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Continuing pollution from the Rum Jungle U–Cu project: A critical evaluation of environmental monitoring and rehabilitation

Gavin M. Mudd [a,*], James Patterson [b]

[a] Environmental Engineering, Dept of Civil Engineering, Monash University, Clayton, VIC 3800, Australia
[b] Environmental Engineering Consultant, Sydney, NSW, Australia

The Rum Jungle U–Cu project underwent extensive rehabilitation in the 1980's, however, it remains a major cause of pollution to the Finniss River.

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ABSTRACT

The former Rum Jungle uranium–copper project, Australia, is an internationally important case study on environmental pollution from and rehabilitation of mining. The Rum Jungle mining project is briefly reviewed, followed by a critical evaluation of monitoring data and pollution loads prior to and after rehabilitation – leading to the conclusion that rehabilitation has clearly failed the test of time after just two decades. The most critical findings are the need to understand pollution cycles holistically, and designing monitoring regimes to match, explicit inclusion of radiological criteria (lacking in original planning), and finally the need to set targets based on environmental criteria. Two examples include polluted groundwater which was excluded from rehabilitation and the poor design, construction and/or performance of engineered soil covers – both leading to increasing acid drainage impacts on the Finniss River. The critical review therefore presents a valuable case study of the environmental performance of uranium mine site rehabilitation.

1. Introduction

In the Australian mining industry, the former Rum Jungle uranium–copper project holds a special place for many reasons. It was the first project to commercially mine and export uranium for nuclear weapons in the 1950's, it was a major part of the post-war Northern Territory economy, it caused widespread ongoing environmental pollution which reached many kilometres downstream, it was among the first generation of polluting former mine sites to be rehabilitated in the 1980's and this was followed by a decade-long post-rehabilitation monitoring program. It is therefore possible to assess the pollution loads leaving the site prior to and following rehabilitation, providing a unique and important case study for such projects, especially the long-term effectiveness of rehabilitating former uranium mines. Although there are numerous papers on specific aspects of Rum Jungle, this paper seeks to synthesize all key data and information and analyse it holistically from an environmental perspective. The paper briefly reviews the Rum Jungle project, followed by a detailed compilation and critical evaluation of the available environmental monitoring data, giving a unique case study of the environmental performance of uranium mine site rehabilitation.

2. The Rum Jungle U–Cu project – a brief history

The Rum Jungle uranium–copper project (U–Cu) has been an important mining project in Australia, for many reasons as noted previously. This section is a brief history to understand the project, its subsequent rehabilitation and environmental monitoring.

The mineral potential of the 'Rum Jungle' region, just south of Darwin, had been noted since the original surveys by Goyder's team in 1869, primarily for Cu and gold (but nothing of economic interest was found) (Barlow, 1962). The name is believed to be derived from a bullock wagon of rum which was bogged in a swamp in 1871 on its way to the Pine Creek gold field, with the bullocky's then drinking the entire cargo – and the name of Rum Jungle has been used ever since (Barrie, 1982). Between 1906 and 1913 the area was evaluated for copper, but nothing of economic interest was discovered (Crohn, 1968). The region is located in the tropical wet-dry climate of northern Australia, shown in Fig. 1.

Following the advent of the nuclear weapons race from August 1945, the Australian Government vigorously promoted uranium (U) prospecting. In 1949, local pastoral owner and amateur prospector Jack White, reading the government pamphlet on U minerals, realised that the unusual green minerals from the bed of the Finniss River were most likely torbenite (they were clearly not Cu) (Annabell, 1971; Barrie, 1982; Raggatt, 1968). The potential significance was quickly realised, with the Australian government taking

* Corresponding author.
E-mail address: Gavin.Mudd@eng.monash.edu.au (G.M. Mudd).

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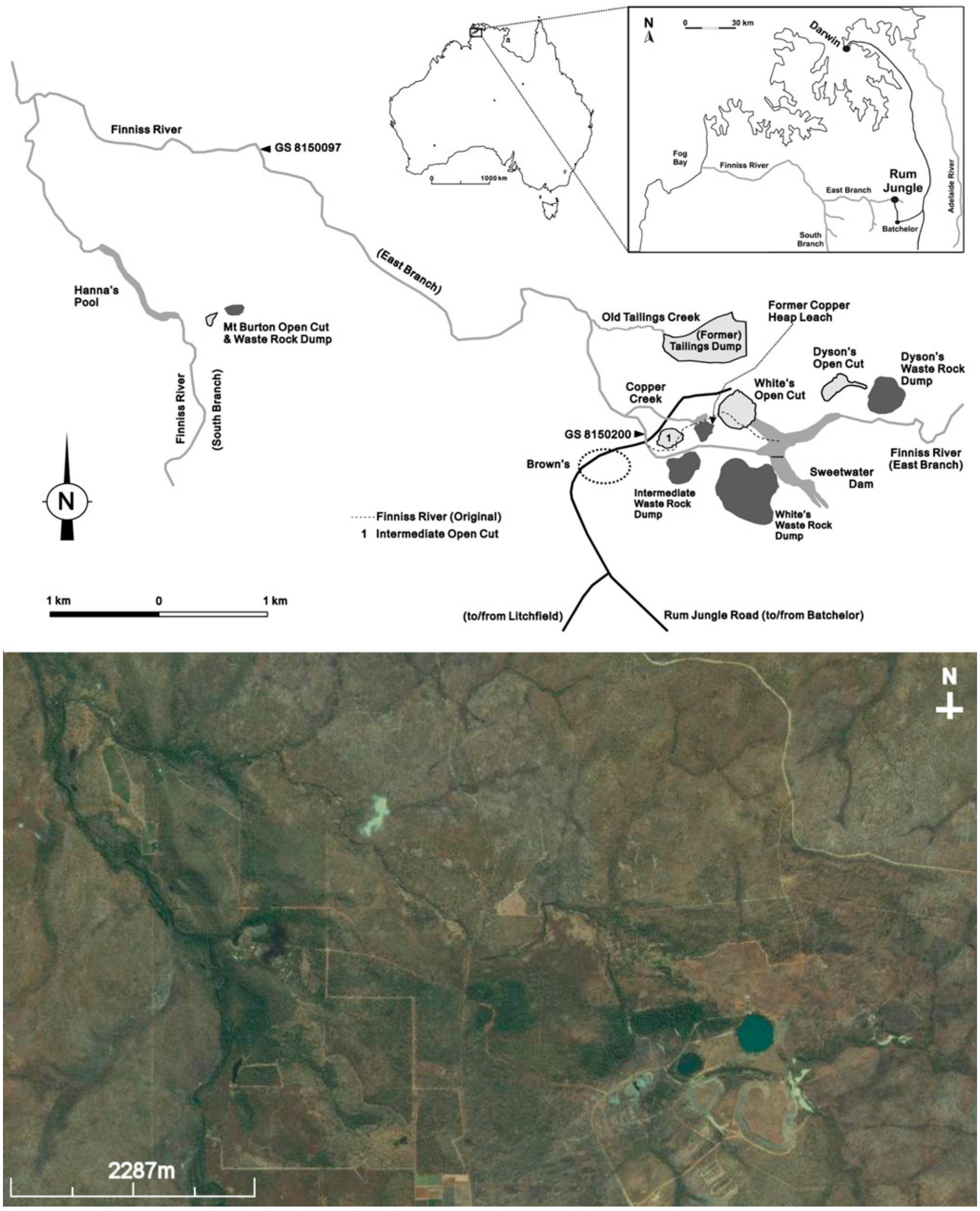

