Catchment-scale assessments of the effects of abandoned metal mines on groundwater quality and stream ecology.

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Abstract. This paper presents an overview of a British Geological Survey catchment-scale research project designed to quantify catchment-derived metal loading on surface water quality. This work is focused on the Rookhope Burn, a tributary of the River Wear in the North Pennines, UK. The river has been identified in the Water Framework Directive (WFD) River Basin Management report as being at risk of failing to achieve Good Status due to mines and minewater pressures. Although geologically relatively simple, the catchment is hydrogeologically complex in that it comprises an area of entrenched karst, characterised by Lower Carboniferous Limestone exposed in the base of valleys overlain by Namurian strata, comprising interbedded shales, sandstones and limestones, which are capped by drained blanket peat. Metal loadings in this catchment result from lead and zinc mineralization and its historic exploitation and processing, which have resulted in both point source and diffuse impacts within the catchment. There have been three main phases of research: (i) collection of hydrological and water chemistry data to enable loading and mass balance calculations to be undertaken; (ii) development of a conceptual understanding of the hydrology and hydrogeology of the catchment, and (iii) application of the hydrological understanding to more recent baseline monitoring of ecological impacts. This work has identified previously unreported mine and groundwater contributions to the catchment, which may have significant implications for the design of remedial measures in the catchment.

Introduction. The Water Framework Directive (2000/60/EC) is the consequence of a European initiative to replace piecemeal legislation with a single integrated management framework for the water environment in the context of entire river basins in the UK through the designation of 15 River Basin Management Plans (RBMPs). It aims to achieve "Good Status" (GS) for all rivers, lakes, estuaries, coastal waters and groundwater by 2015. The measurement of GS for surface waters through an ecological (physico-chemical, biological, specific pollutant and hydromorphological) assessment, as well as the chemical component, represents a significant shift of approach (Environment Agency, 2007). For groundwater GS has a quantitative and a chemical component. Key management issues and the actions required to address them form an integral part of the management process and as such, there are clear aims to identify procedures to achieve cost effective remediation. The Northumbria River Basin District Management Plan (Environment Agency, 2009) identified the Rookhope Burn, a tributary of the River Wear, as being of moderate ecological status and a catchment that is at risk from mines and minewater pressures in the Northumbria River Basin District. The Rookhope Burn catchment formed the focus for a catchment-scale monitoring exercise, to determine seasonal variation in diffuse and point source impacts derived from abandoned mine workings. This was undertaken between May 2007 and January 2008 and was used to refine the conceptual model of the catchment and was extended to incorporate baseline ecological monitoring. The results from the different work packages are summarised in this paper, together with a consideration of the implications for remediation design and potential research directions.

Typical of the mining industrial heritage of the North Pennines, the Rookhope catchment (Figure 1) lies towards the centre of an Area of Outstanding Natural Beauty with its source in grouse moorlands at an elevation of ~600 to 540 m OD. Down slope, the moorlands give way to hill farming and isolated settlements in a relatively treeless landscape scarred by abandoned quarries, the remnants of mine workings and mounds of abandoned mine waste. The mines were worked in a number of phases dating back to the Roman period, but primarily focused on the period from the end of the C17th to the end of the C19th (Dunham, 1990). The catchment is underlain by mineralized Dinantian limestone capped by Namurian sandstones and mudstones of the Yoredale Group. Namurian strata underlie the upper part of the catchment. They are almost horizontal, with a slight regional dip to the east, such that the underlying limestones are exposed downstream of Bolts Burn. Glacial till covers the solid geology below an elevation of ~370 m OD. Other superficial deposits include river terrace deposits associated with the River Wear at the southern end of the catchment, ribbons of alluvial deposits associated with the river valleys, blanket peat that caps the higher ground and anthropogenic deposits, primarily mine waste. Mineralization is hosted by normal faults of limited vertical throw with local occurrences of horizontal mineral replacement (flats) in the limestones, which were found to be particularly productive. Primary minerals include: galena, fluorite, quartz and siderite with an extensive range of trace and secondary minerals. Draining an area of approximately 37 km^2, the southerly flowing Rookhope Burn contributes a discharge ranging from 100 to 2300 l/s to the River Wear at Eastgate (Figure 1). The stream hydrograph is flashy, i.e. there are frequent, rapid, short term changes in stream flow and the stream responds rapidly to runoff events, reflecting the occurrence of low permeability bedrock, antecedent conditions and artificially drained peat. Dolines (shakeholes) characterise the areas of till-capped bedrock, which is indicative of void forming (karst) processes in the limestones at depth, further contributing to the flashy response of the hydrograph, as do the artificial drainage adits (including the Boltsburn and Tailrace Levels, Figure 1) constructed to drain the mines. Younger (2000) and Johnson and Younger (2000; 2002) gained access to Frazer's Grove Mine (Figure 1), the most recently closed (1903) mining centre in the catchment, for hydrogeological investigation. This included underground and surface sampling of waters from Frazer's Grove prior to and during groundwater rebound following the cessation of minewater abstraction. The results identified zinc as the primary contaminant of concern in this catchment. It was established that the chemistry of the groundwater is stratified, reflecting the influence of variations in the bedrock geology. Three waters were characterised, primarily on the basis of the concentrations of: Zn, Ca, HCO_3^- and SO_4^{2-}. The rise in groundwater levels was associated with an increased discharge of Zn-rich water (up to 35.6 mg/l) from the Tailrace Level (Figure 1; Johnson and Younger 2000, 2002). Stratification in the water column following groundwater rebound resulted in an amelioration of the chemistry of the water discharged from the Tailrace Level and was clearly indentified in the results obtained during this study (Table 1).

