maximums) being more varied and trough (minimums) relatively stable. If it is suggested that the peak concentrations represent baseflow from

TABLE 8.4 : SATURATION INDICES FOR CALCITE AND DOLOMITE FOR WATER SAMPLES COLLECTED FROM THE MAIN DEEP BASIN PRIOR TO AND SINCE DISCHARGE FROM THE NORCHARD DRIFT

A. DEEP BASIN PRIOR TO DISCHARGE FROM NORCHARD DRIFT

SITE	DATE	CALCITE	DOLOMITE
NORTHERN UNITED	070564	-0.04	-0.70
NORTHERN UNITED	030665	-1.39	-3.27
NORTHERN UNITED	070765	-0.61	-1.66
NORCHARD COLLIERY	141063	+0.11	-0.18
NORCHARD COLLIERY	141063	+0.16	-0.16
NORCHARD COLLIERY	141063	+0.02	-0.33
NORCHARD COLLIERY	291063	-0.46	-1.30
NORCHARD COLLIERY	291063	-0.08	-0.05
NORCHARD COLLIERY	291063	-0.11	-0.56

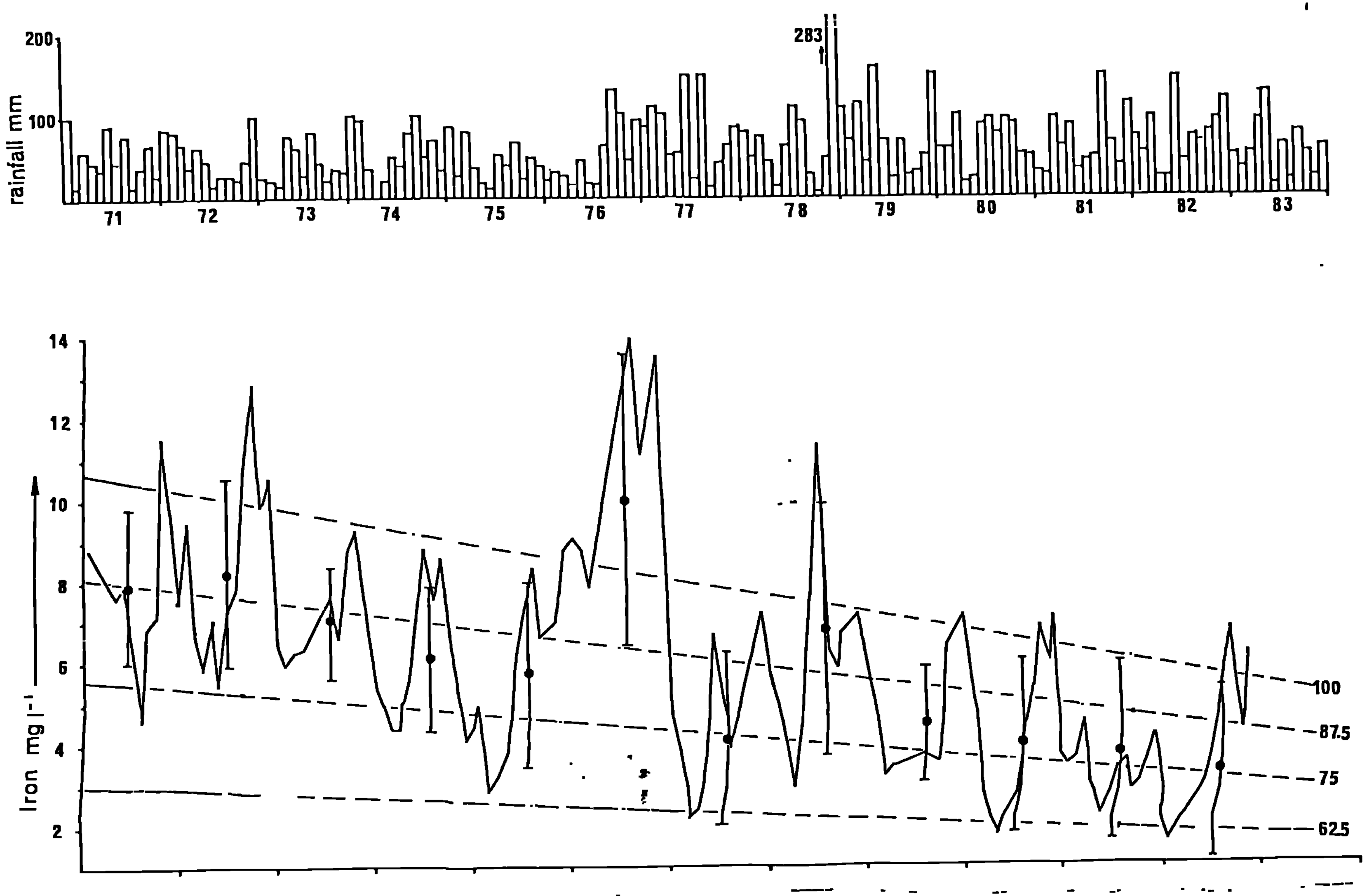
B. NORCHARD DRIFT AFTER DISCHARGE COMMENCED JUNE 1966

DATE	CALCITE	DOLOMITE
040571	-0.13	-0.49
250674	+0.03	-0.34
230974	-0.11	-0.53
261174	+0.01	-0.31
090175	-0.03	-0.30
070575	+0.30	+0.22
170675	+1.08	+1.72
280875	+0.16	0.00
170975	+0.30	+0.04
101175	+0.06	-0.22
031275	-0.06	-0.45
101275	-0.06	-0.43
060176	+0.22	0.00
060276	+0.25	+0.24
151082	+0.06	-0.16
161284	-0.06	-0.43

All data is calculated from NCB chemical analyses except those for 1982 and 1984 for comparison from STWA Archives.

Calcite and dolomite saturation indices calculated by WATPSEC (Wigley 1977).

FIGURE 8.8 : Short term temporal changes in chloride, total hardness and iron concentrations for the period from 1971 to 1983 at the Norchard Drift. These changes can be used to indicate e proportions of quick flow and baseflow at the discharge throughout the year.



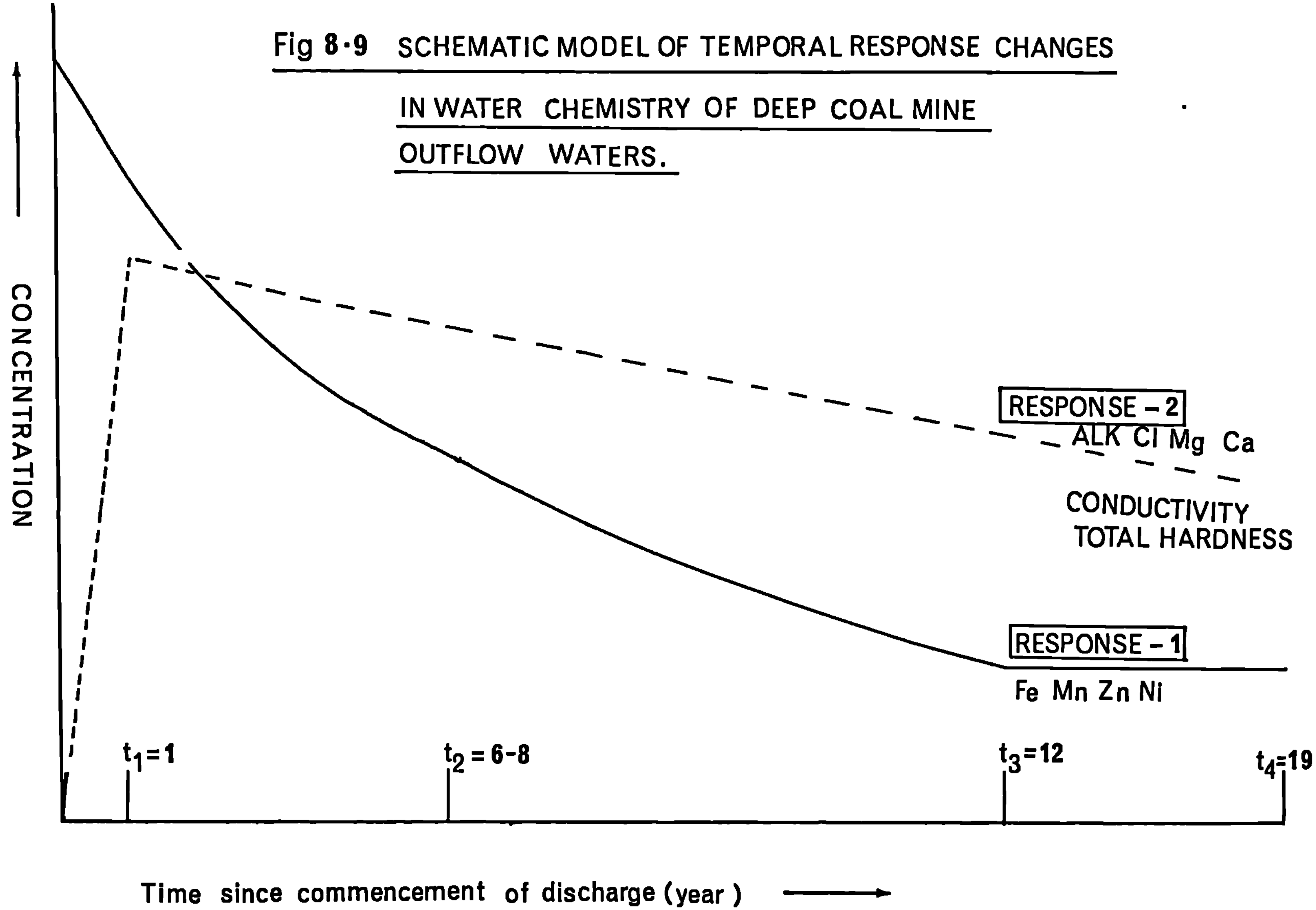
the deep basin and that the lower concentrations are a mixture of the deep basin water with lower concentration Pennant Sandstone recharge water. If the recharge water is assumed to have a chloride concentration of 20 mgl^{-1}, total hardness of 250 mgl^{-1} and iron of 0.5 mgl^{-1}. (this is typical of the Miles and Old Furnace Levels), a simple two component mixing model can be developed (Pinder and Jones 1969). From this it is possible to calculate the percentage of baseflow, that is discharged at any one time, (Figure 8.8). This does however assume that the linear decline in baseflow concentration is attributable to a leaching process and not a change in discharge composition.

The average winter discharge composition is between 50 and 62.5 % ba eflow water (50 and 37.5 % recharge water). The difference in results between the three determinands is small. The percentage baseflow proportion lines marked on figure 8.8 converge slightly, (most marked in the case of the iron data). This is a product of the numerical calculation of the two component mixing model, and the assumed change in baseflow compostion attributed to leaching. The numerical effect is that the deep basin component changes in magnitude while that of the recharge water is constant. Furthermore, the percentage change in the baseflow composition is most marked in the case of iron, a change of 45 %, while the difference in the case of chloride is only 17 %. Although this assumption was made, it cannot be assumed to be exactly correct because the percentage of flow from the deep basin in comparison to the volume of more recent Pennant Sandstone recharge waters may have varied over this period as well. This change however, if present is small and does not effect the general arguments supported by the mixing model.

8.7 CONCLUSIONS AND DISCUSSION.

In conclusion, the changes in water chemistry composition falls into two general categories (Figure 8.9) (although there are deviations from this, for instance sulphate). Firstly, the changes in metal composition. The metals originate from pyrite oxidation in the coal voids and initially these products are flushed from the open voids, but as the voids collapse the volume of water derived directly from this source becomes smaller. Furthermore, as oxic conditions are replaced by anoxic the potential for oxidation to take place is limited to an area clo e to the water table. The production of oxidation products in this annually inundated zone is small in comparison and only the major elements (iron and manganese) remain in sufficiently large concentrations to be detectable. The remaining metals are diluted by the large volume of better quality water derived from the

Fig 8·9 SCHEMATIC MODEL OF TEMPORAL RESPONSE CHANGES IN WATER CHEMISTRY OF DEEP COAL MINE OUTFLOW WATERS.



Pennant sandstone aquifer. This indicates that the proportion of flow derived from the deep basin mined void decreases, and therefore collapse at depth must also occur. The changes in metal composition are the most significant, however this effect on the conductivity of the water is small, indicating that the major ion chemistry is relatively stable and that this changes only very gradually. The second repsonse is reflected in the major cations and anions (calcium, magnesium, chloride, alkalinity, total hardness and conductivity). As described earlier this is characterised by two components an initial low mineralised water, which is subsequently replaced by a highly mineralised water. This change is associated with a change in transport mechanism. The initial flow is relatively quick and through the remaining open coal mined void and major haualge roadways, while the latter is associated with a longer residence time, with a high proportion of flow being derived from the Pennant Sandstone Aquifer.

The analysis of the seasonal cycles of total hardness, chloride and iron have indicated a two component flow mechanism is present in deep groundwater circulation. This comprises of a concentrated deep basin component that is diluted by a lesser evolved water that has originated from Pennant Sandstone recharge. The transportation of this mixed water to the discharge outlet is relatively quick, not being appreciably lagged behind winter rainfall and emerging at the discharge outlet during the mid winter months (Figure 8.8). It is suggested that this has travelled via the remaining open haulage roadways, having little further contact with the Pennant Sandstone or adjacent mined void. This particular case has been demonstrated by the tracer test discussed in chapter 7.

The environmental implication of the response changes in outflow chemistry determined from the general model outlined here, is that an initial poor quality water results from a primary flush of oxidation products which improves and stabilises through time. From a resource management and environmental protection view point the possibility of predicting outflow water chemistry and changes in composition of these would be advantageous. The only previously reported predictive equation is that referring specifically to iron levels (Glover 1983). Glover states:

"the initial flows from freshly submerged workings tend to be ferruginous commonly containing between 10 and 200 mgl^{-1} of dissolved iron ,,,, the iron concentration falls by 50% in each subsequent period equal to that taken to fill the workings originally", Applying this case to the Forest of Dean by using the period of 18 months to flood the workings (Chapter 3) this would indicate that that iron levels should fall from the initial 23.5 mg^{-1} to 11.7 within 18 months and to 5.875 mg^{-1} in 3 years. This unfortuanetley is not true for the Norchard Drift. Iron levels fall by 50% in 5.5 years to 11.75 mgl^{-1} and by another 50% in another 5.5 years (11 years since commencement of discharge) to 5.875 mgl^{-1}. If the basis of the model proposed by Glover is assumed to be correct, the failure of the model is related directly to the problems of determining the time period for waterlogging and flow to commence (discussed in chapter 3). The general problem is determining when precisely did mining and pumping finish, because in most cases abandonment operations for a coalfield occur over many years. Furthermore when individual mines are closed the process of closure covers many months during which time deep parts of the mine may be allowed to flood many years prior to total coalfield closure. This later case may well have occured in the Forest of Dean. There is no reported work that has attempted to predict the initial concentrations of outflow waters, and this remains an important research area. However, this work has indicated schematically the more important long term changes in outflow chemistry and indicated the differences between initial abandonment and post abandonment chemistries.

CHAPTER 9

HYDROCHEMICAL FACIES SEPARATION OF GROUNDWATER FLOW COMPONENTS AND VOLUMES.