Fig. 1. Location and site map of the Rum Jungle U–Cu project, Northern Territory (top) (adapted from Pidsley, 2002); corresponding Google Earth image – date 7 June 2005 (bottom) (adapted from GE, 2009).

over in the 'national interest' (Lichaz and Myers, 1977). By late 1951 two modest U deposits were proven at White's (U–Cu) and Dyson's (U). In August 1952 U export arrangements were agreed to with the UK/USA, being for nuclear weapons, and the final contract was signed on 6 January 1953 (Gowing, 1974). The project was owned by the Australian Government, operated under contract by Consolidated Zinc (ConZinc, later to become CRA Ltd, now Rio Tinto Ltd) and was financed by the US–UK Combined Development Agency (CDA) (Griffiths, 1998). The project was considered a military project and was therefore regulated as a project of national security – not based on normal mining law and regulations (DNT, 1978; Rafferty, 1982).

After a difficult construction period, including switching from underground to open cut mining which necessitated a 1 km diversion of the Finniss River, the project was officially opened in September 1954 and produced its first uranium oxide (U_3O_8) (Cawte, 1992). The White's and Dyson's open cuts were completed by late 1958, with the mill processing stockpiled U and U–Cu ore as well as a small amount of purchased U ore. In 1959, exploration discovered the Rum Jungle Creek South (RJCS) U deposit, and this proved larger than White's and Dyson's combined (Berkman, 1968). The RJCS site was mined over 1961–63, and allowed processing to continue at Rum Jungle until 1971 with all U from RJCS stockpiled by the Australian Government.

The Intermediate Cu deposit adjacent to White's was mined by ConZinc over 1964–65 separate to the CDA contract and toll processed through the mill, plus an experimental Cu heap leach project (Fraser, 1979). The Brown's Pb–Cu–Ni–Co–Ag prospect was studied but abandoned as uneconomic due to low grades and difficult processing (the Brown's 'oxide' project was developed in 2008, mining oxide ore only, but went bankrupt in early 2009 due to the collapse of commodity prices; a major sulfide project could still be developed in the future). A compilation of relevant mining data is given in Table 1.

The Rum Jungle project was operated on a 'production' basis – environmental impacts were clearly not considered important (Lichaz and Myers, 1977). During the early years of operation (1954–61), tailings were discharged to a flat low-lying area (later known as 'Old Tailings Creek) adjacent to the mill, though the tailings proved highly erodible (Davy, 1975). About 1 million L/day of liquid effluent was discharged into the Finniss River, containing acids (pH 1.5), metals and radionuclides – at times liquid wastes would disappear into holes which opened up at the Cu cementation launders for several weeks, until the area was covered and later abandoned (see Davy, 1975). About 640,000 t of tailings was discharged and covered 35 ha, with some 10–25% of these tailings having been eroded by 1984 when rehabilitation was undertaken. In 1961, tailings were directed to the former Dyson's open cut and two small retention dams were built on the Finniss to store process liquors during the dry season, namely the Acid and Sweetwater dams. It was hoped that early wet season rains would generate sufficient flows for dilution – though later calculations in the 1970's showed this attempt at managing water impacts could never have worked. Tailings and liquid wastes were then directed to White's from 1965 to 71 with regular overflowing during the wet season.

Rum Jungle was a major source of environmental pollution for the Finniss River – due to tailings and liquid waste discharges but also due to the acid mine drainage (AMD) derived from the tailings but especially waste rock dumps (Richards et al., 1996). The scale of the problem was identified by the late 1950's but was ignored due to the political nature and perceived importance of the Rum Jungle project (Lichaz and Myers, 1977).

After closure in 1971, no major works were undertaken to reduce pollution and by the mid-1970's the Rum Jungle project was infamous for its extreme pollution, such as the absence of all biota for 15 km down the Finniss River and contamination of ~100 km^2 of floodplains (Davy, 1975). The environmental legacy of Rum Jungle was also a major issue during the Ranger Uranium Environmental Inquiry (Fox et al., 1977).

The Australian government conducted major rehabilitation works over 1982–86 costing some $18.6 million (Richards et al., 1996). The project was amongst one of the earliest in Australia to remediate an AMD site, with the primary objectives being: (i) reduction in Finniss River pollution loads (70% each for Cu–Zn, 56% for Mn); (ii) reduction in public health hazards (including radiation); (iii) reduction in pollution loads in White's and Intermediate open cuts; (iv) aesthetic improvements and revegetation (Allen and Verhoeven, 1986).