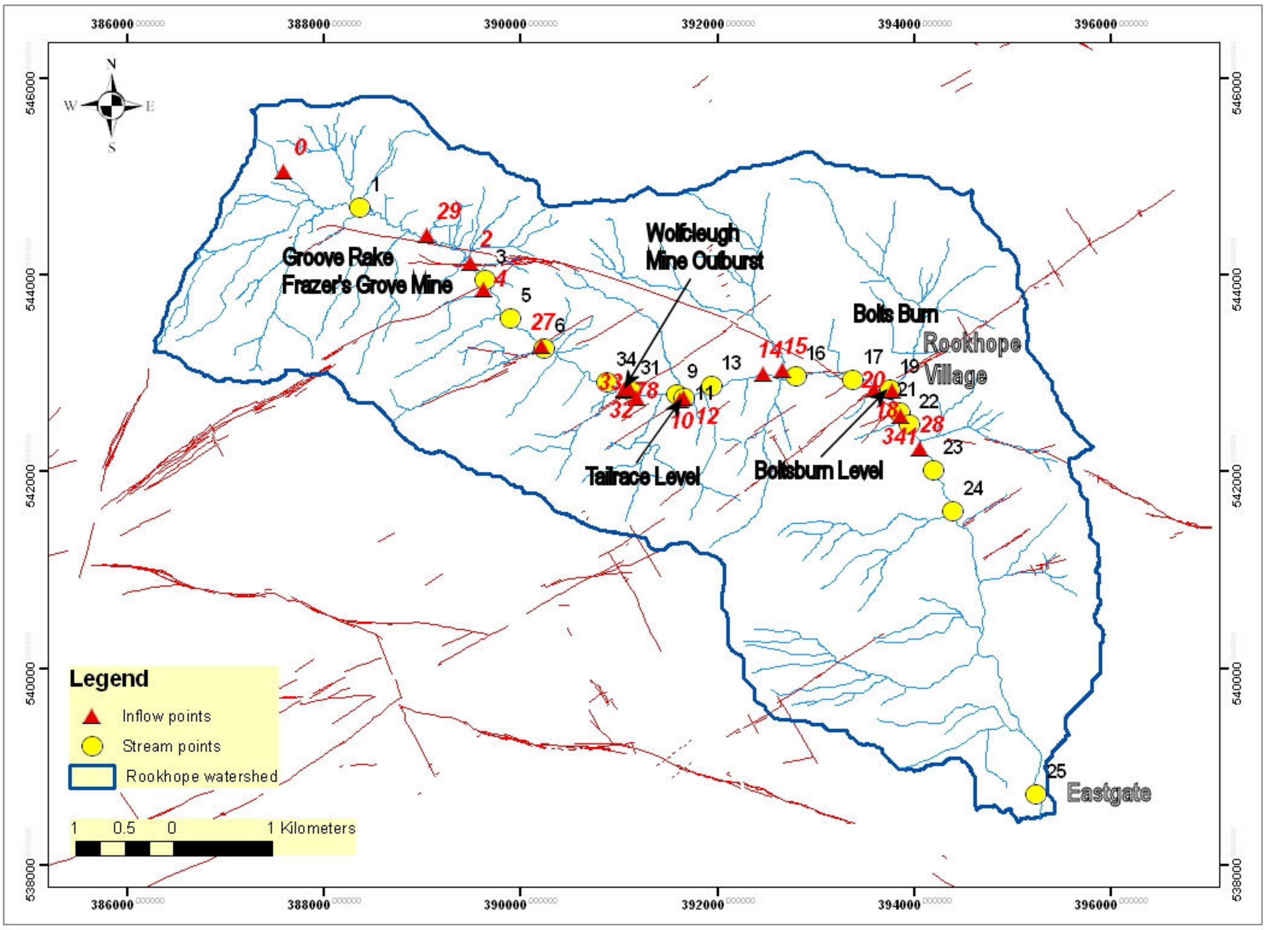

Figure 1: Rookhope Burn Catchment, North Pennines showing sampling locations and mineral veins.

Table 1: Rookhope Burn, synoptic instream water quality and discharge.

The monitoring programme. Data from previous monitoring, literature review, aerial photograph studies and the BGS database of mine adits were used to establish 23 sampling sites. At each location, synoptic flow monitoring and sampling for chemical determinations of major ions and trace elements was undertaken. This included sampling of the Rookhope Burn (instream sampling) upstream and downstream of visible mine water discharges, at the confluence of the main tributaries and on tributary inflow sites. Surveys were scheduled to coincide with different hydrological conditions (May 2007, June 2007 and January 2008), although these were difficult to determine remotely. May 2007 was closest to baseflow conditions, whilst the June 2007 survey coincided with the tail end of a storm event. Immediately prior to the commencement of monitoring there was a Ca, Mg, Mn, Zn and SO_4 –rich groundwater outburst from an abandoned mine shaft at Wolfcleugh (NY91059 42828, site 7, Figure 1), which is likely to have occurred as a response to excess pore water pressure build-up as a consequence of a downstream collapse within the abandoned mine workings, and had a marked impact on the chemistry of the Rookhope Burn (Table 1). A further survey of water chemistry and flow was undertaken at the time of a baseline ecology survey in April, 2009. This comprised 3-minute kick samples covering all available habitats and centred on riffles at the instream sites (Table 1). The ecological survey was timed to occur prior to the peak emergence period of riverflies (e.g. mayfly, stonefly and caddisfly) that overwinter as larvae in the river and are in intimate contact with the substratum during this period.