9.1 INTRODUCTION

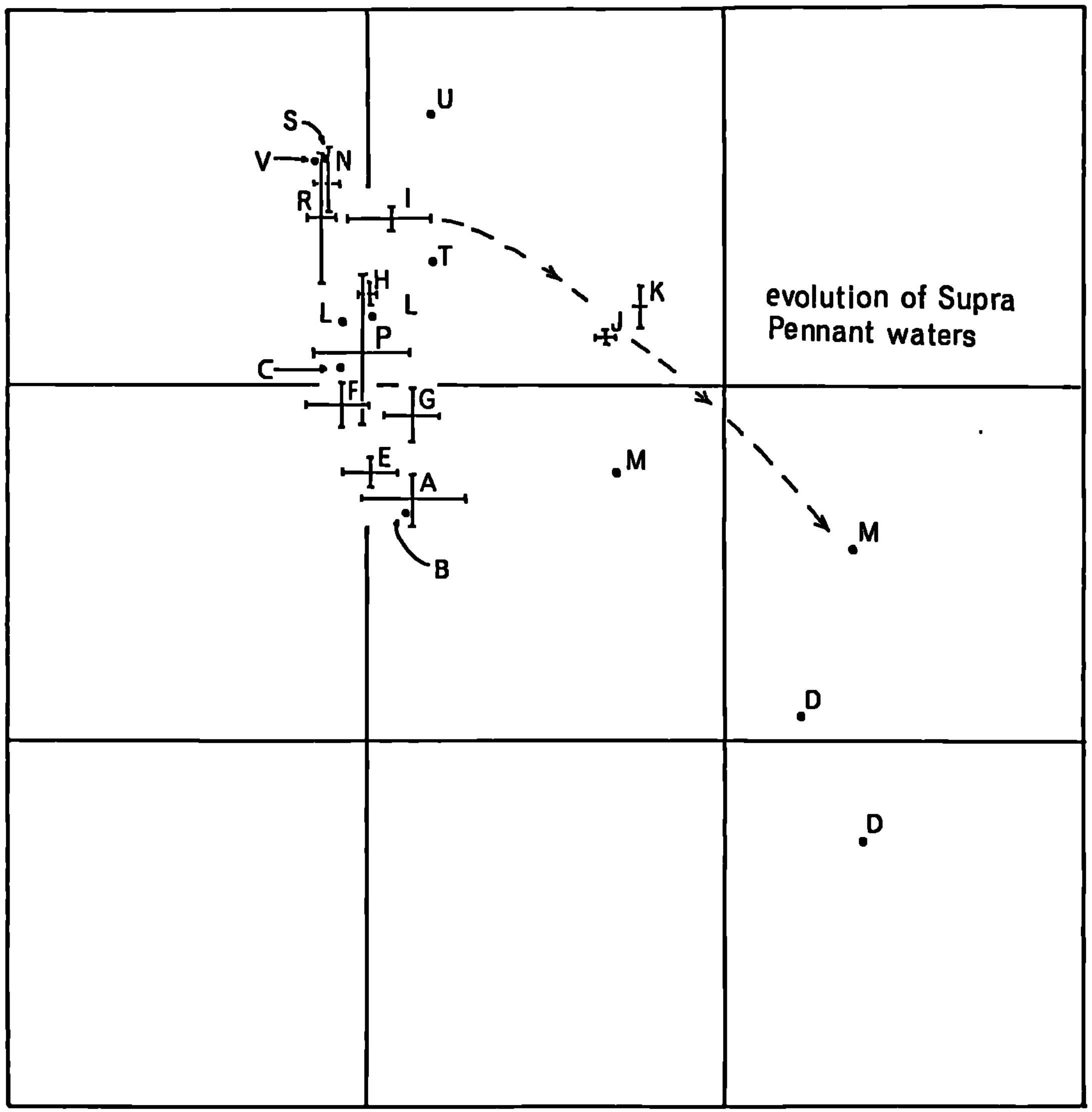
There is often a necessity to determine groundwater flow volumes and conditions without the possibilty of extensive field studies. The use of an archive chemical data base together with a few discharge values is often the only data available to undertake this. This chapter aims to identify groundwater discharge volumes from differing source areas by the use of discharge and chemical data collected during the field study and to compare these results with those determined by other methods. The techniques used are readily available and easy to use (a criteria important in the day to day management of water resources) being based upon the Durov-Zaporovec diagram and a two component mixing model which was previously developed by Pinder and Jones (1969). The use of both of these techniques has already been demonstrated in the previous chapter.

9.2 A CLASSIFICATION OF THE WATER TYPES PRESENT TODAY IN THE FOREST OF DEAN.

Figure 9.1 shows the chemistries of the major adits, levels and shafts plotted on a Durov-Zaporovec diagram. This diagram also shows the range of the values which occur through out one particular water cycle at the major discharge locations (the bars on figure 9.1 are +/- one standard deviation). (The general interpretation of a Durov-Zaporovec diagram was examined in the last chapter (Figure 8.2)).

The most significant finding from this diagram (Figure 9.1) is that the chemical composition of the groundwater at the majority of the discharges varies little. This is clearly demonstrated by the small standard deviation bars. The largest variations are associated with the deep basin discharge at the Norchard Drift and the three free-drainage levels at Tufts Level, Parkhill Level and Oakwood Level. These later three levels do not only drain the abandoned workings in the Pennant Group but also penetrate the surrounding Carboniferous Limestone from which iron ore was extracted.

The groundwater from the Norchard Drift and the Cannop Cross Borehole plot very closely. This is contrary to that expected as chapter 5 has demonstrated that the Norchard Drift drains the Coleford High Delf Aquifer and that the free surface rest water level within this borehole is actually that of the Yorkley Aquifer. Furthermore, the Yorkley coal seam has not been mined at depth and



LEGEND :

LETTER	SITE NAME	No. OF OBSERVATIONS
PENNANT DEEP BASIN		
A	MORCHARD DRIFT	50
B	CANNOP CROSS BOREHOLE	1
C	FLOURMILL SHAFT	1
D	CANNOP COLLIERY SHAFT	2
PENNANT SHALLOW WORKINGS DISCHARGES		
E	OLD FURNACE LEVEL	43
F	MILES LEVEL	43
G	QUEST SLADE	9
H	SCOTTS LEVEL	6
SUPRA PENNANT DISCHARGES		
I	INDEPENDENT LEVEL	42
J	CANNOP LEVEL	8
K	PARKEND COLLIERY SPRING	2
L	SPECULATION COLLIERY SPRING	2
M	OLD BOES COLLIERY SPRING	2
CARBONIFEROUS LIMESTONE AND PENNANT DISCHARGES		
N	TUFTS LEVEL	39
P	PARKHILL LEVEL	32
R	OAKWOOD LEVEL	10
S	TUFTS IRON MINE	1
T	SHAKEMANTLE IRON MINE	1
U	PRINCESS LOUISE LIMESTONE SHAFT	1
V	OLD HAM IRON MINE	1

N +/- 1 S.D.

FIGURE 9.I : Durov-Zaporovec diagram showing the chemistries and variation in chemistry at the major discharges in the Forest of Dean.

anoxic conditions can be expected to be present within this aquifer while oxic conditions will have been or are present within the Coleford High Delf coal seam workings, and therefore different chemistries would be expected. Because the Durov-Zaporovec relies on the major cations and anions for the discrimination between samples it can be concluded that the similarity between the samples may be due to the dominance of groundwater originating from the Pennant Sandstone, which is present in both aquifers. Furthermore this would also indicate that the more dramatic, major changes in groundwater chemistry due to mining, effects minor constituents such as iron, nickel and zinc more dramatically. This would also accord with the hypothesis suggested for the changes in outflow chemistry discussed in chapter 8.

Unfortunately few other samples could be taken from the deep basin, due to problems with access to the rest water level via shafts because of extensive abandoned winding gear (extreme difficulty was experienced even with small borehole dippers), borehole headworks, contamination by fluorescent dyes from tracer tests and industrial activities. The latter case can be clearly demonstrated with regard to the samples taken from the Cannop Colliery Shaft (Samples D Figure 9.1). At this site a large road salt pile within the perimeter surrounding the shaft, drains directly into the shaft access hole and recharges shaft water with high sodium and chloride levels, which adversely affects the chemistry of the samples taken. The samples shown (taken at maximum and minimum groundwater levels) cannot be considered as representative. It is interesting to note that another sample site (M Figure 9.1) also shows increased sodium and chloride levels. However, this site drains a different aquifer the Supra Pennant Aquifer, although it is only 125 m distant from the rock salt piles.

The samples for the shallow free-drainage level discharges also plot closely but more importantly these contain small variations in the chemistries although substantial sampling was undertaken throughout the field monitoring period. This will be discussed further below.

The samples for the Supra Pennant discharges are more interesting. Those from the Independent Level (I Figure 9.1), which drains the extensively worked area of the Lowery coal seam south of an east-west barrier, plot as relatively juvenile waters being close to the area of the diagram associated with recharge waters (Figure 8.2). Samples from the sites at the Cannop Level and the Parkend Colliery Spring are isolated from the other sites but on a line with those from the Old Bobs Colliery site. If the Old Bobs Colliery samples are representative this may depict the chemical evolution of ground waters within the Supra Pennant

Group. The older water sites J, K and M would represent an increase in residence time associated with increased ponding. This would also accord with the case hypothesised from the location of the remaining intact coal barriers, the discharge recession curves and storage volumes. The Speculation Colliery Spring is the only Supra Pennant site which does not follow this evolution, but as discussed in chapter 7 it appears that at this site there is a loss of water further down dip towards ponding associated with the Old Bobs Colliery and Cannop Level sites and that this site only discharged relatively recent recharge waters, similar to those from the Independent or other essentially free draining sites.

The remaining sites are those associated with groundwater discharged from both the Pennant Sandstone and Coal Measures and the Carboniferous Limestone Aquifer. These samples show the most marked variation in chemistry. This is because they are a mixture of waters draining two distinct and differing aquifers. Samples from pure limestone sites (S, T, U, V) plot differently. The separation of these two components will be attempted in section 9.4

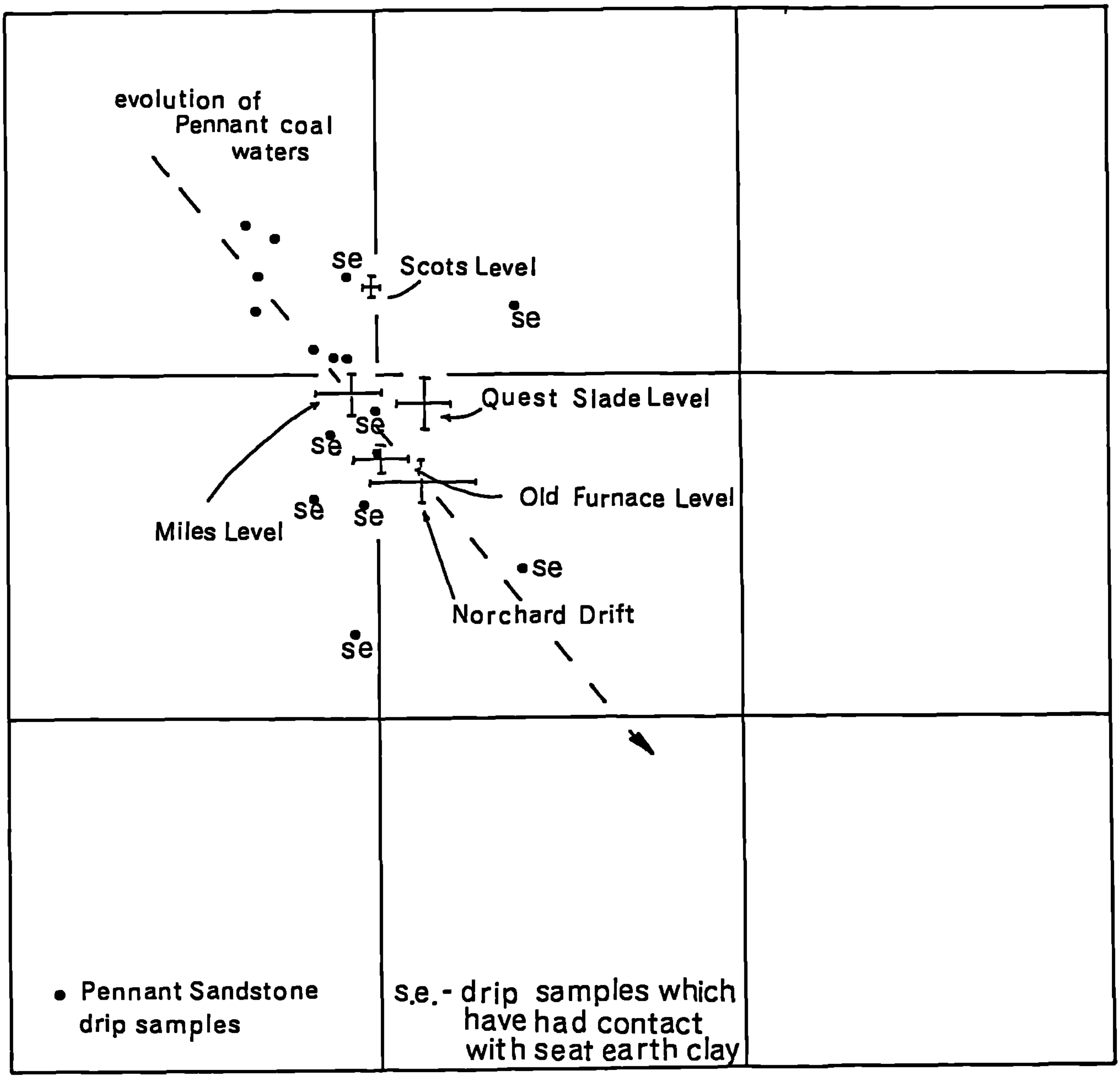
9.3 SEASONAL CHANGES IN OUTPUT CONCENTRATION FOR THE FOREST OF DEAN DISCHARGES

The aim of the intensive chemical sampling at the major groundwater discharges (Miles, Old Furnace, Independent Levels and Norchard Drift) was to enable the differentiation of flow proportions discharged from differing source areas (particularly waters from the Pennant Sandstone and the mined void). The seasonal variation in chemical composition of discharge waters (baseflow and recharge waters) from the Norchard Drift has been discussed in the previous chapter. But one distinct problem arose with the remaining sites.

The problem was in two forms, the number of representative samples that could be collected and the chemical changes that were present.

The aim of collecting specific source waters (for instance pure Pennant Sandstone water from drips and active recharge during underground exploration) was not successful because these sites only flowed for 6 weeks enabling the collection of 16 samples on two underground exploration periods. These samples are plotted on Figure 9.2. Although these samples were collected at only two times, there appears to be considerable variation within the data, and a close examination of the sample areas is required to understand this. The samples which are marked S E on Figure 9.2 were Pennant drips that were collected from the Pennant Sandstone where the Yorkley coal seam seat earth clay lies above, while the remainder are pure percolation waters from the Pennant Sandstone where

Figure 9.2 : Durov Zavorovec diagram showing the tentative indication of the evolution of Pennant Aquifer mine drainage waters.



no Coal Measure Strata is overlying. The samples which appear to plot nearest to the free-drainage levels are those that may have had contact with the seat earth clay and contain larger concentrations of magnesium and sulphate. The samples of pure Pennant Sandstone water would not have been in contact with a seat earth clay and are therefore representative of a juvenile recharge water. This sequence of events is tentatively interpretated as the evolution of the free-drainage levels and deep basin water chemistries, as shown in Figure 9.2.

The second problem was that there was no detectable change in chemical composition of the outflow waters during the monitoring period. (No change within the limits of detection and sensitivity of the chemical analysis methods used (Chapter 4)). This was not expected. Figure 9.3 shows the seasonal changes detected at the Norchard Drift (the trend lines have been fitted by using the S graph plotting computer package (Becker and Chambers (1984)), while Figure 9.4 shows the stable levels of chloride at the Independent Level and calcium at the Miles Level, (plots such as these are typical for the range of chemical parameters determined (Table 4.7) for all the sites monitored. The expected response was a decrease in concentration similar to that observed at the Norchard Drift, especially at sites such as the Independent Level where there is a distinct change between a discharge from an indirect recharge source to a direct recharge source and vice versa through the hydrological cycle, and at the Miles and Old Furnace Levels where discharges rise abruptly with the onset of winter recharge. The presence of this stable chemistry can only be explained by two factors.

The first case is hydrological. The stable chemistry indicates that the water that is discharged is always at the same equilibrium and must therefore be discharged from the same source area throughout the year, this source would be from an extensive saturated zone. The annual recharge replenishes this store, but only water that has been present within the store is discharged (analogous to a stack system), and the only short circuit system present is that associated with the temporary fracture storage identified in chapter 7 (and sampled on only 16 occasions (see above)). Unfortunately the storage volume of this store is small and its presence is also short (20 - 60 days chapter 7) and therefore its influence on the cumulative discharge chemistry is small.