Although the RJCS site was ignored during the Rum Jungle rehabilitation program, as it was considered to have no major pollution problems, it was later found to present a public radiological exposure issue due to its popularity for recreational swimming. RJCS was then addressed with additional works in 1991 to cover the waste rock dump and achieve unrestricted public use of the site (see Kvasnicka et al., 1992).

Rum Jungle has been visited over 2004–2007, and clearly remains a major AMD pollution source to the Finniss River – despite the extent of rehabilitation works. It is in this context that the available environmental monitoring is presented, analysed and discussed. The site remains a critical case study, providing numerous insights into the effectiveness of mine rehabilitation – with particular relevance for uranium mining.

3. Geology and hydrogeology of the Rum Jungle region

The geology and hydrogeology of the Rum Jungle region is complex, with the most recent descriptions given by McKay and Miezitis (2001) and CR (2005), summarised herein.

Rum Jungle is on the western part of the Pine Creek Geosyncline, with regional geology comprising Palaeoproterozoic metasediments (low-grade greenschist facies) unconformably overlying Archaean granitic basement (the Rum Jungle Complex). Surficial rocks are often intensely weathered. The Giant's Reef Fault has caused some 4–5 km of displacement, leading to an embayment structure which is the location of most mineralised zones. Geologic cross-sections of White's, Dyson's, Intermediate and Rum Jungle Creek South are given by Fraser (1979).

The hydrogeology is comprised primarily of surficial weathered aquifers and underlying fractured rock aquifers of varying significance, shown in Fig. 2. Groundwater is found between 2 and 12 m from the surface, and varies with the wet-dry monsoonal climate, suggesting active recharge into unconfined aquifers and dynamic discharge processes such as transpiration or to surface water features (CR, 2005). Karstic solution features in dolomite are often present (e.g. liquid wastes were often known to vanish into solution features; see Davy, 1975). The extent of hydraulic connection between shallow and deep aquifers remains uninvestigated.

4. Rum Jungle rehabilitation project

Given the importance of Rum Jungle as a test case for AMD remediation in mining, a major environmental monitoring program was initiated after rehabilitation, running from 1986 until 1998. The

Table 1
Principal mining data for the Rum Jungle field.

Open cut	White's	Dyson's	Rum Jungle creek south	Intermediate copper	Mt Burton
Period	1953–Nov 58	1954–Nov 58	Apr 61–Aug 63	64–65	Oct–Nov 58
Volume	3,560,000 m^3	917,000 m^3	2,220,000 m^3	971,000 m^3	101,000 m^3
Surface Area	110,000 m^2	60,000 m^2	~110,000 m^2	50,000 m^2	–
U Ore	396,000 t[a]	156,000 t	663,000 t	–	6100 t
Grade	0.27% U_3O_8	0.341% U_3O_8	0.43% U_3O_8	–	0.21% U_3O_8
Contained U	1070 t U_3O_8	530 t U_3O_8	2850 t U_3O_8	–	12.8 t U_3O_8
Other Metals	2.7% Cu	–	–	–	1.04% Cu
Low-Grade Ore	*no data*	47,800 t, 0.077% U_3O_8	116,000 t[c], 0.066% U_3O_8	*no data*	3500 t, 0.072% U_3O_8 0.69% Cu
Waste Rock	~8,640,000 t[b] at ~0.004% U_3O_8 304,000 m^2 [b]	2,032,000 t, 84,300 m^2	4,877,000 t at ~0.018% U_3O_8 219,000 m^2	1,727,000 t at 0.005% U_3O_8, 0.2% Cu, 0.5% Pb	254,000 t at 32,800 m^2
Base Metal Ores	295,000 t at 2.8% Cu, 0.3% Co, and 87,000 t at 5.1% Pb, 0.8% Cu, 0.3% Co[d]	–	–	907,000 t at 2.2% Cu	1400 t at 2.66% Cu

[a] Some 102 t of 0.178% U_3O_8 ore was also mined from Whites Extended in late 1958, in between White's and Dyson's.
[b] Approximate only, White's data is based on estimates of overburden to ore ratios, alternative heap volumes and references cited; includes former Whites North heap (removed during rehabilitation).
[c] Trucked to Rum Jungle for milling 1969–1971.
[d] Lead ore was not processed and was buried during rehabilitation.
References: AAEC (1963), Barlow (1965), Berkman (1968), CG (1988), Davy (1975), DNT (1978), Fraser (1979).

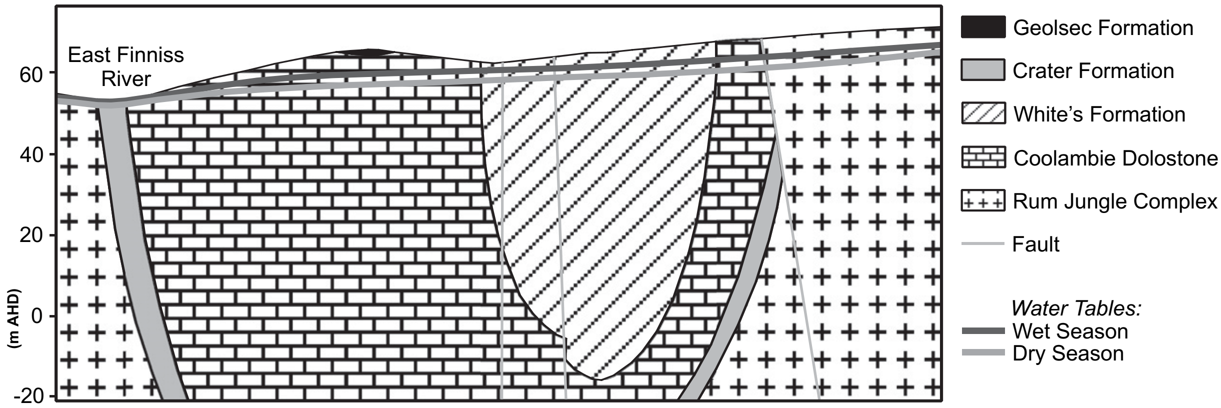

Fig. 2. Conceptual hydrogeologic cross-section of Brown's area, Rum Jungle (adapted from CR, 2005).

data and associated analysis of results are contained in Allen and Verhoeven (1986), Kraatz and Applegate (1992), Kraatz (1998) and Pidsley (2002), with pre-rehabilitation environmental studies given by Davy (1975).