Discharge was determined at each location using a Columbia 2 Digital Stream Meter (impeller-type) and the velocity-area method of calculation (Shaw, 1999). There is some uncertainty in the results, due to the difficulty of monitoring in areas where the bed of the river is formed of granular material that enables a proportion of the groundwater flow to bypass the monitoring. Water pH, temperature, Eh and conductivity were measured in the field using a Water Quality Multiparameter meter. Water samples were filtered (0.45 µm) and preserved (1% HNO_3). Chemical analyses were undertaken in the laboratories of the BGS. Alkalinity was determined by titration, major and trace elements by ICP-AES, Fe (II) by colorimetric analysis and major anions by ion chromatography. Duplicate and blank sample determinations were made for quality control purposes.

Chemical and ecological characterisation. Whilst one of the aims of this work was to determine the baseflow chemistry, in practice the flashiness of the hydrograph response in the upland setting made this difficult. Contaminant loadings were determined utilizing an approach that was applied by Kimball et al. (2002). At each instream and inflow monitoring site the zinc and other chemical loads were calculated from the product of the discharge and the Zn concentration. The May 2007 instream zinc loads have been plotted against distance downstream from the head of the catchment (Figure 2). Mass balance calculations, based on an assumption that the load at the end of a stream segment includes the load from the site upstream plus the contribution from all surface and subsurface inflows along the stream segment, have also been derived (Figure 2). As a result, sources of Zn have been identified between sample sites 9-11 and 17-19. The spiked form of these contributions suggests that they are point source groundwater inputs.

Figure 2: Zinc load in the Rookhope Burn, 2-3 May 2007.

Table 2: Biotic Indices; instream sampling locations.