The second explanation is associated with the sampling pattern. It has been mentioned above that the time period available for sampling Pennant Sandstone drips was small and the presence of this second flow component (temporary fracture storage) was similar. Because the chemical sampling was undertaken on a

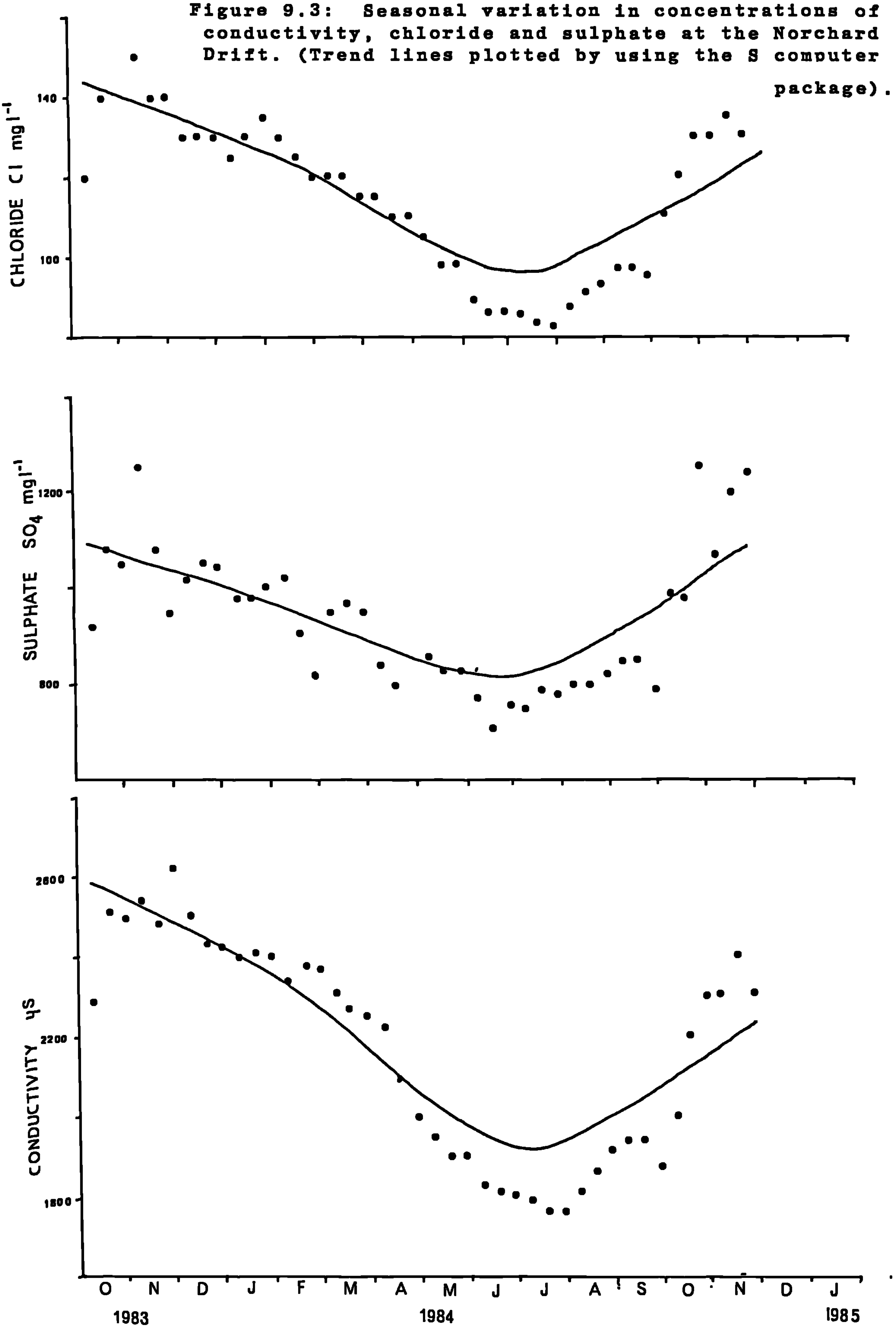
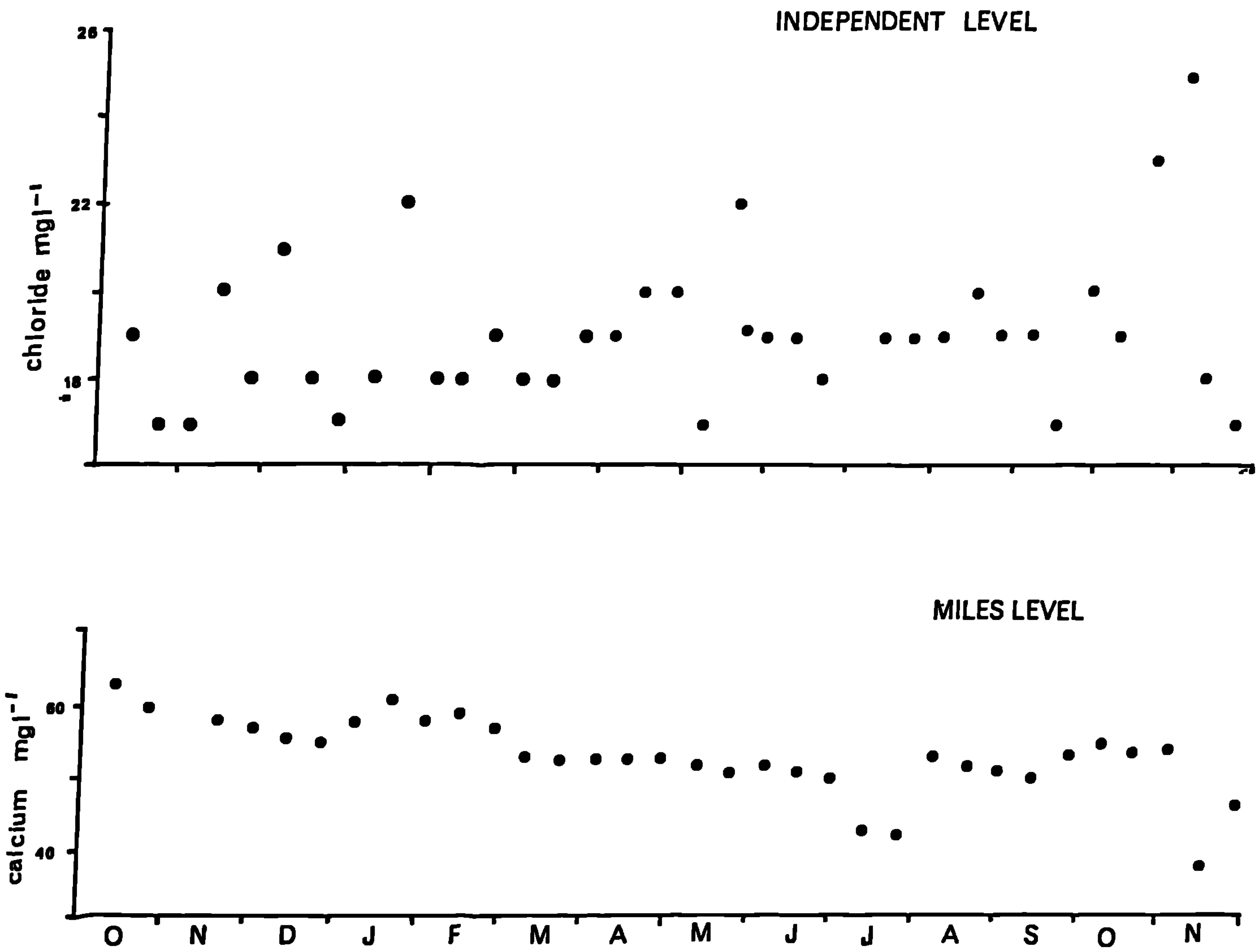


Figure 9.3: Seasonal variation in concentrations of conductivity, chloride and sulphate at the Norchard Drift. (Trend lines plotted by using the S computer package).

Figure 9.4 : Stable calcium and chloride chemistry at the Independent and Miles Levels.



seven or ten day interval at the larger discharge outlets, (because a much slower and longer response was expected) the number of possible samples that would represent this period would also be small and in some cases may have been missed.

9.4 THE USE OF A TWO COMPONENT MIXING MODEL TO DETERMINE GROUNDWATER DISCHARGE VOLUMES FROM THE CARBONIFEROUS LIMESTONE AND PENNANT SANDSTONE AQUIFER (INCLUDING COAL WORKINGS) AT TUFTS AND PARKHILL LEVELS.

In summary, the two major discharges at Tufts and Parkhill Level drain water from all of the Carboniferous Limestone Aquifer, the abandoned coal workings associated with the Trenchard, Coleford High Delf, Whittington and Yorkley coal seams (Figure 10.4), and the Pennant Sandstone. The above section has described the complications encountered with respect to the attempt at differentiating between Pennant Sandstone and coal seam waters, so in this instance the two will be considered together, and termed Pennant/coal waters.

To use a two component mixing model like that developed by Pinder and Jones (1969) requires the determination of specific values (known as end points) which characterise the components which are being separated. The values determined for the end points (of each component) must lie either greater than or less than that observed for the particular determinand present in the mixed water. This is an important point and will be returned to below.

The end points for the Pennant/coal water was determined from the combined analyses of the Old Furnace Level, Miles Level, Scotts Level, and Quest Slade Level, while those for the Carboniferous Limestone water was determined from sixteen extra samples taken underground in abandoned iron ores mines, from iron ore colliery shafts or surface springs. This data was then combined and analysed by using a computer-based discriminant analysis package. The discriminant analysis indicated that the major differences between the waters was attributable to the ions of calcium, magnesium, bicarbonate and sulphate, and the mean values for these determinands were calculated (Table 9.1). The mean values of these determinands were then used as the end points in the two component mixing model shown in equations 9.1 and 9.2 (Table 9.2). Unfortunately further complication arose because the concentrations of sulphate in the Parkhill Level averaged 160.5 mgl^{-1} (with a standard deviation of +/- 32.6, n = 32) while the Pennant/coal endpoint was only 123.0 mg/l^{-1} and a similar case existed for the Tufts level for this determinand with an average value being present of 40.25mgl^{-1} (with a standard deviation of +/- 6.1, n = 39) and a Carboniferous Limestone end member of 33.0 mgl^{-1}. This indicated that the Tufts

Table 9.1 : End points determined for both Pennant/coal waters and Carboniferous Limestone discharges.

PENNANT/COAL WATERS				CARBONIFEROUS LIMESTONE WATERS		
DETERMINAND	MEAN	STANDARD DEVIATION	No. OF OBSERVATIONS	MEAN	STANDARD DEVIATION	No. OF OBSERVATIONS
Calcium	54.9	15.2	101	92.5	25.5	16
Magnesium	24.7	4.6	101	17.6	11.8	16
Bicarbonate	114	27.4	101	338	55.0	16
Sulphate	123	44.2	101	33.0	12.0	16
Legend : All units are mgl^{-1}						

Table 9.2 : Discription of a two component mixing model as developed by Pinder and Jones (1969).

$$C_1 Q_1 + C_2 Q_2 = C_t Q_t \quad \text{..............Equation 9.1}$$

$$Q_1 + Q_2 = Q_t \quad \text{..............Equation 9.2}$$

Where : C_t is the concentration of the mixed two component water.
: Q_t is the discharge of the mixed two component water.
: C_1 is the endpoint concentration of component one.
: Q_1 is the discharge of component one.
: C_2 is the end point concentration of component two.
: Q_2 is the discharge of component two.

water was pure Carboniferous Limestone derived and that of Parkhill was pure Pennant/coal water, the contrary to this was known to occur, from both historic mining activities and the water budgets in chapter 6. A similar instance also occurred with the magnesium values because Tufts Level contained an average level of 36.1 mgl^{-1} (with a standard deviation of 4.4, n = 39) compared to an endpoint of 24.7 mgl^{-1} for even the Pennant/coal component. This was also the case at the Parkhill Level for magnesium concentrations, average 43.4 mgl^{-1} (with a standard deviation of +/- 13.0).

Therefore the only useable endpoints where those associated with the calcium and bicarbonate ions. The results in Table 9.3 show the proportion of flow from each source as a percentage of the total flow.

Table 9.3 : Results form the two component mixing models for Tufts and Parkhill Levels showing percentages of water derived from the Carboniferous Limestone and Pennant/coal Aquifers.

DETERMINAND	TUFTS LEVEL	PARKHILL LEVEL
Calcium	61 % Carboniferous Limestone 39 % Pennant/coal	66 % Carboniferous Limestone 34 % Pennant/coal
Standard deviation	+/- 17 % n = 39	+/- 40% n = 32
Bicarbonate	74 % Carboniferous Limestone 26 % Pennant/coal	70 % Carboniferous Limestone 30 % Pennant/coal
Standard deviation	+/- 14 % n = 39	+/- 26 % n = 32

Legend : - % values mean for data set quoted.

9.5 DISCUSSION OF RESULTS.

The mean value results determined for the two different source areas compare favourably with the differences in discharge determined from the water budgets in chapter 6 (Table 6.2). To recap in chapter 6 there was additional discharge at the Tufts Level of 71 % compared to that expected from the mine plan catchment area associated with the Pennant Sandstone and abandoned coal workings. Similarly, the addition of discharge at the Parkhill Level was 53 %. The use of the hydrochemical facies discrimination method and two component mixing model has demonstrated the source of this water. However, extreme care is required with the use of this technique because the determination of the endpoints is particularly susceptible to providing incorrect results. Especially if reaction between the two components occurs, or the chemical evolution of the water is slightly different at the mixed site compared to that used for the determination of the end points. This may be case with respect to the sulphate and magnesium concentrations at the Parkhill and Tufts Levels, because an open cast site has operated recently within the catchment area of the levels and adversely effected the water quality and also substantial ponding must exist in the coal workings close to the intersection of the free-drainage level with long measure roadways because the presence of blockage collapses are known (see chapter 10).

9.6 CONCLUSIONS

This chapter has demonstrated that the determination of hydrochemical facies and flow volumes in Coal Measure Aquifers is complex. The use of the Durov-Zaporovec diagram appears to be insensitive to minor changes in chemistry while that of the mixing models is far toosensitive to differences between sites draining the same aquifer unit. This is primaril y because of the absence of long term seasonal changes, but also due to the chemical evolution of groundwaters within abandoned workings being affected by surface open cast operations and the extent of unpredictable subsidence and ponding. Further work will be essential if the use of these techniques is to be encorporated within a policy for site appraisal studies for the future management of water resources in Coal Measure Aquifers.

CHAPTER 10.

GROUNDWATER MANAGEMENT PROBLEMS IN ABANDONED COAL MINED AQUIFERS A CASE STUDY FROM THE FOREST OF DEAN.

10.1 INTRODUCTION.

This chapter presents case histories of groundwater related problems experienced in the Forest of Dean since abandonment of the major collieries in 1965. The significance of the past mining activity for present day management of the water resources is assessed using the hydrogeological information presented in the previous chapters. Although these case histories relate specifically to the management of water resources in the Forest of Dean, the general principles used in their analysis have a wider application in any abandoned coal mined aquifer system (Aldous et al 1986).

10.2 THE EFFECTS OF DEEP BARRIER REMOVAL.

Abandoned coal mines are widely recognized as having prolonged detrimental effects on surface water quality due to the development of substantial point discharges of acidic and ochreous mine drainage waters (Porges et al 1966, Emrich and Merritt 1969 and Ahmad 1974), but the good management of a coalfield during its closure period can help to minimize these water resource pollution and contamination problems. The production of point sources of mine drainage in both the Lowery and Coleford High Delf Coal Seams have been discussed in chapter 4. Here the effect of those discharges on the Cannop Brook is discussed, together with the effect of deep barrier removal on minimising the possible long term pollution is shown.

In the case of the Lowery coal seam the major east-west barrier was not removed on abandonment (Figure 3.4) and numerous ferruginous springs exist around the coal seam outcrop. However, the proportion of baseflow in the Cannop Brook derived from the Supra Pennant Group is relatively low due to the high proportion of shales in this group (approximately 9 % estimated from a survey of summer low flow conditions). The overlying clayey stagnogley soils retard recharge, and vertical leakage through the shales is also small. Thus, these ferruginous mine discharges are readily diluted by the larger baseflow from the Pennant Group, and the water quality of the surface stream (the Cannop Brook) remains good (Figure 10.1).

In the Coleford High Delf coal seam, barrier removal (Figure 3.4) allowed the development of a single integrated groundwater body which flows from north to south to a single outlet at the Norchard Drift. Whilst the Cannop Brook downstream of this discharge point has a poor quality (Figure 10.1), the total length of river affected is small in comparison with that which would have been expected had the major coal barriers remained intact and overflow occurred at many separate locations. Chapter 8 has presented the historical chemistry data for the discharge and it is of interest here to note the progressive improvement in water quality that has occurred over the last 20 years with respect to the abandonment procedure. As stated in Chapter 8 the most rapid quality improvement involves the minor constituents, in particular iron, which was well documented. This quality improvement accords well with the model of Cairney and Frost (1975), who suggested that static conditions minimise the rate of production of iron pyrite oxidation products. Thus, it is suggested that initially there was a period of flushing which involved groundwater movement through the worked Coleford High Delf coal seam as the abandoned mined voids became flooded, but more stable groundwater conditions then followed (as discussed in chapter 8) leading to a decrease in pyrite oxidation. At present, the annual average water level fluctuation in the abandoned Cannop Colliery shaft varies between 8 and 15m. Continued oxidation in this annually inundated zone may limit further water quality improvement at the Norchard Drift. Therefore, whilst initially iron levels fell exponentially, halving over an approximately 5.5 year period, in the future this decline will be less rapid and the concentrations will stabilize at a lower but still significant level.