4.1. Rehabilitation measures (1982–86)

The Rum Jungle rehabilitation program from 1982 to 1986 was primarily aimed at reducing the metal loads reaching the Finniss River, as well as reducing public hazards. Specific components included: excavation of remnant tailings and the Cu heap leach pile for deposition into and backfilling of Dyson's open cut, re-contouring of waste rock dumps and construction of engineered soil covers to limit infiltration and AMD generation, treatment of polluted waters in White's and Intermediate open cuts, rehabilitation of the former mill and stockpile areas, and partial re-diversion of the East branch of the Finniss River and removal of the Acid and Sweetwater Dams.

4.2. Environmental monitoring (1986–1998)

Environmental monitoring was undertaken during rehabilitation works and for some 12 years afterwards, including surface water hydrology and water quality, groundwater, biodiversity (e.g. fish or macroinvertebrate surveys), waste rock dump hydrology, and sediment analyses. Sampling and analytical methodology are detailed in the four principal reports (see earlier). All results presented below are derived from these reports (unless otherwise noted). Some additional data has been included from subsequent research work (years 1998/99 to 2000/01).

No pre- and post-rehabilitation radon or gamma surveys are available, despite recommendations of the need for such assessments (see Pidsley, 2002).

The primary point for determining the effectiveness of the rehabilitation project in reducing metal loads in surface waters was set as GS8150097 (~5.6 km downstream, see Fig. 1). Monitoring has been reported as both concentration and load data, usually including metals, sulfate and pH. Analytical methods have evolved over time, such as early years being totals only, while later years included total and dissolved metals. Furthermore, the majority of water quality samples were composites taken by the auto-sampler based on pre-set flow stage levels. Despite U being a critical issue, it has commonly not been included in routine water quality analyses for all wet seasons. Similarly, radium (^{226}Ra) was only monitored for the first two wet seasons after rehabilitation.

5. Monitoring results

5.1. Open cuts

White's open cut (OC) remains a major source of pollutants, with Intermediate OC minor only. A water quality profile of White's OC is given in Table 2, and clearly shows the more polluted waters at depths below 30 m. It is considered that White's OC is still contributing some 2–3 t Cu per wet season at GS8150097. The Intermediate OC appears to be maintaining reasonable water quality with respect to rehabilitation targets, though data is very sparse.

On Dyson's OC, which was completely backfilled and covered with an engineered soil cover, dieback of surface vegetation was

Table 2
Water quality profile of White's open cut, April 1998 (data from Pidsley, 2002).

Depth	pH	DO	E.C.	Ca	Mg	SO_4	Cu	Mn	Zn	Ni	Fe	Al
m	–	mg/L	μS/cm	all mg/L								
0	6.8	6.6	157	4	13	61	0.1	0.31	0.04	0.06	0.46	0.09
5	6.5	5.9	172	–	–	–	0.1	0.34	0.05	0.06	0.44	0.13
10	6.1	5.3	110	3	8	41	0.1	0.32	0.03	0.06	0.35	0.18
15	5.7	5.2	115	–	–	–	0.1	0.46	0.04	0.06	0.19	0.13
20	5.4	5.5	151	6	11	64	0.2	0.74	0.04	0.09	0.06	0.13
25	5.4	5.4	171	–	–	–	0.2	0.78	0.05	0.08	0.07	0.14
30	4.4	4.6	274	12	20	137	0.8	2.45	0.11	0.23	0.13	1.88
31	4.1	3.6	458	–	–	–	1.3	4.42	0.18	0.37	0.21	5.2
32	3.7	0.1	993	–	–	–	3.1	17.65	0.42	1.01	0.87	14.8
33	3.8	0	7168	–	–	–	54	244	5.49	18.55	378	215
34	3.8	0	7478	–	–	–	60	269	7.4	16.7	404	226
35	3.8	0	7558	481	902	8270	62	254	7.75	19	420	236

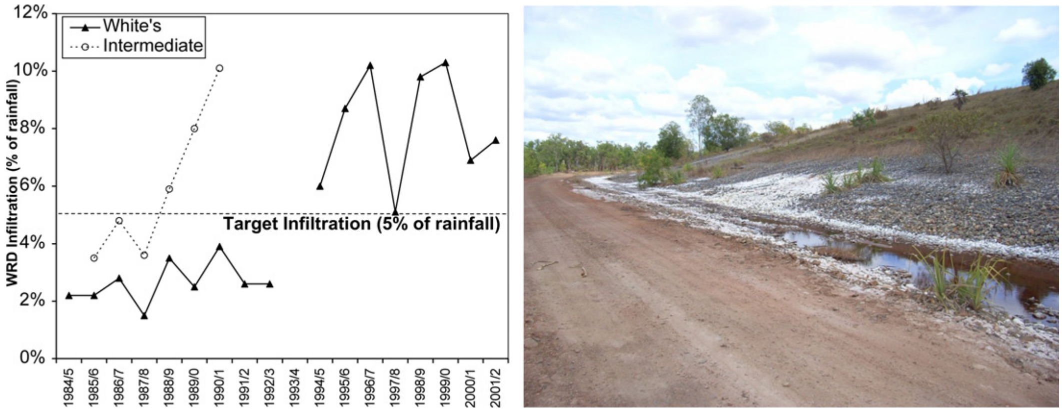

Fig. 3. Waste rock dump infiltration: monitored infiltration rate (left) (Kraatz and Applegate, 1992; Taylor et al., 2003), White's WRD in July 2007 (right) – note the active seepage flow and characteristics (photo G M Mudd).

noticed within 5 years of rehabilitation (Menzies and Mulligan, 2000). The main reasons for the dieback were found to be capillary action, pulling moisture and the underlying acidic leachate from mine waste up through the cover, as well as inadequate cover design in not including a capillary break layer and, finally, poor construction giving thin covers and/or erosion problems (Pidsley, 2002).