(BMWP Biological Monitoring Working Party; ASPT Average score per taxa)

Sample site	0	1	3	5	6	9	11	13	21	23	24	00A	25
BMWP	70.1	45.2	59.3	79.1	69.7	26	28.4	51.8	105.3	39.4	45.2	108.6	46
ASPT	7.79	7.53	8.47	8.79	7.74	8.67	9.47	8.63	9.31	7.88	7.53	7.76	7.67
Taxa	9	6	7	10	9	3	3	6	12	5	6	14	6
Abundance	122	16	44	45	3	4	7	50	71	27	75	181	77

Ecological monitoring identified 26 macroinvertebrate taxa including 8 stonefly, 4 mayfly and 4 caddisfly species. The macroinvertebrtate community was assessed using a range of biotic indices including the Biological Monitoring Working Party score (BMWP) and its derivative the average score per taxa (ASPT) (Extence et al., 1987). The BMWP scores taxa from 1 to 10 in increasing order of putative sensitivity to organic pollution; the score (Table 2) being the sum of all scores from invertebrate families in the sample. Sites 0 and 00A (National Grid Reference 387597 545057 and 394394 541547 respectively) comprised the catchment control sites. The results clearly indicate a marked reduction in BMWP score at both site 9 and 11 coinciding with a marked increase in the ASPT score.

Discussion and conclusions. Zinc is a key contaminant of (ecological) concern in this catchment. It exceeds the Environmental Quality Standard (EQS; Mance and Yates, 1984) values for fisheries (salmonid and cyprinid) throughout most of the catchment. The findings presented here indicate that this is largely attributable to point source inputs of mine water. Interpretation of the results is dependent on a good conceptual understanding of the catchment. The most significant impact on the water quality of the Rookhope Burn is the contribution of mine water from the outburst at Wolfcleugh (site 7, Figure 1). Remedial measures, which entailed capping the shaft and feeding the discharge into an outlet channel, occurred at some point between the June 2007 and January 2008 visits. This appears to be reflected in reductions in the discharge and improved water quality (lower SO_4, F, Fe, Mn and Zn). It is likely that the improved quality is attributable to the re-establishment of stratification of chemistry in the water column, as observed in Frazer's Grove Mine (Johnson and Younger, 2000 and 2002; Younger 2000). Inputs via the bed of the river have been identified from the Zn load plots, between instream sampling positions 9 - 11 and 16 – 19 (Figure 2). The former corresponds closely with the position of the Tailrace Level and it is suspected that this contribution rises via the mineral vein, where it intersects the river bed. A comparable point source, associated with the mineralisation at Boltsburn is thought to account for the latter.

The biotic indices indicate that these point sources have an impact on instream ecology: there is a significant reduction in BMWP score, number of taxa and abundance downstream of the mine outburst, sites 9 and 11 (Table 2). This also coincides with an increase in the ASPT score associated with the presence of a small number of stonefly taxa known to be resistant to metal pollution (Doi et al., 2007). It was not until site 13 that the indices display a degree of community recovery in the Rookhope Burn. However, it should be recognised that the biotic indices have been drawn from a single monitoring event and that further detailed investigation would be beneficial given the difficulty of establishing background conditions in heavily mined catchments.

Given that sampling in this study did not include any extreme weather events the results are likely to underestimate diffuse source contaminant contributions; for example, leachate (SO_4, F, Pb and Zn -rich) has been monitored emanating from some of the extensive minewaste stockpiles. It is assumed that the concentration of the leached elements reflects the porewater-waste contact time and that this has significant impacts on stream water chemistry when it is flushed into the stream. This is particularly the case at the end of a prolonged period of low rainfall, typically during dryer summer months. There is visual evidence to suggest that high energy storm events result in significant surface erosion of mine waste, particularly in the vicinity of tailings lagoons, which makes its way into the surface water courses and exposes fresher material for surface weathering and leaching.

Synoptic monitoring has established that the mine outburst and the point sources of minewater ingress to the stream have a measurable impact on the ecological status of the Rookhope Burn. This poses difficulties in the context of any requirements for remediation and points to a need for further understanding of the stability of the underground mine workings. It is clear that any blockages will result in rises in porewater pressure elsewhere in the system, which could result in further outbursts. Accordingly, the BGS has been exploring methods of using 3-D geological modelling to host engineering information with a view to predicting mine stability.

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Table 1: Rookhope Burn, synoptic instream water quality and discharge.