10.3 EFFECTS OF SHALLOW BARRIER REMOVAL.

Shallow barriers are those associated with the free-drainage levels, and the hydrogeological importance of these has been discussed in detail in chapter 6. However as was outlined, present day abstraction of coal has necessitated the piercing or in some cases total removal of the barriers. This results in a loss of discharge from the adit portal (Figure 6.13). The implications of this with respect to the determination of catchment boundaries from water budgeting techniques, the effects on deep basin recharge and groundwater flow paths and patterns have been discussed. It is necessary here to examine the impact of reduced flows on the recreational and surface water resources in the Forest of Dean.

The most significant effect of the shallow barrier removal is the reduction of summer baseflow in the Cannop Brook due to the diversion of flow. The dependence of the summer baseflow in the Cannop Brook on the discharge of

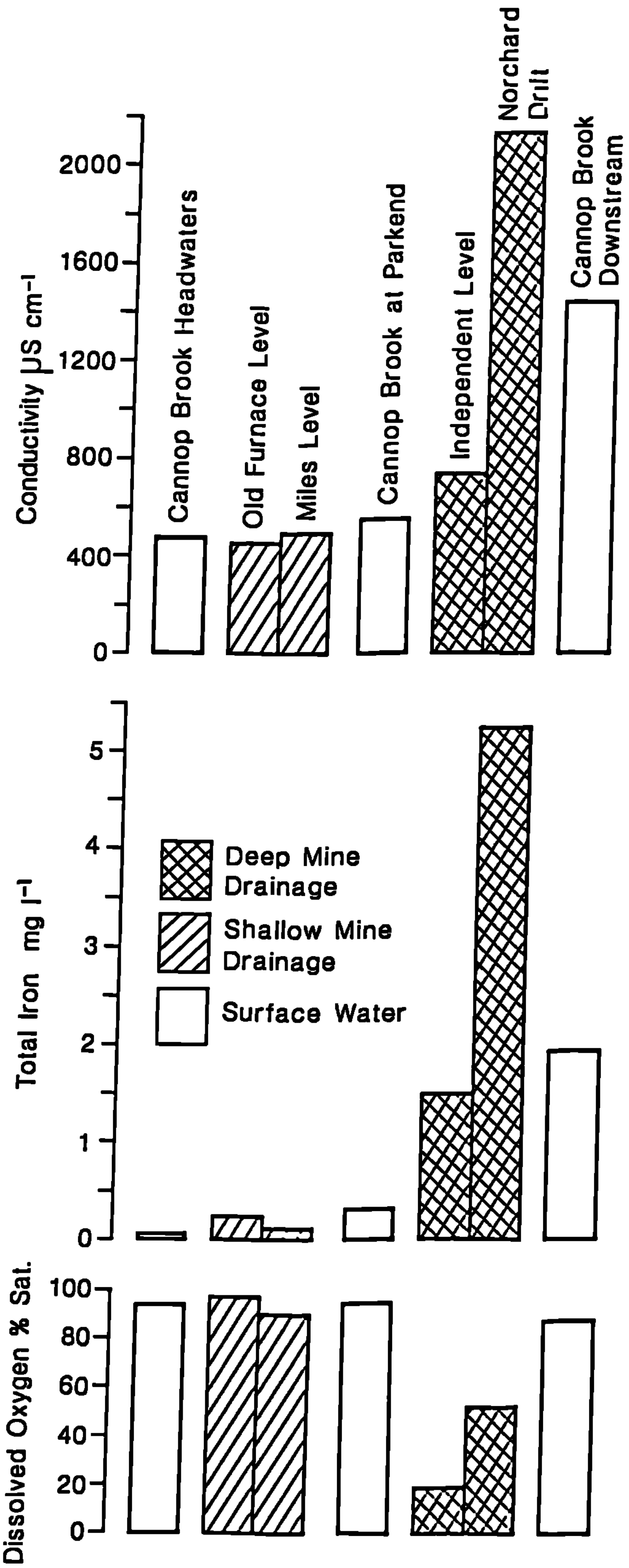


Figure 10.1 – Conductivity, total iron and dissolved oxygen for mine drainages and the Cannop Brook. Figures are the best long term averages (1974 – 1984).

shallow mine drainage waters is clearly demonstrated in Figure 10.2. Reduction of this flow could seriously affect the amenity value of the recreation areas in the headwaters, and reduce the viability of the coarse and game fisheries by reduction in rates of ventilation and turnover of impounded lakes. The effect would be particularly serious in the Cannop Ponds, where the Old Furnace Level supplies 59 % of the summer baseflow, and drains two coal mines where barriers are actively being extracted (Chapter 6). The water from the shallow free-drainage levels is of good quality because it is primarily derived from the Pennant Sandstone and has limited contact with the pyritiferous shales and coals (Figure 10.1). Reduction of the free drainage inflow could, therefore, reduce the dilution available for the poorer quality mine drainage from the deep basin. This is of greatest importance at the Independent Level which is tributary to the Cannop Brook upstream of an extensive fishery (Figure 10.2).

10.4 THE IMPLICATIONS OF POST-ABANDONMENT COLLAPSE AND INTEGRITY OF ABANDONED MINED VOIDS.

The gradual reduction in the mined void which occurs on abandonment of a colliery, due to expansion and extrusion of the seat-earth clay underlying the coal, together with settlement of the roof (and the effects of differing mining methods and roof support procedures) has been discussed in chapter 3. However, the distinction between the integrity of mined void and mine roadway (or haulage roadway) should be made, because this has wide implications with respect to possible pollution transport and the identification and prediction of potential pollutant pathways.

The tracer experiment which was conducted in the flooded Coleford High Delf coal seam workings of the Flourmill Colliery Shaft (Chapter 7), yielded information as to the integrity of the mined void and major haulage roadways of the deep basin. The tracer was detected after 7.5 days at the Norchard Drift outfall, a straightline distance of 3.5 km from the injection shaft. Furthermore, the tracer breakthrough curve shows remarkably little dispersion (Figure 7.11), the dye pulse duration at the Norchard Drift being only 1.3 days, indicating non dispersed 'plug-flow' (Aldous and Smart 1987). This would suggest that flow is concentrated into a major conduit, probably developed along the lines of the main haulage roadways, rather than more dispersed flow occurring throughout a laterally extensive mined void.

A similar closure of workings is also observed in the unsaturated zone. Direct exploration has demonstrated that few extensive workings greater than 10 years old are open, although some main roadways are still accessible after 125 years.

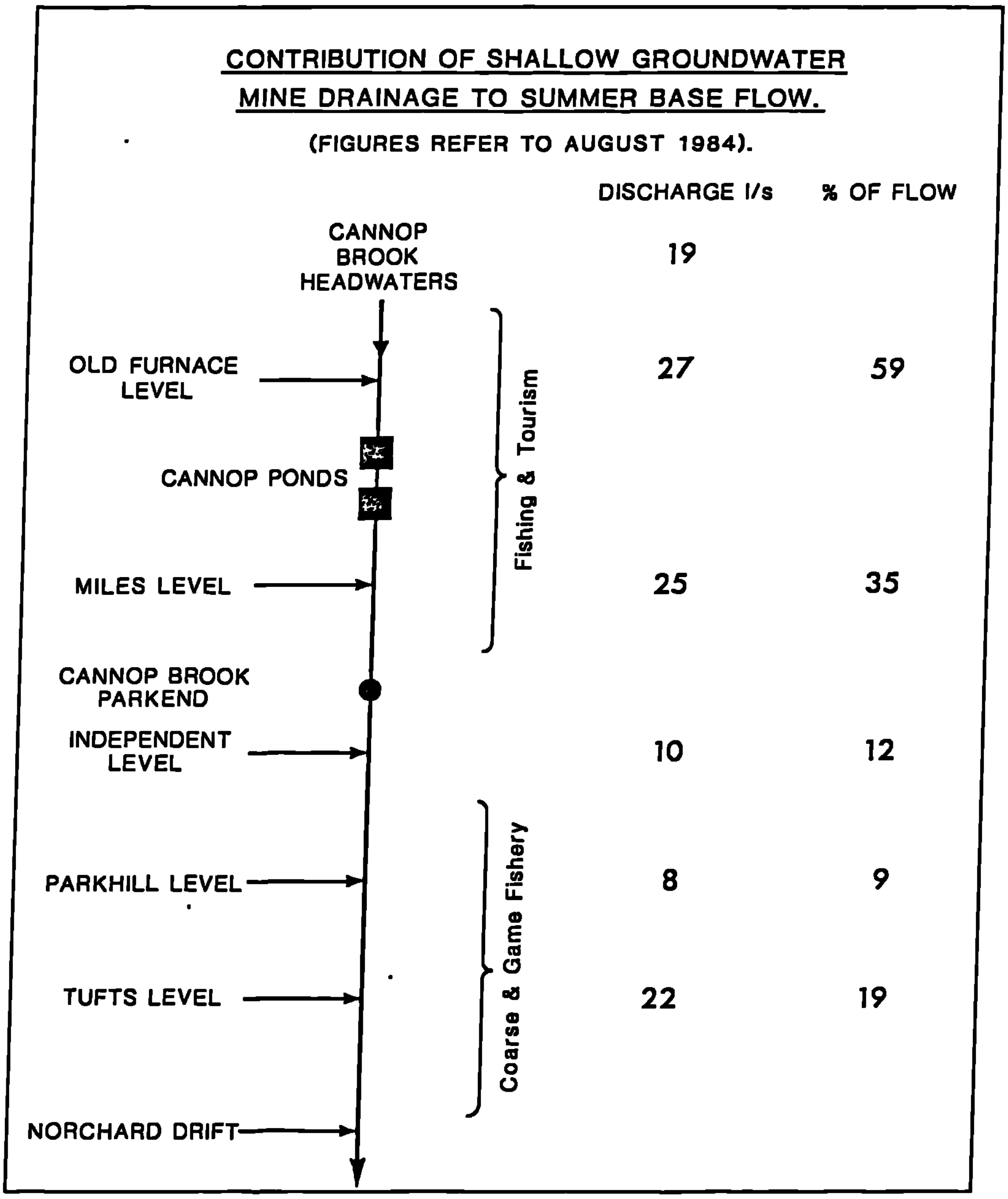


Figure 10.2 –
Contribution of shallow groundwater mine drainage to summer baseflow in the Cannop Brook for August 1984.

The latter serve as the major drainage routes, and have streams with discharges of several litres per second, with sufficient competance when flowing down dip (4-5°) to erode the seat earth (Plate 2.4). This prevents complete closure of the roadway. The walling of many main roadways with sandstone blocks was also common, and this retards both roof subsidence and entry of the seat earth. The two tracer test conducted in these shallow unsaturated workings (Chapter 6) also show that the main roadways are open and form concentrated flow paths. The tracer breakthrough curves (Figure 6.14) show little longitudinal dispersion and residence times are very short, with flow velocities typically 0.02 ms^{-1}. However, collapse does occur even in these roadways. Spalling and roof collapse being the main closure mechanisms. These form what are termed blockage collapses (Chapter 6).

In the cross and long measure levels, such blockage collapses are particularly frequent at the intersection with the coal seams, where the collapse causes substantial ponding. This is the case for the Tufts Level, where access beyond the Yorkley coal seam is prevented by an extensive collapse. One feature typically associated with such blockage collapse features is the extent of ponding that is caused. In the Bixslade Upper Level, the ponding is over 5m deep with water emerging from over and between the foundered sandstone blocks. Such ponding may divert flow to an adjacent free-drainage level, as is demonstrated in the case of the Tufts Level (see below section 10.6).

A further complication is that through time, ferruginous deposits (ferric hydroxide), seat earth and rock waste transported in the slow moving ponded water is deposited behind the blockage will substantially reduce the void volume (Chapter 6). Areas of ponded workings such as these represent an environmental hazard if catastrophic failure of the blockage occurs, because this suddenly releases large volumes of water and sediment. Henton (1983) reported such a sudden release at Dalgharren, Ayrshire where a section of prime salmon river was destroyed overnight by waters with a pH of 3.5 and iron content of 1000 mg/l. In the Forest of Dean, a similar event occurred during mining (before 1900) at Tufts Level, where water burst out from behind a collapse, flooding a cottage close to the adit portal. More recently, in April 1984, a deep seated earthquake measuring 3.3 on the Richter scale with an epicentre near Knighton, South Wales (some 75 km distant) affected the area. The discharge from Tufts Level which was being monitored at the time, and following the shock there was a sudden decrease in flow of about 4 ls^{-1}. this was followed by a slow return to the original discharge, aided by rodding of the Yorkley coal seam collapse, to increase flow to an adjacent trout hatchery.

There were no changes in the sediment content or chemistry of the water. This example demonstrates the potential instability of such collapses in the abandoned workings, although it did not result in a catastrophic release.

10.5 THE DETERIORATION OF LINED CHANNELS.

During the development of the deep basin mines, sections of the surface rivers were lined to prevent infiltration into the mine workings and so reduce the cost of drainage by pumping. The problem of infiltration from rivers was most severe in the Pennant Sandstone which had been fractured as a result of mining subsidence, and was also traversed by the Cannop Fault Belt (Figure 10.3). The Cinderford and Blackpool Brooks, therefore were lined with concrete channels along their entire course traversing the Pennant Sandstone. These channels were both cast in situ and of block construction. The problem was most severe at Cannop Colliery, and much of the adjacent Cannop Brook was similarly lined. Downstream, the Cannop Ponds had been constructed to provide power for the iron furnaces at Parkend and were probably sealed with seat earth, so additional lining was therefore not necessary.

Since abandonment of the large collieries, there has been deterioration of the concrete linings due to further differential subsidence and also due to vehicular damage during timber extraction (Plate 10.1). The channel linings have been extensively cracked and in places walls and floor have foundered. At several points it is possible to observe loss of water from streams at medium to low flows. For example, the Blackpool Brook is completely lost within the Pennant outcrop. Of the 9.5 km of lined channel in Figure 10.3, 50 % is currently damaged. The overall extent of leakage from these channels is not known, but as stated above, any loss of summer baseflow in the Cannop Brook could be serious. This problem of infiltration will increase as further sections of the lined channel deteriorate.

Problems may arise if poor quality surface water contaminates good quality groundwater following channel deterioration. This has occurred at Pastors Hill, where a small surface stream was periodically contaminated by effluent from a large intensive pig farm established in 1981. Ammoniacal nitrogen concentrations in the surface water during pollution events reached 17.5 mg/l, with much lower values at other times. Prior to the development of the pig farm the groundwater quality at the Tufts Level, which drains mine workings underlying the small surface stream had been good (Table 10.1), but subsequent to development ammoniacal nitrogen levels became much more variable, and occasionally reached very high levels (maximum 5.0 mg/l). On inspection it was

Plate 10.1 : Lined channelof a tributary to the Cannop Brook which flows over the Pennant Sandstone outcrop area. A section of the channel has been destroyed by recent forestry operations and the complete discharge (5 ls^{-1}) is completely captured. The discharge is lost by infiltration through the thin arenaceous soil cover over the Pennant Sandstone.