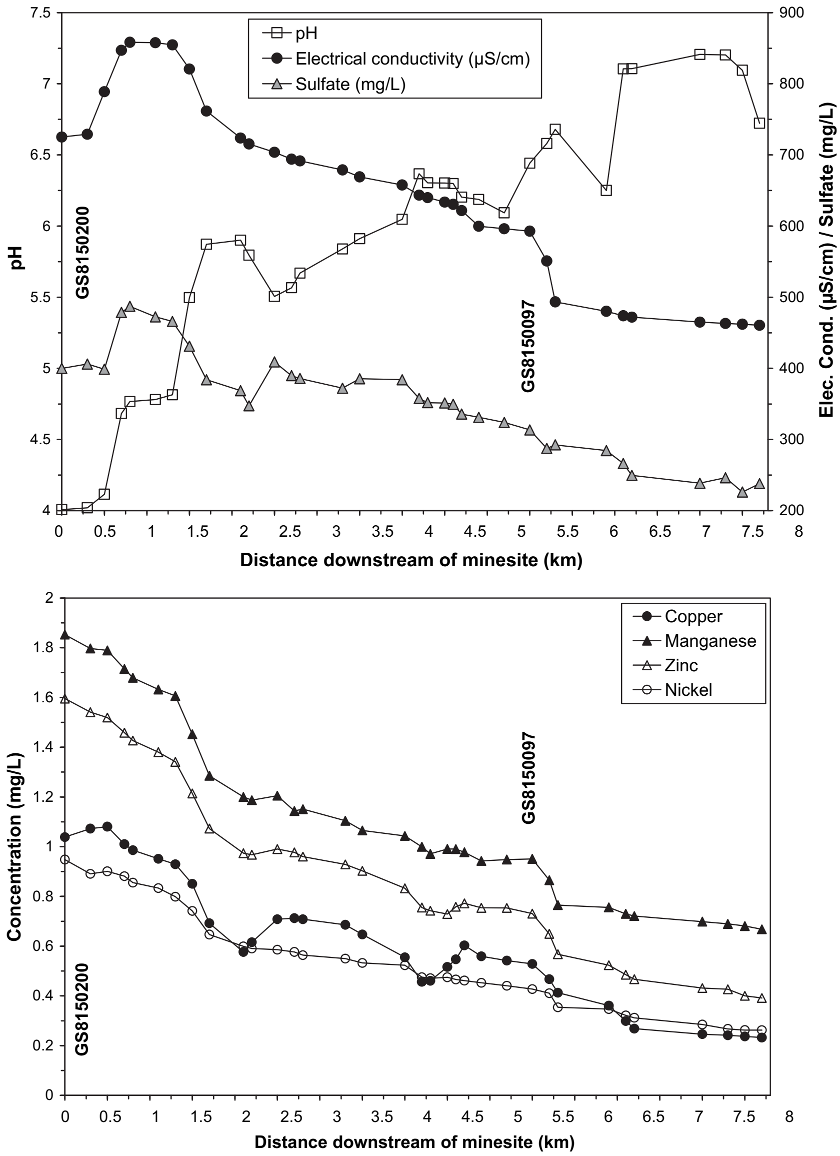

Fig. 4. Profile of Finniss River water quality downstream from Rum Jungle (22 April 1994) (data from Pidsley, 2002).

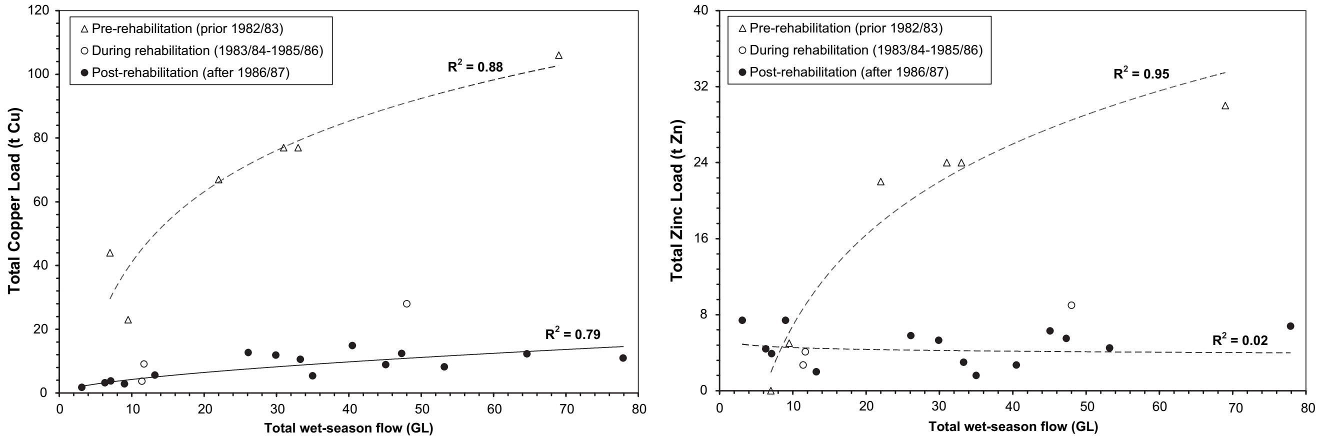

Fig. 5. Cu–Zn loads in Finniss River at GS8150097 before, during and after rehabilitation (data compiled from Davy, 1975; Kraatz, 1998; Kraatz and Applegate, 1992; Pidsley, 2002).