Site	Description	Easting	Northing	Date	Sample Code	T	pH	Eh	Cond	Alk (HCO_3)	Ca	Mg	Na	K	Cl	SO_4	Mn	Tot Fe	Fe(II)	Zn	Pb	Flow
						°C		mV	uS/cm	mg/l												l/s
1	Rookhope	388362	544696	02/5/07	WD101	15	7.90	294	194	94	27.7	4.90	6.53	2.80	14.29	10.66	0.469	0.629	0.613	0.015	<0.01	7
	Burn -			27/6/07	WD201	11	6.37	348	48	9	5.32	1.38	3.93	0.57	5.36	4.78	0.199	1.67	1.37	0.035	<0.01	134
	headwaters			17/4/09	WD401	11	6.81	231	148	113	18.8	3.51	7.16	1.97	8.86	5.82	0.303	0.58	0.64	0.019	<0.01	
3	Rookhope	389645	543961	02/5/07	WD103	18	7.95	413	179	60	22.2	4.37	6.56	2.35	12.77	12.29	0.305	0.613	0.542	0.037	<0.01	11
	Burn - d/s			27/6/07	WD203	13	7.03	299	64	8	6.38	1.65	4.07	0.81	5.06	7.47	0.184	0.992	0.742	0.068	0.024	450
	Grove Rake			28/1/08	WD 303	5	6.21	503	76	34	5.88	1.55	4.42	0.90	7.20	6.97	0.151	0.426	0.426	0.060	0.01	166
	adit			17/4/09	WD 403	11	6.91	224	140	93	18.10	3.58	6.98	1.92	11.90	9.92	0.276	0.637	0.574	0.042	<0.01	20
5	Rookhope	389900	543562	02/5/07	WD105	20	7.69	441	177	52	19.7	4.35	7.45	2.21	13.03	16.25	0.153	0.403	0.332	0.059	<0.01	30
	Burn			27/6/07	WD205	13	6.81	328	61	12	6.89	1.79	4.14	0.82	5.21	8.89	0.158	0.916	0.681	0.087	0.023	289
	(intermediat			28/1/08	WD305	6	6.41	505	88	44	7.26	1.87	4.87	1.02	8.51	9.97	0.141	0.488	0.488	0.083	0.01	179
				17/4/09	WD405	11	6.61	253	144	85	18.1	3.74	7.26	1.78	11.90	12.40	0.202	0.381	0.379	0.070	0.01	37
6	Rookhope	390241	543261	02/5/07	WD106	19	7.89	381	166	45	17.9	3.85	6.68	1.87	12.43	15.20	0.174	0.443	0.373	0.044	<0.01	42
	Burn at			27/6/07	WD206	13	6.92	295	67	9	6.83	1.76	4.38	0.79	5.08	8.23	0.156	0.904	0.686	0.095	0.026	299
	footbridge			28/1/08	WD306	6	6.44	498	83	88	6.42	1.68	4.42	0.92	8.13	9.24	0.123	0.453	0.453	0.074	0.011	294
				17/4/09	WD406	9	7.13	184	0	73	16.5	3.48	6.91	1.70	11.30	11.20	0.21	0.409	0.510	0.068	<0.01	4
9	Rookhope	391591	542785	02/5/07	WD109	17	8.02	294	551	109	84.4	14.8	7.94	5.78	11.04	174.45	3.44	0.066	0.118	1.02	<0.01	26
	Burn-			27/6/07	WD209	11	7.23	276	127	32	22.0	4.74	5.06	1.79	5.89	47.40	0.877	0.869	0.690	0.435	0.026	606
	upstream			28/1/08	WD309	7	6.63	450	225	83	25.7	5.19	5.73	2.35	7.05	36.85	0.975	0.578	0.544	0.419	0.01	26
				17/4/09	WD409	8	6.95	193	400	175	60.2	10.5	7.93	5.41	11.50	93.80	1.82	0.227	0.392	0.619	<0.01	126
11	Rookhope	391668	542756	02/5/07	WD111	17	8.03	385	547	107	81.1	14.4	7.62	5.55	11.27	174.90	3.28	0.070	0.085	0.922	<0.01	94
	Burn- d/s			27/6/07	WD211	11	7.29	270	177	28	22.5	4.79	4.95	1.79	5.89	47.48	0.855	0.855	0.506	0.430	0.026	621
	Tailrace			28/1/08	WD311	7	6.64	432	220	93	25.5	5.16	5.69	2.32	9.57	50.65	0.951	0.531	0.530	0.410	0.01	767
				17/4/09	WD411	8	7.16	199	394	207	59.2	10.4	7.88	5.18	6.72	76.00	1.70	0.249	0.40	0.591	<0.01	101