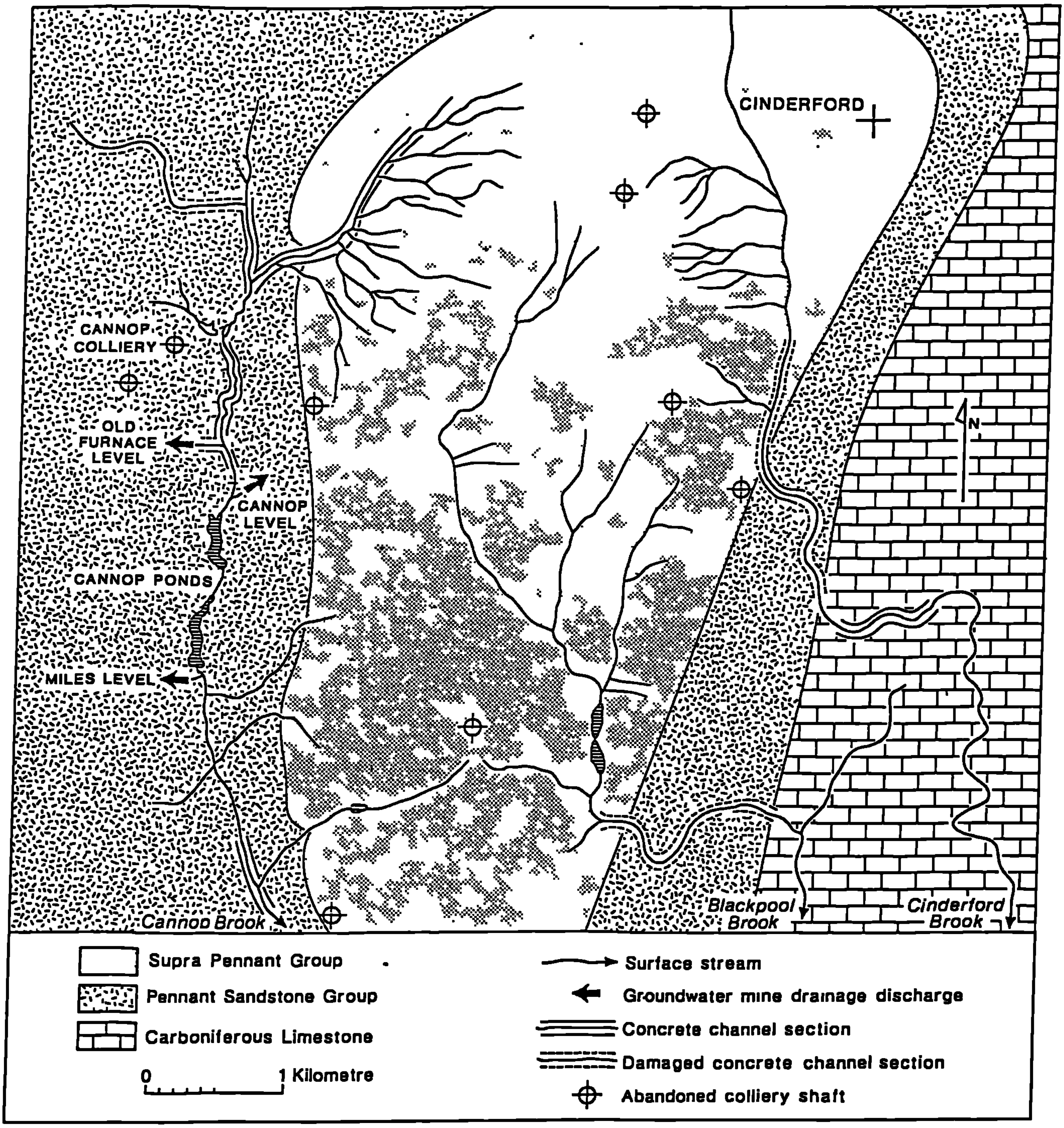


Figure 10.3 - Integrity and extent of lined channel in the northern part of the Forest of Dean.

TABLE 10.1

AMMONIACL NITROGEN CONCENTRATIONS FOR TUFTS LEVEL BEFORE AND AFTER ESTABLISHMENT OF AN INTENSIVE PIG FARMING UNIT

	PRE PIG FARM 1974 - 1981				POST PIG FARM 1981 - 1984				+ MANN-WHITNEY U
	n	$\bar{x}$	S.D.	MAX	n	$\bar{x}$	S.D.	MAX	
Ammoniacl Nitrogen as N	95	0.01	0.008	0.15	57	0.145	0.632	5.0	*

Units in mg/l.
+ Mann-Whitney U differences at 95% confidence level expressed as *.

TABLE 10.4

NICKEL AND ZINC CONCENTRATIONS IN MINE DRAINAGE WATERS FROM THE FOREST OF DEAN. FIGURES ARE AVERAGES FOR THE YEARS 1983/1984 EXPRESSED AS μg/l.

SAMPLE SITE	Ni			Zn			Ni/Zn
	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	
NORCHARD DRIFT	48	100.6	27.4	48	44.8	20.8	2.2
OLD FURNACE LEVEL	43	30.0	1.5	43	34.4	17.4	0.9
MILES LEVEL	43	31.4	5.6	43	27.9	14.2	1.1
INDEPENDENT LEVEL	41	31.0	4.4	41	17.9	10.6	1.7
CANNOP LEVEL	7	35.7	3.5	7	21.0	14.6	1.7
PARKEND MINE DRAINAGE	5	30.0	—	5	22.0	8.4	1.4
SPECULATION LEVEL	2	30.0	—	2	10.0	—	3.0
OLD BOBS MINE DRAINAGE	2	30.0	—	2	10.0	—	3.0
WOORGREENS LEVEL	1	30.0	—	1	20.0	—	1.5

found that a section of the lined channel of the surface stream had foundered, following collapse in the underlying Trenchard coal seam workings. The stream was wholly captured into the workings, and the water discharged into Tufts Level, giving rise to the observed pollution. During transmission through the workings there was little or no attenuation of the pollution, but dilution occurred on mixing with the much greater flow in the level.

10.6 GROUNDWATER POLLUTION FROM POST ABANDONMENT OPENCAST COAL MINING.

In the Forest of Dean, opencast coal mining has not been limited to previously unmined areas, but has included those where underground workings are known to exist. Pollution of surface water courses by open cast sites has been widely reported (Addis et al 1984, Hackbath 1979), however, in mined areas there is an additional hazard associated with unattenuated transmission of pollutants through existing mine voids.

Figure 10.4 shows the detailed geology and documented mine workings in the Pastors Hill area, where opencast extraction has recently taken place from the Trenchard, Coleford High Delf and Whittington coal seams. At the opencast site, abandoned underground workings were found to be present in all three coal seams: the Trenchard coal seam had been worked from the surface outcrop and at depth from Parkhill Level, the two sets of workings being interconnected. A similar situation existed in the Coleford High Delf coal seam, but for the Whittington coal seam the two areas of workings were isolated. During excavations of the open cast site the abandoned workings were intersected, they were generally dry and had not completely closed, significant open voids being present.

Prior to 1978 the water from Tufts Level had been used for public supply, but when regular analyses indicated occasional high bacterial counts it was abandoned. At present the water supplies a trout hatchery, while that from the Parkhill Level is unused and discharges direct to the Cannop Brook. It was initially thought that the Tufts Level would not be affected by operations at the opencast site. Although there is a connection to the level within the Trenchard coal seam, the Parkhill Level is at a lower elevation than the Tufts Level and the seam is downthrown 2.5m to the north along a small fault. it was therefore argued that free drainage would be to the north into Parkhill Level.

Occasional water analyses are available during the period of opencast mining and are compared with the pre and post mining conditions in Table 10.2 and Figure 10.5. The data is non-normally distributed and there is generally a much

Figure 10.4 : Drainage and extent of underground mining in the vicinity of the Pastors Hill open cast mine site.

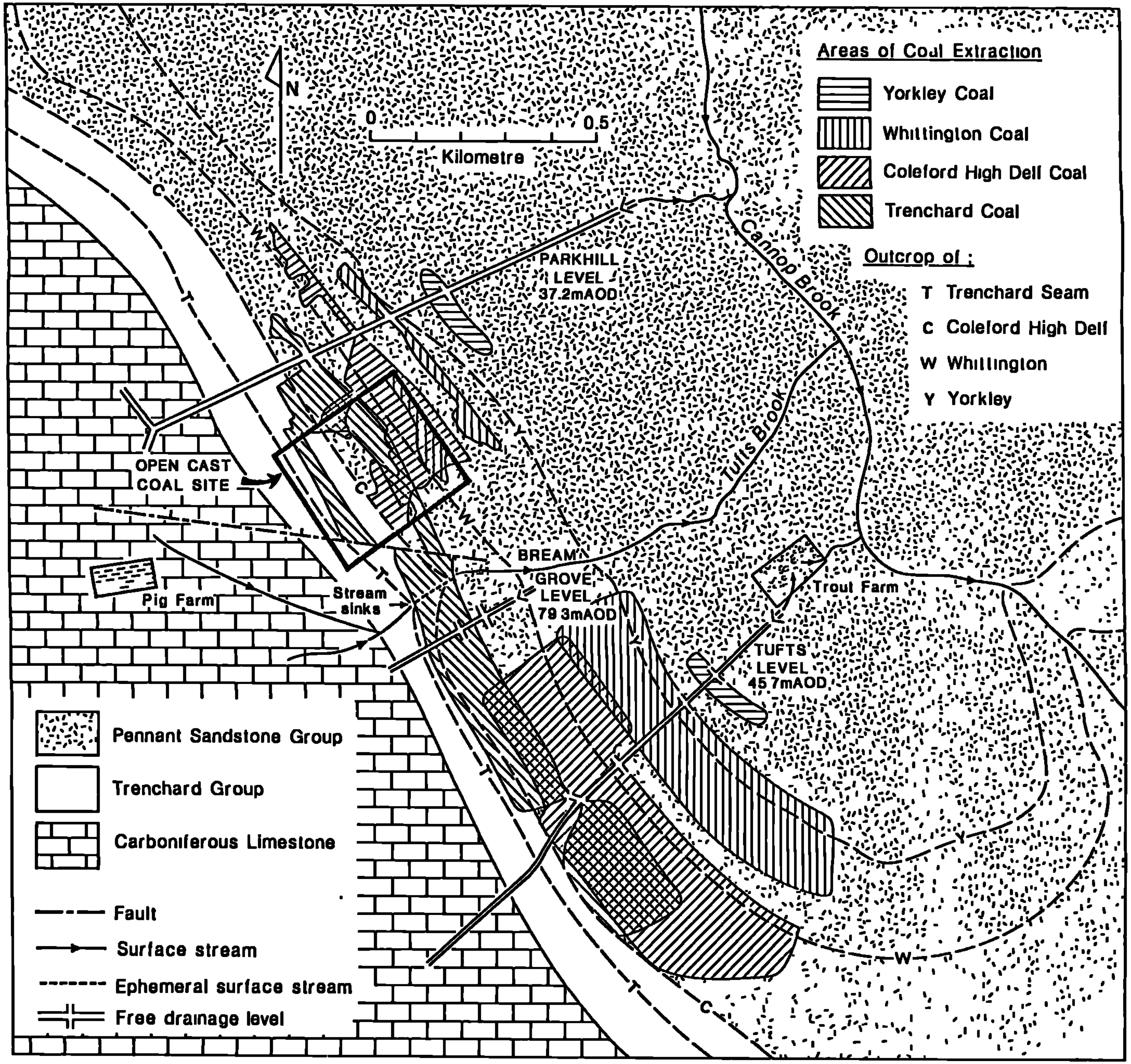


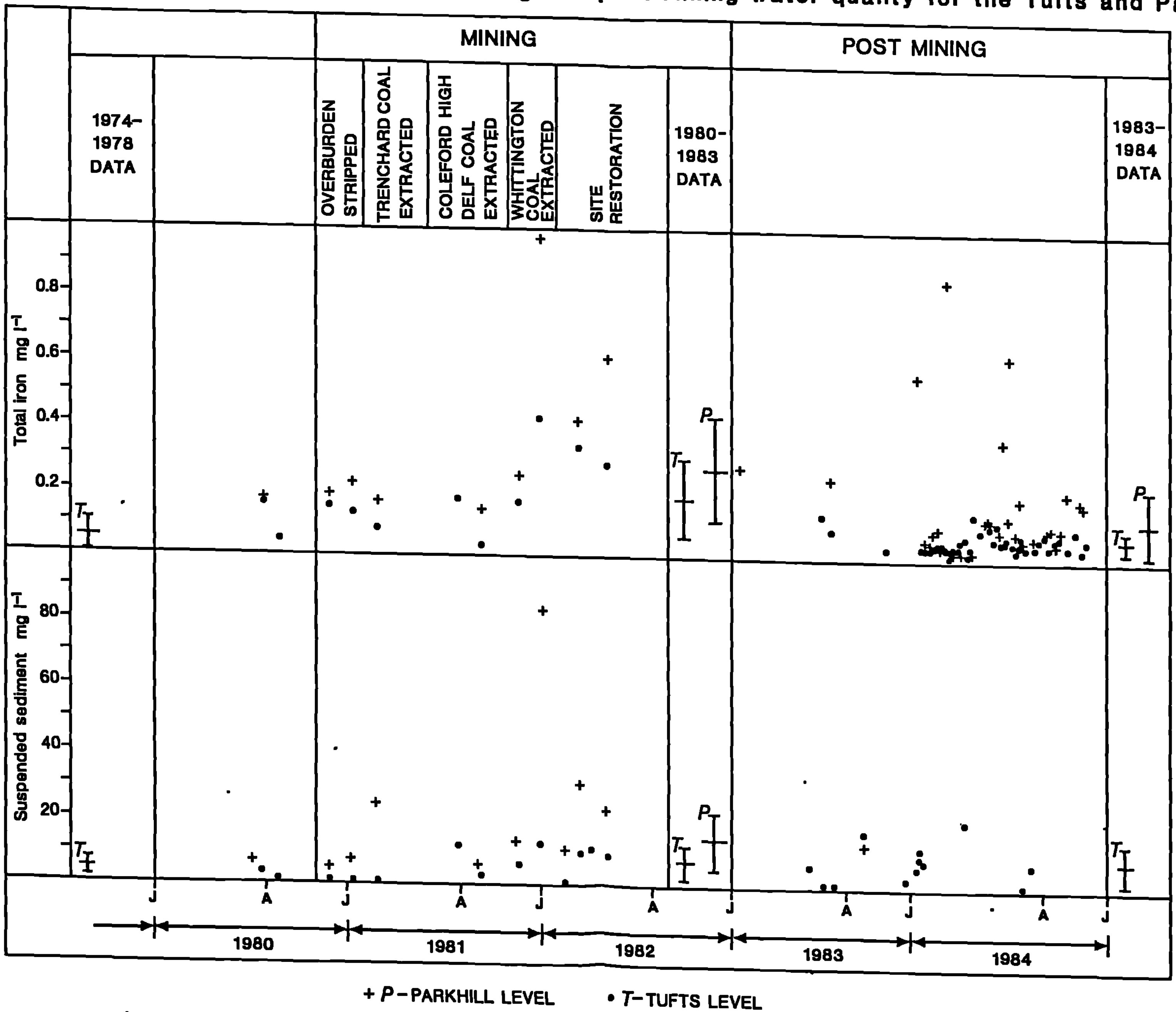
TABLE 10.2

COMPARISON BETWEEN PRE MINING, MINING AND POST MINING WATER QUALITY FOR TUFTS AND PARKHILL LEVELS.

DETERMINAND	PRE - MINING 1974 - SEPT 1980				DURING MINING OCT 1980 - SEPT 1982				POST - MINING OCT 1982 - NOV 1984				MANN-WHITNEY U +		
	n	$\bar{x}$	S.D.	Max	n	$\bar{x}$	S.D.	Max	n	$\bar{x}$	S.D.	Max	1	2	3
TUFTS LEVEL															
pH	96	7.39	0.08	7.65	11	7.78	0.09	7.8	39	7.26	0.22	7.8	*	*	*
Alkalinity as $CaCO_3$	70	243	10	256	-	-	-	-	39	228	33	258	-	-	*
Iron	89	0.05	0.05	0.32	9	0.2	0.13	0.42	40	0.07	0.1	0.66	*	*	*
Manganese	89	0.01	0.004	0.03	9	0.02	0.008	0.03	39	0.03	0.11	0.7	*	-	*
Sulphate	42	40	4.0	50	-	-	-	-	39	40	7.0	60	-	-	-
Suspended Sediment	89	4.7	3.4	13	11	6.3	5.0	13	12	7.6	6.2	20	-	-	-
PARKHILL LEVEL															
pH	-	-	-	-	8	7.6	0.2	7.9	32	7.3	0.2	7.6	-	*	-
Alkalinity as $CaCO_3$	-	-	-	-	-	-	-	-	32	162	55	258	-	-	-
Iron	-	-	-	-	9	0.49	0.69	2.28	33	0.18	0.21	0.88	-	*	-
Manganese	-	-	-	-	9	0.05	0.04	0.13	34	0.05	0.07	0.43	-	-	-
Sulphate	-	-	-	-	-	-	-	-	32	156	60	340	-	-	-
Suspended Sediment	-	-	-	-	9	21.2	23.9	84.0	1	13.0	-	-	-	-	-

Units in mg/l except pH.
+ Mann-Whitney U differences at 95% confidence level expressed as *.
1. Difference between Pre and During Mining 2. During Mining and Post Mining 3. Pre and Post Mining.