5.2. Waste rock dumps

The infiltration target for soil covers over WRD's was set at 5% of incident rainfall (compared to ∼50% previous; Menzies and Mulligan, 2000; Richards et al., 1996). Although there have been significant problems with the lysimeters used to monitor infiltration, including failure of several lysimeters and wicking leading to inaccurate infiltration monitoring (Taylor et al., 2003a), the available monitoring data showed good performance initially (ie. <5%), followed by a gradual increase in estimated infiltration, as shown in Fig. 3. This is considered to be related to the fact that during the dry season the clay soil cover dries and cracks, leading to increasing infiltration and re-emergence of AMD generation in subsequent seasons (Lottermoser, 2007). Internal convection due to temperature gradients can also be important in understanding oxidation rates in the WRD's at Rum Jungle (Kuo and Ritchie, 1999). Similarly to Dyson's OC, there are also areas of White's WRD where the soil cover was constructed too thin (Pidsley, 2002).

Recent visits to the Rum Jungle site clearly show that significant infiltration rates must still be occurring, as seepage flows from White's WRD can be seen throughout the dry season (photo included in Fig. 3). Although direct sampling and analysis of this water is not available, it is known to contain U from 1 to 8 mg/L (pers. comm., Brown, 2002). It is abundantly clear that the WRD's continue to act as major pollutant sources for the Finniss River.

5.3. Surface water

Only a brief examination of hydrologic and surface water quality data is possible herein, and so only key data is presented. The results of a Finniss River water quality profile are shown in Fig. 4, with metal loads for Cu and Zn shown in Fig. 5. A comparison of water quality at GS8150097 with current guidelines is given in Table 3.

There is clearly seasonal behaviour in metal concentrations and loads (Table 3). To further illustrate this, typical maximum concentrations in the first flush waters of the early wet season are compiled and shown in Fig. 6. Smaller wet season flows lead to higher concentrations, with a gradual decline over time. Additional photos of the former Sweetwater Dam are given in Fig. 7.

5.4. Groundwater

Groundwater remains the least monitored and investigated environmental component of the Rum Jungle site. Although some monitoring and assessment has been undertaken, the latter stages of the monitoring program did not include groundwater (see Pidsley, 2002). It is important to note that there was no remediation of contaminated groundwater during the rehabilitation project, despite it being identified as heavily polluted and an ongoing source of pollutants into the Finniss River.

The recent failed development of the Brown's oxide mine did not sufficiently address groundwater issues on the Rum Jungle site during its environmental assessment, thereby missing an important opportunity to further scientific understanding of groundwater behaviour, possible pollutant stratification, groundwater-surface water relationships and so on.

The available groundwater monitoring data, shown in Fig. 8, suggests a linear relationship between pollutant concentrations and EC, with Cu and sulfate generally extremely high. Given the nature of AMD, this relationship can be expected.

Table 3
Summary of GS8150097 water quality during the 1992/93 wet season, compared to and current water quality guidelines (data from Kraatz, 1998).

	mg/L			μg/L									
	Al	Ca	Fe	As	Co	Cr	Cu	Mn	Ni	Pb	Th	U	Zn
Average	3.6	9.9	1.7	4.1	176	5	**485**	860	**169**	**76**	3.3	**33**	**209**
Minimum	0.21	4.2	0.096	0.6	53	0.7	**180**	430	**53**	**2**	0.02	**6**	**49**
Maximum	9	29	14	41	480	33	**1 100**	2000	**430**	**880**	26	**63**	**670**
ANZECC [a]	ND	ND	ND	14	ND	1[b]	1.4	1900	11	3.4	ND	6[c]	8

ND – not determined.
[a] Water quality values based on 95% species protection for fresh waters (ANZECC and ARMCANZ, 2000).
[b] Value is for Cr^{6+} only.
[c] Value is from the operating Ranger uranium project (Note: a low reliability value of 0.5 μg/L is given by ANZECC and ARMCANZ (2000), due to insufficient ecotoxicological testing. The Ranger value is based on additional local species testing; see van Dam et al., 2002).

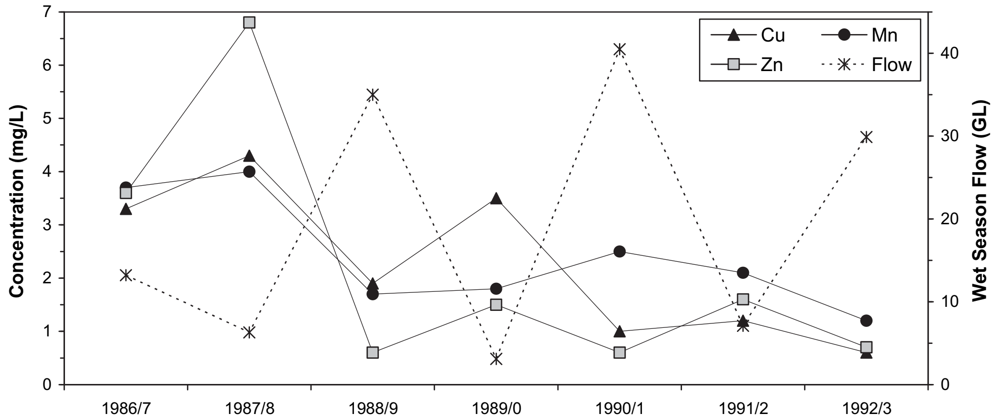

Fig. 6. First flush (early wet season) metal concentrations and total wet season flows (data from Kraatz, 1998; Kraatz and Applegate, 1992).

5.5. Sediments

Concentrations of metals in streambed sediments have been examined, though only at specific times for a Finniss River profile. Some data has been obtained for sediment quality, while other data was obtained during ecological studies. The sediment data, Table 4, clearly shows the essentially background concentrations upstream compared to elevated levels downstream.

5.6. Biodiversity

The biodiversity in the Finniss River has been studied in the 1970's and again following rehabilitation works, mainly through fish diversity and abundance surveys and macroinvertebrate species and diversity studies (including benthic surveys and pollutant bioavailability and archival studies in mussels).

The original 1970's surveys established that the Finniss River immediately downstream of Rum Jungle was largely devoid of biota, with the first flush of wet season rains being particularly polluting. Following rehabilitation works, various biodiversity surveys have established a return of biota to the East Branch, with apparently lower overall bioavailable metal loads. In addition, recent research on Cu ecotoxicity to black-banded rainbow fish (*Melanotaenia nigrans*) from the Finniss River has suggested an evolving Cu tolerance to the mine leachates still emanating from the site (Gale et al., 2003) – though this is not exactly sound evidence of a sustainable ecosystem. Although biodiversity surveys suggest some measure of success, this has to be moderated with the significant physical and chemical evidence of ongoing pollutant generation and release (e.g. Figs. 3 and 7).