13	Rookhope	391946	542876	02/5/07	WD113	17	8.23	427	521	108	74.5	13.7	7.93	5.18	11.17	160.40	2.66	0.034	<0.050	0.718	<0.01	132
	Burn			27/6/07	WD213	11	7.37	287	149	25	20.9	4.42	5.05	1.68	6.00	42.06	0.741	0.810	0.712	0.370	0.028	716
				28/1/08	WD313	5	6.87	316	191	54	20.6	4.15	5.31	1.87	9.42	39.48	0.699	0.441	0.440	0.307	0.01	558
				17/4/09	WD413	7	7.68	194	377	161	54.9	9.87	7.94	4.80	11.50	85.10	1.48	0.189	0.320	0.517	<0.01	110
16	Rookhope	392799	542973	02/5/07	WD116	16	8.34	440	455	104	64.0	11.2	7.25	3.91	11.39	129.19	1.71	0.045	<0.050	0.416	<0.01	97
	Burn			27/6/07	WD216	11	7.46	292	140	18	16.0	3.52	5.29	1.30	6.90	29.86	0.481	0.716	0.575	0.232	0.020	616
				28/1/08	WD316	7	7.12	458	168	93	17.8	3.71	5.97	1.69	10.12	31.31	0.521	0.364	0.360	0.214	0.01	728
				17/4/09	WD416	8	7.57	223	303	166	48.6	8.56	8.09	4.12	11.90	67.00	0.99	0.173	0.16	0.303	<0.01	177
19	Rookhope	393756	542833	02/5/07	WD119	11	8.40	402	447	111	66.3	11.7	8.15	4.18	10.01	108.44	1.30	0.032	<0.050	0.362	<0.01	197
	Burn d/s			27/6/07	WD219	11	7.60	313	150	24	18.0	3.72	5.44	1.41	6.81	30.33	0.395	0.715	0.574	0.217	0.018	965
	Boltsburn			28/1/08	WD319	5	7.22	405	173	59	17.7	3.46	5.70	1.60	10.38	29.71	0.402	0.340	0.340	0.180	0.01	911
				17/4/09	WD419	9	7.74	209	331	192	50.5	8.44	8.53	4.04	12.60	63.60	0.686	0.113	0.281	0.206	<0.01	95
21	Rookhope	393862	542610	02/5/07	WD121	11	8.21	351	476	136	69.9	12.6	9.52	4.18	10.93	117.45	0.924	0.035	<0.050	0.245	<0.01	274
	Burn d/s			27/6/07	WD221	11	7.59	316	163	29	19.3	4.13	5.50	1.37	6.85	33.43	0.322	0.612	0.526	0.170	0.020	1361
	Bolts Burn			28/1/08	WD321	5	7.21	352	179	29	18.5	3.86	5.58	1.31	9.54	31.40	0.304	0.298	0.300	0.139	0.01	1591
				17/4/09	WD421	10	7.67	238	359	241	54.5	9.87	9.41	4.00	11.60	69.60	0.531	0.092	0.091	0.150	<0.01	334
23	Rookhope	394203	542016	02/5/07	WD123	9	8.25	358	453	133	67.9	11.9	9.36	3.84	10.98	110.63	0.810	0.047	<0.050	0.229	<0.01	168
	Burn d/s			27/6/07	WD223	10	7.66	324	82	29	18.0	3.81	5.70	1.23	6.89	29.26	0.283	0.666	0.511	0.159	0.020	1472
	spoil heaps			28/1/08	WD323	7	7.24	550	194	141	21.6	4.38	6.01	1.67	9.83	35.56	0.307	0.268	0.270	0.145	0.01	1127
				17/4/09	WD423	7	8.20	205	361	208	55.2	9.66	9.57	3.83	11.80	67.40	0.469	0.109	0.20	0.151	<0.01	307
25	Rookhope	395248	538715	02/5/07	WD125	9	8.22	354	480	148	71.1	11.8	10.6	3.75	15.14	107.62	0.186	0.046	<0.050	0.088	<0.01	276
	Burn at			27/6/07	WD225	10	7.99	288	191	42	25.3	4.23	6.04	1.36	8.10	31.49	0.136	0.559	0.484	0.106	0.018	2099
	Eastgate			28/1/08	WD325	5	7.39	376	221	49	24.9	4.14	6.18	1.43	11.49	35.75	0.142	0.216	0.200	0.086	0.01	2304
				17/4/09	WD425	7	7.78	335	395	296	60.4	9.79	10.5	3.48	14.80	68.70	0.218	0.089	0.085	0.099	<0.01	298