Figure 10.5 : Comparison between pre-mining, mining and post mining water quality for the Tufts and Parkhill Levels



(vertical bars indicate +/− 1 standard deviation around the mean value).

larger variation in the determinands during and after mining. The Mann-Whitney U Test (Siegel 1956) was therefore used to determine whether the three data groups were drawn from the same population. For Tufts Level, during and after mining there were significant changes in most quality parameters measured, indicating a connection between the level and the opencast site. For Parkhill Level, full analytical information is limited to the post mining period, and the extent of water quality change cannot therefore be determined. Whilst the values tend to be higher by a factor of 2 than for Tufts Level, this is probably due to the lower proportion of limestone derived waters entering Parkhill Level (see chapter 9).

The significant dilution by the limestone derived waters may explain why the quality changes in Tufts Level were not large compared to those experienced in surface streams affected by opencast coal workings (Addis et al 1984 and Hackbath 1979). However, other factors may also be important. The method of working involved each seam being successively exposed and then back-filled as working proceeded from west to east. The lower workings in the Trenchard coal seam (the ones which connect to the Tufts Level) were therefore only penetrated towards the base of the excavation, limiting the period for potential pollution. Surface water was also cleared from the floor of the excavation by pumping, and was discharged on the surface of an undisturbed area remote from the site. Thus only limited volumes of polluted water could have entered the lower mine workings in the Trenchard coal seam, and the resulting effects on the water quality were small.

The unanticipated discharge of this polluted water into Tufts Level, contrary to the topographic gradient of the workings suggests that substantial ponding caused by collapse must occur in the Trenchard workings or in Parkhill Level, developing a hydraulic gradient towards Tufts Level. This case history demonstrates that the probable flow directions in abandoned workings cannot therefore be simply deduced from the geology and mine plans, because free vadose flow will be progressively replaced after abandonment by pressure flow caused by ponding in the mine voids.

10.7 WASTE DISPOSAL IN ABANDONED COAL MINED AQUIFERS.

Pollution arising from the disposal of industrial wastes into abandoned mine workings have been reported from other coalfields (Henton 1974). In the Forest of Dean no serious environmental problems have been encountered to date, despite two major waste disposal operations.

At Fetter hill, a disused Pennant Sandstone Quarry (Figure 3.4) driven into the valley side was used for waste disposal before closure in 1977 (Carter 1979). Prior to 1963, used tyres, glass cutlet and quantities of acidic liquid fruit processing waste were tipped. After this date heavy metal bearing liquids and hydroxide sludges including up to 10000 mg/l of cadmium, chromium, zinc, nickel, iron and cyanide were disposed of at a rate of 90000 litres per week. In addition organic wastes including methylchloride and trichloroethane were also discharged. The liquid level in the quarry never rose, the waste apparently discharging via fractures in the quarry walls and an adit in the south western corner of the site. Despite a probable connection between the adit and workings in the Coleford High Delf coal seam underlying the site, no heavy metal contamination of ground or surface waters was detected (Table 10.3). It should be noted that this sequence of events occurred before realistic controls could be imposed over the siting of sanitary landfill sites, and the lack of pollution is entirely due to chance as no hydrogeological studies were carried out. Furthermore, the site closed before the Control of Pollution Act Part I was implemented.

Examination of the plans for the abandoned workings in the area show that the Coleford High Delf coal seam was extracted in a succession of gales parallel to the strike. These were originally separated by drainage barriers which have been partially or totally removed (Figure 6.7). Only the major barriers diverting the free-drainage into the Miles Level remain, and any other discharge point seems unlikely. There are two possible explanations for the absence of pollution at the Miles Level. Ponding of water in the workings will permit flow to occur in the Pennant Sandstone overlying the coal, which may be strongly fractured in the vicinity of the barrier due to differential subsidence following abandonment (Aston 1982, Cartwright et al 1983 and Neate 1980). Thus substantial amounts of water may be lost to the deep basin by flow over the barrier (Ashley 1930, and Miller and Thompsom 1974). Secondly, the Miles Level barrier was actually penetrated to the south of Fetter Hill by a single roadway driven from the Union Colliery of the Miles and Mapleford Engine Gale (Figure 6.7) down dip of the barrier. This penetration was accidental, and resulted in the flooding of the adjacent deep basin colliery with the loss of two horses. The mine manager was dismissed, and the mine was subsequently pumped out and later incorporated into the NCB deep basin mines, which discharges to the Norchard Drift. It therefore seems possible that this route was taken by the liquid waste tipped at the quarry.

TABLE 10.3

WATER CHEMISTRY DATA FOR 1976 FROM SURFACE STREAMS, SPRINGS AND GROUNDWATER MINE DRAINAGE DISCHARGES NEAR TO THE FETTER HILL WASTE DISPOSAL SITE FOREST OF DEAN

SITE	NGR	DISTANCE FROM WASTE DIPOSAL SITE (km)	pH	Cl	Fe	Cd	Cr	Cu	Ni	Zn
SURFACE STREAMS AND SPRINGS										
ROPEHOUSE DITCH	SO61101350	4.8	7.4	20	0.12	<0.01	0.02	<0.01	0.01	0.02
VALLETS WOOD	SO60901180	1.9	7.4	10	0.37	<0.01	0.02	<0.01	<0.01	0.03
UNNAMED 1	SO60801130	1.0	7.1	12	3.7	<0.01	0.01	<0.01	0.01	0.05
UNNAMED 2	SO60201030	0.8	7.8	14	0.21	<0.01	0.01	<0.01	0.01	0.01
MILL HILL	SO60800780	1.0	7.2	12	0.14	<0.01	0.01	<0.01	0.01	0.03
FETTER HILL 1	SO60000810	0.1	7.2	21	0.6	<0.01	0.02	<0.01	<0.01	0.04
FETTER HILL 2	SO60000810	0.1	7.7	21	0.24	<0.01	0.01	<0.01	0.01	0.02
CLEAVE HILL	SO60700830	0.5	7.0	12	0.35	<0.01	0.02	<0.01	0.02	0.06
GROUNDWATER MINE DISCHARGES										
OLD FURNACE LEVEL	SO60751155	2.9	7.8	18	0.1	<0.01	0.02	<0.01	<0.01	0.02
MILES LEVEL	SO60710995	2.0	7.1	14	0.07	<0.01	0.02	<0.01	0.01	0.03

All figures expressed as mg/l except pH.

The nickel and zinc concentrations at the Norchard Drift are at present higher than for other mine drainage sites in the Forest of Dean (Table 10.4), but the concentrations have mirrored those of iron and declined exponentially with time (Figure 10.6). The ratio of nickel to zinc are also within the range observed at other sites in the Forest of Dean, and does not suggest significant contributions from the Fetter Hill leachate. It must, therefore, be concluded that the large dilution and residence time of the water in the deep basin have prevented significant transmission of the pollutants, whose mobilisation would also have been restricted by the high pH of the mine waters (pH 6.5-7.2) in comparison to those of the disposed sludge (pH 10.5-12.5).

This example illustrates the importance of minor roadways which may penetrate barriers and substantially influence the groundwater circulation. Unfortunately such small exploratory and robber roadways (those entering gales for illegal coal extraction) are not as well documented as this example, and may not be shown on even the most detailed plans. Furthermore, this case history has also shown that disposal into flooded mine workings presents a low risk of pollution, although relatively rapid transmission through such workings can occur, as indicated by the tracer test results. The average velocity indicated by time to peak concentrations was 460 m/d. In comparison the only other reported similar velocity is between 160 and 130 m/d, determined by Parsons and Hunter (1972) in the South Wales Coalfield. Therefore this leads to the primary conclusion that artificial tracing experiments thus not only provide an indicator of probable groundwater residence times, but may also indicate the potential pollutant pathway.

At a second disposal site, Howlers Hill Quarries (Figure 3.4), the situation is geologically similar to that at Fetter Hill, except that the Ridge Anticline interupts the easterly dip of the beds, causing local flow to the north along the Coleford High Delf coal seam workings. The quarry is, however, very close to the Old Furnace Level, which discharges directly to the Cannop Brook. Although there is some ponding behind a collapsed section of the Level (Chapter 6), travel times are likely to be very short, as indicated by the tracer tests (Aldous and Smart 1987), and attenuation of any pollution is unlikely. Domestic refuse is the major component of the waste disposed at this site, but there is a high proportion of inert compared with putrescible material. Furthermore, prior to tipping, the site was prepared by construction of a thick infill of sandstone rock waste and top soil on the quarry floor. The quarry walls were also partially lined with polythene to retard groundwater inflow. Site restoration has also incorporated a thick clay cap to mimnimise infiltration.

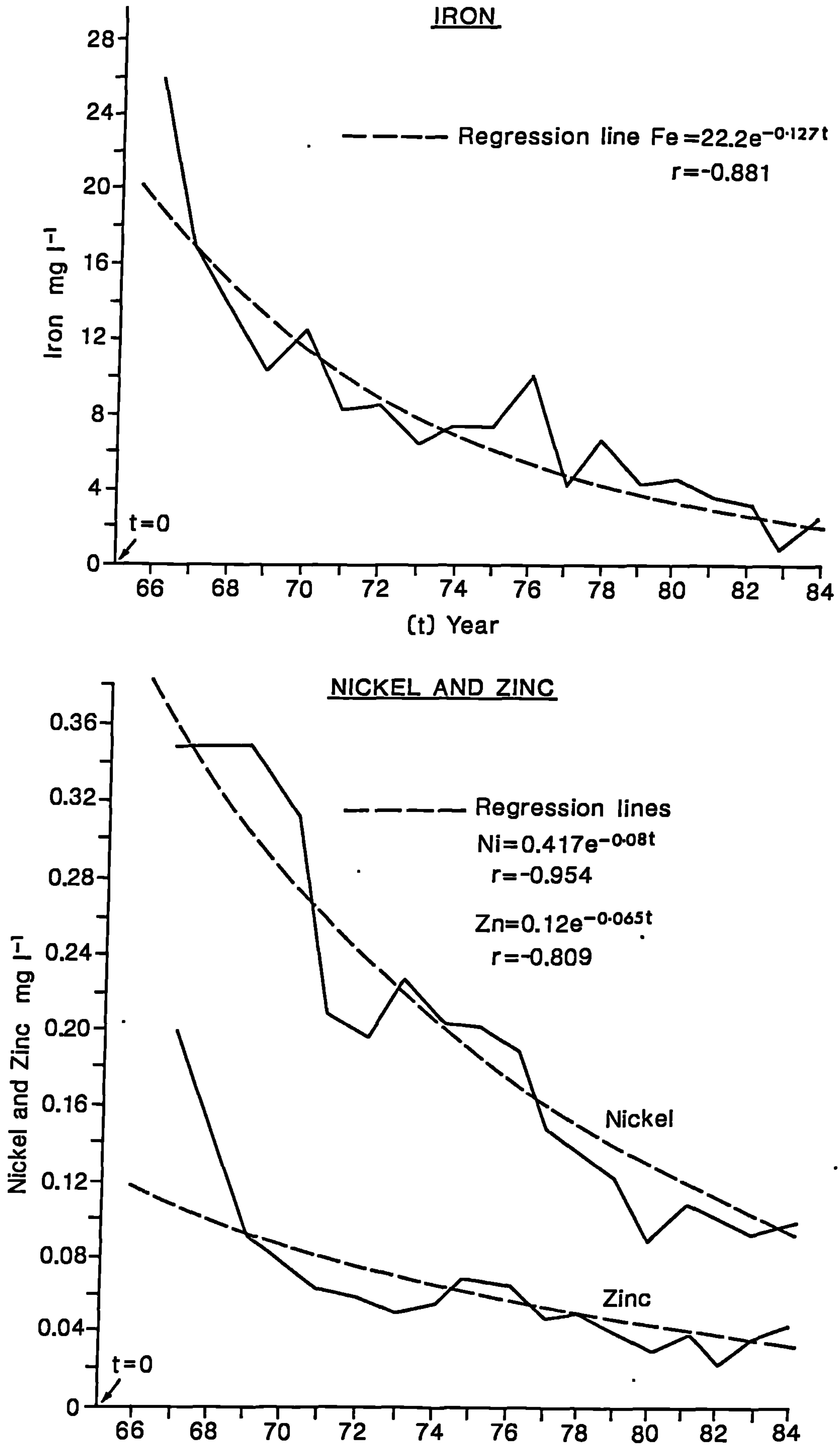


Figure 10.6 –

Mean annual total iron, nickel and zinc concentrations at the Norchard Drift for the period from commencement of discharge in 1966 to 1984.

After 7 years there has been no measurable contamination of the Old Furance Level discharge.

This succesful outcome of the waste disposal at Howlers Hill can be attributed to the careful site preparation, management and restoration, and the high proportion of inert waste. However, the site also has several favourable hydrogeological characteristics. The unsaturated zone above the level of the Coleford High Delf coal seam workings which partially underlie the site is about 60 m thick, permitting some improvement of leachate quality during percolation despite the flow being predominantly in fractures. The Coleford High Delf coal seam and associated seat earth is in fact absent under part of the site where the Horse Washout occurs (Buddle 1842). Percolating leachate may therefore continue vertically downward through the Pennant Sandstone and into the deep basin, rather than being deflected downdip into the Coleford High Delf coal seam workings and along the coal barrier into the Old Furnace level in the manner decribed in Chapter 6. Furthermore because of the westerly dip associated with the Ridge Anticline which underlies Howlers Hill, any leachate intercepted by the Coleford High Delf coal seam workings will be diverted towards the Horse Fault, and may thus again not enter the Old Furnace Level.

These case studies indicate that safe disposal of waste within Coal Measures strata is possible, particularly when groundwater discharge is to a deep confined basin.

10.8 CONCLUSIONS.

This chapter has examined the groundwater related problems experienced in the Forest of Dean Coalfield since abandonment of the major collieries in 1965. These indicate that careful planning prior to abandonment of the collieries can reduce the number of poor quality discharges, and so substantially limit surface water pollution. Small scale mining activity continuing after major collieries have been abandoned can have a serious hydrogeological effect by removal of in situ coal from drainage barriers designed to promote free drainage of the mines. In association with the deterioration of lined river channels which retard surface water infiltration, this disruption of subsurface flow can result in a significant loss of summer baseflow from surface rivers. The two case histories show that safe disposal of wastes to voids in mined Coal Measures Aquifers is possible. However, the prediction of the hydrogeological behaviour of the mined aquifer is difficult because of the possibility of unrecorded workings, random collapse and associated ponding, and uncertainty over the hydrogeological behaviour and integrity of the coal barriers.

The following chapter concludes this thesis and discusses the advances in the knowledge of the hydrogeological behaviour of mined Coal Measure Aquifers which have been made in this work. These advances permit a better groundwater management policy to be employed, together with the best techniques to solve the typical groundwater problems discussed in this chapter (which will continue to arise in the foreseeable future), also areas where research is still required are outlined.

CHAPTER 11

CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS FOR FURTHER WORK.

More recently with increasing abandonment of coal mines and coalfield closures Coal Measure Aquifers have become a management burden to Regional Water Authorities. This is because due to problems associated with surface water and groundwater pollution, waste disposal, open cast coal mining operations and the maintenance of recreational resources. The aim of this study was to identify and understand the processes that control groundwater movement in abandoned coal mines and to assist future resource management with the development of (a) conceptual model(s) of aquifer behaviour.

An examination of historic records which details coalfield development, mining methods and documentation of mining concessions is an important part in the understanding of the processes that control water movement in coalfields. From these records the location of the major controls of water movement such as areas of intact coal which form barriers to free drainage can be determined. Furthermore, this examination demonstrated that careful planning of drainage routes prior to coalfield abandonment (deep basin coal barrier removal) is necessary to minimize water quality problems associated with these discharges. Furthermore archive chemical data can be used to understand the changes in discharge composition (both volume and chemical) and hydrogeological regime present between the time of abandonment and twenty years later. Also to aid an understanding of the effect of deep mine discharge chemistries on receiving waters a schematic model was developed of the temporal changes in outflow chemistry. However, the limited quantity of detailed hydrogeological information (pumping records and discharge volumes) limited the extensive analysis of the effect of coal mining on adjacent aquifers during coalfield development. This could be the aim of a future study where a coalfield is due to close and records have not been misplaced.