6. Discussion

The Rum Jungle rehabilitation project has been a critical case study on AMD pollution and remediation, especially for U mining. There is a common belief that the legacy of the Rum Jungle project has been addressed and rehabilitated satisfactorily (perhaps people who have not visited the site in recent years). The above review of the rehabilitation project and associated monitoring data raises a significant number of issues.

Despite the extent of reported monitoring and studies, critical gaps remain in facilitating a more holistic and accurate picture of the ongoing pollution cycle at Rum Jungle. Samples upstream of the site are extremely rare, with the only known data being that obtained for biodiversity surveys – despite being a very common design in environmental monitoring and impact assessment studies. Sampling and monitoring is often insufficient in spatial and temporal scale to allow an accurate whole-of-site mass balance to be assessed, meaning pollutant load accounting from primary source terms is difficult or impossible. Since most water quality samples were actually composites and not grab samples, the true peaks in concentrations are not known – which are critical in understanding potential biological impacts. It can be expected that the first rains of the wet season would give rise to extremely high concentrations of salts and metals given the loads on the bed of the Finniss River (see Fig. 7). Overall, this leads to the conclusion that

Fig. 7. Former Sweetwater Dam, July 2007; Note – the water and flow in the left photo is continuing seepage from White's waste rock dump (see Fig. 3) (photo's G M Mudd).

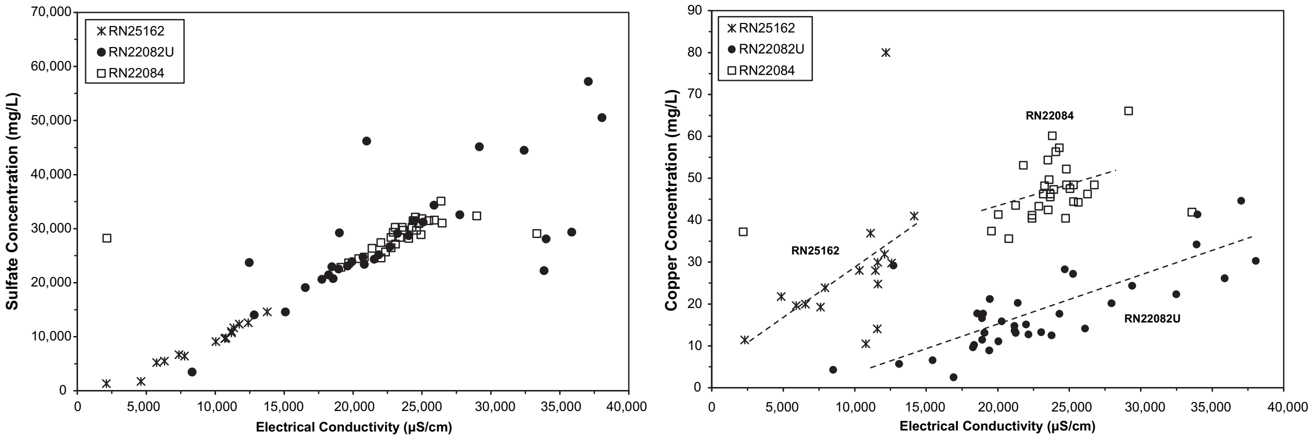

Fig. 8. Sulfate (left) and Cu (right) concentrations versus electrical conductivity in 3 bores in the vicinity of White's waste rock dump (dashed lines indicative only) (data compiled from Kraatz, 1998; Kraatz and Applegate, 1992).

environmental monitoring was not robust in its design to allow accurate pollutant accounting, especially with respect to sources and cycles.

In addition, there is possible groundwater discharge ~0.5–1 km downstream of GS8150200 (Fig. 4), potentially explaining spikes in sulfate and Cu. Groundwater remains heavily contaminated and is very likely to be contributing to major pollutant loads in surface waters along with loads derived from White's OC and all WRD's. There is historic evidence of preferrential flowpaths through the dolomite sequence (e.g. acid liquors), as well as concerns over stratification of pollutants in groundwater.

The radiological characterisation and assessment of the site remains poor, despite clear evidence of extreme U concentrations in seepage from White's WRD and accumulated U in Finniss River sediments (Table 4). Further work is required to address gamma, radon and progeny exposures, especially for members of the public.

The issue of design and construction of soil covers is critical, since this is now the most widely used approach to managing and rehabilitating sulfidic mine wastes (e.g. Taylor and Pape, 2007). The experience at Rum Jungle shows that more robust cover designs are required which allow for a capillary break layer as well as a greater ability to maintain saturation throughout the full range of climatic conditions, especially in the wet–dry tropics. Unlike the cover design, however, poor construction quality (ie. thin covers) cannot be considered acceptable – especially given the public prominence of the project.

The final and perhaps most critical issue of all, is that rehabilitation targets were only set based on expected pollutant load reductions – not on achieving salt and metal concentrations which would lead to sustained recovery of aquatic biodiversity. The fact that fish, for example, are being forced to adapt to higher Cu concentrations should not be interpreted as a healthy ecosystem. By comparing water quality to the current guidelines (Table 3), several metals are in excess by up to two orders of magnitude (e.g. Cu, Ni, U, Zn). To achieve a long-term and stable recovery in ecosystem health, the water quality targets should be based on ecological toxicity, as per (ANZECC and ARMCANZ, 2000).

The current environmental status of the former Rum Jungle project clearly requires further remediation works. During the 1980's, the option of excavating waste rock and emplacement in open cuts was ruled out on cost grounds. In light of continuing and growing acid drainage problems from rehabilitated waste rock dumps, however, this must be re-assessed. By placing the sulfidic waste rock in the open cuts, a large proportion of the waste would be below the water table – thereby limiting further oxidation and pollutant generation. This strategy is now well recognised, and has been implemented in the rehabilitation of waste rock at the former Ronneburg open pit uranium mine in eastern Germany (Hagen and Jakubick, 2005), as well as other sulfidic mine wastes in gold or base metal mining (e.g. former Woodcutters lead–zinc mine, 25 km east of Rum Jungle).