Small scale mining continues in many coalfields after abandonment of the major mines. Until recently the possible hydrological and environmental effects of this activity had not been seriously considered. This can be significant because much of the remaining coal forms barriers to free-drainage (shallow barrier removal) and the reduction and diversion of flow in free-drainage levels can occur together with a decrease in surface water summer baseflow discharges as a result of continued extraction.

In Britain there is a statutory obligation to survey the extent of mine workings. These plans form an essential though imperfect basis for the interpretation of catchment areas and the hydrological function of the workings. However, many mine plans are incomplete and sometimes erronous. Because interpretation of the flow routes in mine voids depends largely on the nature of any coal barriers remaining, a single unrecorded roadway may substantially alter the flow conditions underground. Furthermore, little is known about the nature of abandoned coal mine voids, and this work suggests that those responsible for substantial water transmission may remain relatively open, but further work is still required on this topic, particularly for the inaccessible deep basin workings. Other difficulties relate to blockage and ponding of the roadways and levels, which can substantially divert groundwater flow, but for which the location, extent and response cannot be predicted.

However, the determination of catchment areas for regional Coal Measure Aquifers can be undertaken from a knowledge of the hydrogeological properties of Coal Measure Rocks, although in certain instances a knowledge of the extent of mining is advantageous. Regional aquifer discharge locations can differ considerably, from large point sources (in this study the Norchard Drift) to large diffuse discharges (the Yorkley Aquifer discharge to the Cannop Brook). The major geological control on groundwater movement is undoubtly the presence of the low permeability seat earth clays which act as regional aquicludes.

This study also suggests that interpretations based upon the essential though imperfect coal mine plan data base and a general understanding of the behaviour of such aquifers will be insufficient for site-specific groundwater resource management, and more detailed studies involving water tracing and borehole investigations of head conditions and the nature of mined voids will be necessary if any adequate prediction of the environmental impacts are to be made. Future work could be undertaken by the use of computer modelling now that the processes that control groundwater movement are understood. For instance, it would be possible to determine the effects of the removal of a particular section of a coal barrier on the discharge outlet and the summer baseflow coinditions in the receiving surface water, or a blockage collapse at a certain location. However, some more detailed field studies may be required to determined further values for both natural and enhanced barrier leakage or blockage collapse permeabilities before this could be undertaken.

The conceptual models of the controls on groundwater movement and the determination of both the processes controlling groundwater movement and the hydrological behaviour of both deep and shallow abandoned coal workings together with utility and validity of the use of coal mine abandonment plans determined here provides a further important data base for use in future groundwater resource management studies.

REFERENCES

Addis, M., Simmons, I. G. and Smart, P.L. 1984. The environmental impact of an opencast operation in the Forest of Dean, England. Journal of Environmental Management. Vol. 19. P79-95.

Ahmad, M.U. 1974. Coal mining and its effect on water quality. Proceedings American Water Resources Association. Vol. 18. P138-148.

Aldous, P.J., Smart, P.L. and Black, J. 1986. Groundwater management problems in abandoned coal-mined aquifers : A case study of the Forest of Dean Coalfield, England. Quarterly Journal of Engineering Geology. Vol. 19. P375-388.

Aldous, P.J. and Smart, P.L. 1987. Tracing groundwater flow in abandoned coal mined aquifers. Ground Water. (In press).

Ashley, G.H. 1930. Barrier pillar legislation in Pennsylvania. Transactions of the American Institute of Mining Enginners (Coal Division), Vol. 69, P76-97.

Ashmead, D.C. 1937. Water pumped from the mines of the anthracite region of North Eastern Pennsylvannia. Transactions of the American Geophysical Union. Reports and Papers in Hydrology. P498-504.

Aston, T.R.C. 1982. Hydrogeological aspects of rock mechanics and mining subsidence around longwall mining excavations. Ph.D. Thesis, University of Nottingham.

Atkins, A.S. and Pooley F.D. 1982. The effects of bio-mechanisms on acidic mine drainage in coal mining. International Journal of Mine Water. Vol. 1. P31-44.

Atkins, A.S. and Singh, R.N. 1982. A study of acid and ferruginous minewater in coal mining operations. International Journal of Mine Water. Vol. 2. P37-57

Atkinson, T.C. 1971. The dangers of pollution of limestone aquifers, with special reference to the Mendip Hills, Somerset. Proceedings of the University of Bristol Speleological Society. Vol. 12. P281-290.

Banaszak, K.J. 1980. Coal as aquifers in the Eastern United States Symposium on Surface Mining Hydrology, Sedimentation and Reclamation. University of Kentucky, Lexington 40506.

Bara, J.P. 1953. Laboratory tests on samples representing proposed impervious borrow materials. U.S. Beareau of Reclamation, Engineering Laboratory Report. No EM 367. 32P

Barnes, I. and Clarke, F.E. 1964. Geochemistry of groundwater in mine drainage problems. United States Geological Survey, Professional Paper 473-A.

Becker, R.A. and Chambers, J.M. 1984. S : An interactive environment for data analysis and graphics. (Wadsworth, Belmont, California).

Bhatt, P.E. and Baker, M. 1976. Factors affecting the selection of mine drainage treatment methods. 5th Symposium on Acid Mine Drainage Research, Mellon Institute.

Brady, B.H.G. and Brown, E.T. 1985. Rock Mechanics for Underground Mining. Allen and Unwin, London.

Braley, S.A. 1954. Acid Mine Drainage. Mechanisation. Vol. 18. P87-107.

Brant, R.A. 1971. Identification of pyrite in rocks. Proceedings of the Acid Mine Drainage Workshop. P124-127.

British Standards Institution. 1964. BS 3680. Methods of measurement of liquid flow in open channels, Part 3. Velocity area methods.

British Standards Institution. 1971. BS 3680. Methods of measurement of liquid flow in open channels, Part 7. The measuremnet of liquid level (stage).

British Standards Institution. 1973a. BS 3680. Methods of measurement of liquid flow in open channels, Part 8a. Current meters : incorporating a rotating element.

British Standards Institution. 1973b. BS 3680. Methods of measurement of liquid flow in open channels, Part 8b. Current meters : suspension equipment.

British Standards Institution. 1974. BS 3680. Methods of measurement of liquid flow in open channels, Part 4c. Weirs and flumes (Flumes).

British Standards Institution. 1980. BS 3680. Methods of measurement of liquid flow in open channels, Part 4e. Free overflow weirs of finite crest width (rectangular broad crested weirs).

Brown, R.L. and Parizek, R.R. 1971. Shallow groundwater flow systems beneath strip and deep coal mines at two sites, Clearfield County. Pennsylvania. Pennsylvania State University. Report CR-66. University Park. P.A.

Buddle, J. 1842. On the Great Fault called the Horse in the Forest of Dean Coalfield. Transactions of the Geological Society. Vol. 6. P215-220.

Cairney, T. 1973. The utilisation of disused coal mines as water storage reservoirs. Journal of Hydrology. Vol. 19. P251-258.

Cairney, T and Frost, R.C. 1975. A case study of mine water quality deterioration, Mainsforth colliery, County Durham. Journal of Hydrology. Vol. 25. P275-293.

Calder, I.R. 1977. A model of transpiration and interception loss from a spruce forest in Plynlimon, Central Wales. Journal of Hydrology. Vol. 33. P247-265.

Calder, I.R. 1979. A model of transpiration and interception loss from a spruce forest in Central Wales. IGS/NERC Report 79/6.

Calder, I.R., Harding, R.J. and Rossier, P.T.W. 1983. An objective assessment of S.M.D. models. Journal of Hydrology. Vol. 60. P329-355.

Carrucio, F.T. 1968. An evaluation of the factors affecting acid mine drainage production and the ground water interactions in selected areas of Western Pennsylvania. 2nd Symposium on Coal Mine Drainage Research. P107-151.

Carrucio, F.T. and Ferm, J.C. 1974. Palaeoenvironment predictor of acid mine drainage problems. 5th Symposium Coal Mine Drainage Research, Lousiville. P5-10.

Carrucio, F.T., Geidal, G. and Sewell, J.W. 1976. The character of drainage as a function of the framboidal pyrite and groundwater quality in Eastern Kentucky. Sixth Symposium on Coal Mine Drainage Research, National Coal Association, Washington D.C.

Carrucio, F.T., Geidal, G. and Pelletier, M. 1981. Occurence and prediction of acidic drainages. American Society of Civil Engineers, Vol. 107. P167-178.

Carter, M.G. 1979. Restoration of a toxic waste quarry. Journal of Environmental Management. Vol. 9. P123-129.

Cartwright, K. and Hunt, C.S. 1978. Hydrogeology of underground coal mines in Illinois. Proceedings of the International Symposium on Water in Mining and Underground Works. Granada. Spain Vol. 1. P61-83.

Cartwright, K., Hunt, C.S., Brower, R.D. and Nelson, W.J. 1983. Pore-water pressures in the roof of an underground coal mine in Illinois. Ground Water Vol. 21. P311-316.

Chadderton, R.A. 1979. A simplified stream model of acid mine drainage effects. Water resources Bulletin (American Water Resources Association) Vol. 15. P1157-1167.

Chadwick, J.W. and Canton, S.P. 1983. Coal mine drainage effects on a lotic ecosystem in Northwest Colorado, U.S.A. Hydrobiologia. Vol. 107. P25-33.

Chilingar, G.V. 1956. Durovs classification of natural waters and chemical compostion of atmospheric precipitation in the USSR : A review. Transactions American Geophysical Union. Vol 37. P193-196.

Cook, J.M. and Miles, D.L. 1980. Methods for the chemical analysis of groundwater. IGS/NERC Report 80/5.

Crookall, R. 1930. Flora of the Forest of Dean Coalfield. Proceedings of the Cotteswold Naturalist Field Club. Vol. 23.

Daly, D. 1976. A preliminary hydrogeological survey of the Castle Comer Plateau, S.E. Ireland. MSc Thesis. University of Birmingham. Department of Geological Sciences.

Dangerfield, B.J. 1979. The structure and management of the British Water Industry. Water Practice Manual. The Institute of Water Engineers and Scientists. London, England.

Downing, R.A. and Howitt, F. 1969. Saline groundwaters in the Carboniferous Rocks of the East Midlands in relation to the geology. Quarterly Journal of Engineering Geology. Vol. 1. P241-269.

Downing, R.A., et al 1970. The hydrogeology of the Trent River Basin. Institute of Geological Sciences Water Supply Paper. Hydrogeological Report No.5, 104P.

Durov, S.A. 1948. Klassifikacija pirodnych vodi graficeskoje izobrazenie ich sostava. Doklady Ak. Navk. SSSR. Vol 59. P87-90.

Edmunds, W.M. 1975. Geochemistry of the brines in the Coal Measures of North Eastern England. Transactions of the Institute of Mining and Metallurgy. B39-52.

Emrich, G.H. and Merritt, G.L. 1969. Effects of mine drainage on groundwater. Ground Water. Vol. 7. P27-32.

Emrich, G.H. and Thompson, D.R. 1968. Some characteristics of drainage from deep bitumous mines in Western Pennsylvania. 2nd Symposium on Coal Mine Drainage Research. P190-222.

Environment Canada. 1979. Analytical Methods Manual. Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Ferguson, B.K. 1985. Watershed planning for acid mine drainge abatement. Water Resources Bulletin. Vol. 21. P253-263.

Fetter, C.W. (Jnr) 1980. Applied Hydrogeology. Elsevier.

Forrest, J.C. 1920. The underground barriers of the Cannock Chase Coalfield. Transactions of the Institute of Mining Engineers. Vol. 59. P115-131.

Freeze, R.A. and Cherry J.A. 1979. Groundwater. Prentice Hall. New Jersey.

Fritz, J.S. and Yamamura, S.S. 1955. Rapid microtitration of sulphate. Analytical Chemistry. Vol. 27. P1461-1464.

Gardner, C.M.K. 1983. A comparison of measured soil moisture deficits with those estimated by the meteorological office system, MORECS : A brief report. Agricultural Water Management. Vol. 6. P307-316.

Gash, J.H.C. and Stewart, J.B. 1977. The evaporation from Thetford Forest during 1975. Journal of Hydrology, Vol. 35. P385-396.

Gash, J.H.C., Wright, I.R., and Lloyd, C.R. 1980. Comparative estimates of interception loss from three coniferous forests in Great Britain. Journal of Hydrology. Vol. 48. P89-105.

Geidel, G. and Carrucio, F.T. 1978. Time as a factor in acid mine drainage pollution. 7th Symposium on acid mine drainage research. P41-50.

Glover, H.G. 1983. The hydrochemistry of the British Coal Measures. Paper presented at the hydrogelogical aspects of mining conference of the Geological Society of London at Aston University, June 1983.

Gray, D.A., Allender, R. and Lovelock, P.E.R. 1969. The groundwater hydrology of the Yorkshire Ouse River Basin (hydrometric area 27), Institute of Geological Sciences, Water Supply Paper No. 4. 40P.

Gregory, O. 1982. Defining the problem of disused coal mine shafts. Chartered land Surveyor/Chartered Minerals Surveyor. Vol. 3. P4-15.

Grenfield, J.P. and Ireland, M.P. 1978. A survey of the macro fauna of a coal-waste polluted Lancashire fluvial system. Environmnetal Pollution. Vol. 16. P105-122.

Grindley, J. 1967. The estimation of soil moisture deficits. Meteorological Magazine. Vol. 96. P97-108.

Hackbath, D.A. 1979. The effects of surface mining of coal on water quality near Grande Cache, Alberta. Canadian Journal of Earth Sciences. Vol. 16. P1242-1253.

Harrison, I.B. 1981. An investigation of the groundwater potential of the Calciferous Sandstone Measures at Haddington, East Lothian. Institute of Geological Sciences. Report 81/6.

Hart, C.E. 1952. Laws of the Dean. (A supplement to the the Laws of the Dean Forest and Hundred of St. Briavels, in the county of Gloucestershire, by J. G. Wood). British Publishing Company, Gloucester. 25PP.

Hart, C.E. 1953. The Free Miners of the Forest of Dean and Hundred of St. Brivals. British Publishing Company. Gloucester.

Hawley, J.R. and Shikaze, K.H. 1971. The problem of acid mine drainage in Ontario. Proceedings of the 3rd annual meeting of the Canadian Mineral Processes; Miners Branch, Department of Energy, Ministry of Resources, Ohama.

Headworth, H.G. 1970. The selection of root constants for the calculation of actual evaporation and infiltration for chalk catchments. Journal of the Institute of Water Engineers and Scientists. Vol. 24. P431-446.

Henton, M.P. 1974. Hydrogeological problems associated with waste disposal into abandoned coal workings. Water Services. October. P349-352.

Henton, M.P. 1976. predicting the quality of mine water discharges. Effluent and Water Treatment Journal. Vol. 5. P568-572.

Henton, M.P. 1979. Abandoned Coalfields; Problem of Pollution. Surveyor. Vol 153. P9-11.

Henton, M.P. 1981. The problem of water table rebound after mining activity and its effect on ground and surface water quality. Studies in Environment Science. Vol.17. P111-116.

Henton, M.P. 1983. Origin and disposal of ferruginous mine waters. Presented at the hydrogeological Group Meeting of the Geological Society of London, 7th June 1983, Aston University.

Herricks, E.E. and Cairns, J. 1976. The recovery of streams stressed by acid mine drainage. 5th Symposium of Coal Mine Drainage Research, Mellon Institute.

Hill, R.D. 1971. Mine drainage monitoring. Proceedings Acid Mine Drainage workshop. Ohio University.

HMSO. 1946. Forest of Dean Regional Survey Report. Ministry of Fuel and Power.

HMSO. 1956. The Quarries and Mines Act.

HMSO. 1983. Control of Pollution Act 1974. Chapter 40.

Hollowell, J.R. 1975. Hydrology of the abandoned coal mines in the Wyoming Valley, Pennsylvania. United States Geological Survey Reports. Open File Series. No. 74-237.

Hollyday, E.T. and McKenzie, S.W. 1973. Hydrogeology of the formation and neutralisation of acid mine waters draining from underground coal mines of Western Maryland, Department of Natural Resources, United States Geological Survey. Report of Investigations No 20.

Huddle, J.W. and Patterson, S.H. 1961. Origin of the Pennsylvanian underclay and related seat rocks. Bulletin Geological Society of America. 72. P1643-1660.

Hughes, B.D. and Edwards, R.W. 1977. Flows of sodium, potassium, magnesium and calcium in the River Cynon, S. Wales. Water Research. Vol. 11. P563-566.

Huntoon, P.W. and Lundy, D.A. 1979. Fracture controlled groundwater circulation and well siting in the vicinity of Larmie, Wyoming. Ground Water. Vol 17. P463-469.

Ineson, J. 1967. Groundwater conditions in the coal measures of the South Wales coalfield. Institute of Geological Sciences, Water Supply Paper Hydrogeological Report No.3. 69P.

Institute of Hydrology. 1981. The MORECS discussion meeting, April 1981. Institute of Hydrology Report No. 78.

Jacob, C.E. 1944. Correlation of groundwater levels and precipitation on Long Island, New York. Transactions of the American Geophysical Union. P928-939

Joynes. J.J. 1889. Description of the seams and some methods of working coal in the Forest of Dean Coalfield. Journal of the British Society of Mining Students No. 6. P136-166.

Joynes. J.J. 1917. Cannop Colliery and its water difficulties. Iron and Steel Trades Review. P685-686.

Karanjac, J and Altug, A. 1980. Karstic spring recession hydrograph and water temperature analysis : Oymapinar Dam Project, Turkey. Journal of Hydrology. Vol.45. P203-217.

Kendal, P.F. 1921. Porosity of rocks and its influence upon the yield of wells and boreholes. Transactions of the Institute of Water Engineers. Vol. 126. P28-43.

Kitteridge, J. 1948. Chapter 9. Interception and Stemflow. In : Forest Influences. Amercian Forestry Series.

Kruseman, G.P. and De Ridder, N.A. 1970. Analysis and evaluation of pumping test data. International Institute of Land Reclamation and Improvement. Bulletin No. 11. Wageningen, The Netherlands.

Law, F. 1958. Measurement of rainfall interception and evaporation losses in a plantation of sitka spruce-trees. International Association of Scientific Hydrology. Vol. 2. P397-411.

Laxen, D.P.H. 1984. Adsorption of Cd, Pb, and Cu during the precipitation of hydrous ferric oxide in a natural water. Chemical Geology Vol. 47. P321-332.

Laxen, D.P.H. 1985. Trace metal adsorption/coprecipitation of hydrous ferric hydroxide under realistic conditions. The role of humic substances. Water Research. Vol 19. P1219-1236.

Letterman, R.D. and Mitsch, W.J. 1978. Impact of mine drainage on a mountain stream in Pennsylvannia. Environmental Pollution. Vol. 17. P53-73.

Littlejohn, G.S. 1979a. Surface stability in areas underlain by old coal workings. Ground Engineering. Vol 12. P122-30.

Littlejohn, G.S. 1979b. Consolidation of old coal workings. Ground Engineering. Vol. 12. P15-20.

Lorenz, W,C. 1962. Progress in controlling acid mine water: A literature review. Bureau of Mines, Information circular 8080, U.S. Department of the Interior. 41P.

Martin, G.N. 1973. Characterisation of simple exponential baseflow recessions. Journal of Hydrology (N.Z.) Vol. 12. P57-62.

Mather, J.D., Gray, D.A. and Jenkins, D.G. 1969. The use of tracers to investigate the relationship between mining subsidence and groundwater occurence at Aberfan, South Wales. Journal of Hydrology. Vol. 9. 136-154.

McWhorter, D.B., Hadley, R.F. and Snow., D.T. 1974. Potential of mine and mill spoils for water quality degradation. In Water resource problems related to mining. American Research Association. Proceeding No. 18. P123-137.

Merkel, R. M. 1972. The use of resistivity techniques to delineate acid mine drainage in groundwater. Ground Water. Vol. 10. P38.

Miles, D.L. and Espejo, C. 1977. Comparison between an ultra violet procedure and the 2,4 xylenol method for the determination of nitrate in groundwaters of low salinity. Analyst. Vol. 102. P104-109.

Miller, J.T. and Thompson, D.R. 1974. Seepage and mine barrier width. 5th Symposium Coal Mine Drainage Research. Louisville. P103-127.

Moran, S.R., Groenewold, G.H. and Cherry, J.A. 1978. Geologic, hydrologic and geochemical concepts and techniques in overburden characterisation for mined land reclamation. N.D. Geological Survey. Report of Investigation No. 63. 152P.

Morris, D.A. and Johnson, A.I. 1966. Summary of hydrologic and physical properties of rocks and soil materials as analysed by the Hydrologic Laboratory of the US Geological Survey. 1948-1960. Denver, Colorado, USGS Open File Report.

Murphy, C.E. and Knoerr, K.R. 1975. The evaporation of intercepted rainfall from a forest stand: an analysis by simulation. Water Resources Research. Vol. 11. P273-280.

Murphy, J. and Riley, J.P. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica. Chemica. Acta. Vol. 27. P31-36.

Mushet, D. 1824. Observations on the South-Western Coal District of England. Transactions of the Geological Society. Vol. 2.

NCB (National Coal Board (Mining Department)). 1985. Technical management of water in the coal industry. National Coal Board. Hobart House, Grosvenor Place, London.

Neate, C.J. 1980. Effects of mining subsidence on the permeability of Coal Measures rocks. Ph.D. Thesis, University of Nottingham.

Norton, P.J. 1983. Groundwater rebound effects on surface coal mining in the United Kingdom. In Surface Mining and Quarrying. The Institute of Mining and Metallurgy. 2nd International Surface Mining and Quarrying Symposium organised by I.M.M. Bristol, 4-6th October 1983.

Nutbrown, D.A. and Downing, R.A. 1976. Normal mode analysis of the structure of baseflow recession curves. Journal of Hydrology. Vol. 30. P327-340.

Packard, F.A. 1981. Reconnaissance of water availability and quantity in abandoned coal mines near Roslyn, Kittitas County, Washington. United States Geological Survey Water Resources Investigations OPen File Report No. 80-955.

Parsons, J.D. 1977. Effects of acid mine wastes on aquatic ecosystems. Water, Air, Soil Pollution. Vol. 7. P333-354.

Parsons, A.S. and Hunter, M.D. 1972. Investigation into the movement of groundwater from Bryan Pit above Ebbw Vale, Monmouthshire. Journal of the Institute of Water Pollution Control. Vol. 71. P568-572.

Pearson, G.M. and Wade, E. 1966. The physical behaviour of seat-earths. Proceedings of the Geological Society of London. 1637. P24-33

Penman, H.L. 1948. natural evaporation from openwater, bare soil and grass. proceedings of the Royal Society. A. Series A. Vol.193. P120-146.

Pinder, G.F. and Jones, J.F. 1969. determination of the groundwater component of peak discharge from the chemistry of total runoff. Water Resources Research. Vol. 5. P438-445.

Porges, R., Lowell, A. and Ballinger, D. 1966. Re-assessing an old problem - Acid Mine Drainage. Proceedings of the American Society of Civil Engineers. Journal of the Sanitary Engineering Division. Vol. 92. P69-83.

Rae, G. 1978. Mine drainage from coalfields in England and Wales. A summary of its distribution and relationship to water resources. Technical Note No. 24. Water Planning Unit, Reading, England.

Rainwater, F.H. and Thatcher, L.L. 1960. Methods for the collection and analysis of water samples. United States Geological Survey Water Supply Paper. No. 1454.

Rawat, N.S. and Singh, G. 1982. The role of micro-organisms in the formation of acid mine drainage in the North Eastern Coalfield of India. International Journal of Mine Water. Vol. 2. P29-36.

Rehm, B.W., Groenewold, G.h., and Morin, K.A. 1980. Hydraulic properties of coal and related materials, Northern Great Plains. Ground Water. Vol. 18. P551-561.

R odda, J.C., Downing, R.A., and Law, F.M. 1976. Systematic Hydrology. Butterworths, London.

Rowe, P.B. 1941. Some factors of the hydrology of the Sierra Nevada foothills. Transactions of the American Geophysical Union. Vol. 22. P90-100.

Royal Town Planning Institute. 1979. coal and the Environment : A submission to the commission on energy and the environment; Coal Study. 138P.

Rushton, K.R. and Ward, C. 1979. The estimation of groundwater recharge. Journal of Hydrology. Vol. 41. P345-361.

Russell, W.L. 1933. Subsurface concentartion of chloride brines. Bulletin American Association Petroleum Geologists. Vol. 17. P1213-1228.

Rutter, A.J. 1967. An analysis of evaporation from a stand of scots pine. In the International Symposium on Forest Hydrology. Ed. Sopper, W.E. and Lull, H.W. Pergamon Press.

Rutter, A.J. et al. 1975. A predictive model of rainfall interception in forests. 2. A generalisation of the model and comparison with the observations in some coniferous and hardwood stands. Journal of Applied Ecology. Vol. 12. P367.

Schubert, J.P. 1978. Reducing water leakage into underground coal mines by aquifer dewatering. Water in Mining and Underground Works. Asociacion Nacional de Ingenieros de Minas, Granada, Spain.

Schubert, J.P. 1980. Fracture flow of groundwater in coal-bearing strata. Symposium on Surface Mining Hydrology Sedimentology and Reclamation. University of Kentucky, Lexington.

Shadbolt, C.H., Whittaker, B.N. and Forrester, D.J. 1973. Recent developments in mining subsidence engineering. Paper presented at the 64th General meeting of the Midland Counties Minerals Division of the R.I.C.S, Nottingham. 19th October 1973.

Shumate, K.S. and Brant, R.A. 1971. Acid mine drainage formation and abatement. United States Environmental Protection Agency. National Technical Information Service Open File Report PB 199-835.

Sibley, T.F. 1912. The Carboniferous succession in the Forest of Dean Coalfield. Geological Magazine. P417.

Sibley, T.F. and Reynolds, S.H. 1937. The Carboniferous Limestone of the Mitcheldean area, Gloucestershire. Quarterley Journal Geological Society. 103. P23.

Siegel, S. 1956. Nonparametric statistics for the behavioural sciences. Mc Graw Hill, New York.

Singer, P.C. and Stumm, W. 1968. Kinetics of the oxidation of ferrous iron. 2nd Symposium Coal Mine Draiange Research. Mellon Institute.

Singer, P.C. and Stumm, W. 1970. Acidic mine drainage : The rate determining step. Science. Vol. 167. P1121-1123.

Smith, D.I. and Atkinson, T.C. 1972. Underground flow in cavernous and fissured limestones. In : Cole, J.A. (Ed.), Groundwater in Europe. Water research centre, Medmenham, England. P409-413.

Sopwith, T. 1841. The award of the Forest of Dean as to the Coal and Iron Mines in Her Majesty's Forest of Dean and the Rules and Regulations for working the same with preliminary observations and an explanation of a series of sixteen engraved plans of the Forest of Dean Mines. London.

Stanton, W.I. and Smart, P.L. 1981 Repeated dye tracers of underground streams in the Mendip Hills, Somerset. Proceedings of the University of Bristol Speleological Society. Vol. 16. P47-58.

Stark, J.R. and McDonald, M.G. 1980. Groundwater of coal deposits, Bay County, Michigan. United States Geological Survey. Open File Report 80-591.

Sternberg, Y.M. and Agnew, A.F. 1968. Hydrology of surface mining - A case study. Water Resources Resaerch. Vol. 4. P363-368.

Stewart, J.B. 1977. Evaporation from the wet canopy of a pine forest. Water Resources Research. Vol. 13. P915-921.

Stewart, J.B. and Thom, A.S. 1973. Energy budgets in pine forests. Quarterly Journal of the Royal Meteorological Society. Vol. 99. P154-170.

Stewart, K.J. 1973. Stability of coal workings. BSc. Thesis. Aberdeen University.

Stone, R. and Snoeberger, D.F. 1978. Cleat orientation and areal hydraulic anisotropy of a Wyoming Coal Aquifer. Groundwater. Vol. 15. P434-438.

Stoner, J.D. 1981. Horizontal anisotropy determined by pumping in two Powder River coal aquifers, Montana. Groundwater. Vol. 19. P34-40.

Stumm, W. and Morgan, J.J. 1970. Aquatic Chemistry. Wiley Inter Science. New York. USA.

Swartzendruber, D. 1962. Non-Darcy flow behaviour in liquid-saturated porous media. Journal of Geophysical Research. Vol. 67. P5205-5213.

Taylor, B.E., Wheeler, M.C. and Nordstrom, D.K. 1984a. Stable isotope geochemistry of acid mine drianage: experimental oxidation of pyrite. Geochimica et Cosmochimica Acta. Vol. 48. P2669-2678.

Taylor, B.E., Wheeler, M.C. and Nordstrom, D.K. 1984b. Isotope composition of sulphate in acid mine drainage as a measure of bacterial oxidation. Nature. Vol. 308. P538-541.

Thompson, N., Barrie, I.A., and Ayles, M. 1981. The meteorological office rainfall and evaporation calculation system : MORECS. Hydrological Memorandum No. 45. Meteorological Office.

Thurman, A.G., Straskrabav, V. and Ellison, R.D. 1978. Development of a groundwater hazard map for an underground coalmine. Proceedings of the International Symposium on Water in Underground Works. Granada. Vol. 1. P273-291.

Todd, D.K. 1959. Ground Water Hydrology. John Wiley and Sons, New York.

Trainer, F.W. and Watkins, F.A. (Jnr) 1974. Use of baseflow-runoff recession curves to determine areal transmissivities in the upper potomac river basin. Journal of Geological Research. U.S. Geological Survey. Vol.12. P125-131.

Trexler, B.D., Ralston, D.R., Reece, D.R. and Williams, R.E. 1975. Sources and causes of acid mine drainage. Idaho Bureau of Mines and Geology. Moscow. Idaho. Pamphlet No. 165.

Trotter, F.M. 1942. Geology of the Forest of Dean Coal and Iron Ore Field. Department of Scientific and Industrial Research. Memoirs of the Geological Survey of Great Britain. H.M.S.O. London. 95P.

Turback, S.C., Olsen, G.J. and McFeters, G.A. 1979. Impact of western coal mining - 1. Investigations of a surface coal mine sedimentation pond. W ter Research. Vol. 13. P1023-1031.

Ure, A.M. and Mitchell, M.C. 1975. Lithium, sodium, potassium, rubidium and caesium. P1-32. In Flame emission and atomic absorption spectrometry. Vol. 3. Elements and matrices. Ed. Dean, J.A. and Rains, T.C. Marcel Dekker, New York.

U.S.E.P.A. 1980. Effects of underground coal mining on groundwater in the Eastern United States. E.P.A. Report 600/7/80/120. PB 60-216757.

U.S.E.P.A. 1986. Surface and groundwater problemss associated with potential strip mine sites. United States of America Environmental Protection Agency. Grant No. R-803727.

Van Voast, W. A. and Hedges, R.B. 1975. Hydrogeolological aspects of existing and proposed strip mines near Decker, South East Montana. Montana Bureau of Mines and Geology. Bulletin No 97. 31P.

Vecchioli, J. 1967. Directional hydraulic behaviour of fractured shale aquifers in New Jersey. Proceedings of the Dubrovnik Symposium. Hydrology of Fractured Rocks Vol II P428-488 Paris IASH-UNESCO.

Vogwill, R.I.J. 1979. Hydrogeological testing associated with underground coal gasification. Journal of Canadian Geotechnology. Vol. 16. P59-68.

Ventz, D.A. 1974. Stream quality in relation to mine drainage in Colorado. Proceedings American Water Resources Association. No. 18. P158-173.

White, W.A. 1956. Underclay squeezes in coal mines. Transactions American Institute Mining Engineering. P1024-1028.

Whiteside, P.J. and Milner, B.A. 1981. Pye Unicam Atomic Absorption Data Book. Pye Unicam Ltd. Cambridge, England.

Wigley, T.M.L. 1977. WATSPEC : A computer program for the calculation of aqueous water speciation. Technical Bulletin of the British Geomorphological Research Group. No. 20. 40p.

Wilson, A.H. 1983. The stability of underground workings in the soft rocks of the Coal Measures. International Journal of Mining Engineering. Vol. 1. P91-187.

Wilson, M.J. 1965. The origin and geological significance of the South Wales Underclays. Journal of Sedimentary Petrology. Vol. 35. P91-99.

Wirres, D.L. and McDonnell. 1983. Drainage quality at deep coal mine sites. Water Resources Bulletin (American Resources Association) Vol. 19 P235-240.

Wood, P.A. 1981. Hydrological problems of surface mining. IEA Coal Research, London, Report No. ICTIS/TR17. 102P.

Woodley, R.A. and Moore, S.L. 1967. Pollution control in mining and processing of Indiana coal. Journal of water pollution control federation. Vol 39. P41-49.

World Meteorological Office. 1971. Guide to meteorological instruments and observing practices. W.M.O. No. 8. TP3. 4th Edition.