Another major aspect of future rehabilitation would be improved soil cover design, construction and monitoring. At Rum Jungle, no capillary break layer was included in the original design – though these are now recognised as an important component of soil cover designs in limiting oxidation rates and AMD generation

Table 4
Sediment quality profile along the Finniss River (East Branch), compared to current sediment quality guidelines (mg/kg dry weight) (data from Pidsley, 2002).

Distance From Rum Jungle (km)		Ba	Cd	Co	Cu	Fe	Mn	Ni	Pb	U	Zn
Upstream	−18	58	0.05	5	17	5454	101	5	16	4	<DL
	−0.2	65	0.04	11	30	9221	230	5	15	2	<DL
	−0.01[a]	77	0.3	7	33	4326	201	3	10	3	<DL
Downstream	4	76	0.3	269	**3 643**	12,284	582	**371**	**127**	129	**1 896**
	8	84	0.35	193	**1 061**	8426	209	**191**	**138**	45	**1 748**
	11	58	0.22	202	**404**	10,510	551	**98**	37	17	112
SQG low[b]		ND	1.5	ND	65	ND	ND	21	50	ND	200
SQG high[b]		ND	10	ND	270	ND	ND	52	220	ND	410

<DL – less than detection limit. ND – not determined.
[a] On upstream junction of East Branch with the Rum Jungle site.
[b] For the sediment quality guidelines (SQG), 'low/high' means low/high probability of biological effects (that is, 'high' values would give rise to effects) (ANZECC and ARMCANZ, 2000).

(partly as a result of failures such as Rum Jungle). Furthermore, the materials used for soil covers at Rum Jungle were inadequate to meet the original design specifications (Taylor et al., 2003b). It is therefore critical that strict criteria be established for soil cover design and materials, and they be met during construction without compromise to ensure longevity in performance.

The final major area of future rehabilitation requirements is polluted groundwater. This is perhaps the most complex and difficult aspect, since very little is known and understood about these contaminant pathways. Possible approaches could include pump and treat systems, permeable reactive barriers or in-situ treatment (especially sulfate reduction techniques), with possible recovery of metals to generate revenue during treatment. Further research is required in this area.

In May 2009, the Australian government allocated $8.3 million over four years to "… support the environmental management and monitoring of the Rum Jungle former uranium mine site" (pp. 5, DEWHA, 2009). A key aim of this work is to underpin future decisions regarding potential rehabilitation, as well as linking this to activities at the failed Brown's Oxide project.

7. Conclusion

The former Rum Jungle mine remains a polluting site – as evidenced by the range of available monitoring data and recent site inspections. Annual pollutant loads remain 4–12 t Cu, 3–7 t Zn and 1250–4800 t sulfate – although they could be seen as meeting rehabilitation objectives, they are clearly ecologically significant metal loads, especially at their average and potential true peak concentrations. Given that groundwater remains contaminated and waste rock dump infiltration is increasing, pollutant loads into the Finniss River can be expected to intensify in the future. The Rum Jungle U–Cu site, despite significant effort, has not met the test of time and remains an important case study to assess the effectiveness of rehabilitation of major AMD-polluting sites, especially former uranium mines.

References

AAEC, 1963. Rum Jungle Project: a Report on the Uranium Mining and Treatment Industry Established by the Commonwealth Government at Rum Jungle, and Its Contribution to the Development of Northern Australia. Australian Atomic Energy Commission (AAEC), Lucas Heights, NSW, p. 16.

Allen, C.G., Verhoeven, T.J. (Eds.), 1986. The Rum Jungle Rehabilitation Project – Final Project Report. NT Department of Mines & Energy (NTDME) for the Commonwealth Department of Resources & Energy (DPIE), Darwin, NT, p. 362.

Annabell, R., 1971. The Uranium Hunters. Rigby, Sydney, NSW, p. 277.

ANZECC, ARMCANZ, October 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy, Australian & New Zealand Environment & Conservation Council (ANZECC) and Agricultural & Resource Management Council of Australia & New Zealand (ARMCANZ), Canberra, ACT.

Barlow, T., 1962. Rum Jungle. Uranium in Australia – A Collection of Articles on the History and Development of the Uranium Mining Industry in Australia. Australian Atomic Energy Commission (AAEC), Coogee, NSW, pp. 29–35.

Barlow, T., 1965. Rum Jungle. In: Proc.. "8TH Commonwealth Mining & Metallurgical Congress". AusIMM, pp. 211–216 (Chapter 9).

Barrie, D.R., 1982. The Heart of Rum Jungle: The History of Rum Jungle and Batchelor in the Northern Territory. S & D Barrie, Batchelor, NT, p. 279.

Berkman, D.A., June 16–21, 1968. The geology of the rum jungle uranium deposits. In: Proc. "Symposium on Uranium in Australia". Rum Jungle Branch, Australasian Institute of Mining & Metallurgy (AusIMM), Rum Jungle, NT, pp. 12–31.

Brown, P., September 2002. Personal Communication. Freiberg, Germany.

Cawte, A., 1992. Atomic Australia 1944–1990. UNSW Press, Kensington, NSW, p. 226.

CG, 1988, Rehabilitation proposals for abandoned uranium mines in the northern territory. In: Prepared by Construction Group (CG) for Commonwealth Department of Administrative Services on Behalf of Department of Primary Industries & Energy (DPIE), Canberra, ACT, April 1988, p. 114.

CR, November 2005, Browns Oxide Project – Public Environmental Report. In: Prepared by Enesar Pty Ltd for Compass Resources Ltd (CR), Hawthorn East, Victoria.

Crohn, P.W., 1968. Bulletin 82. The Mines and Mineral Deposits of the Katherine-Darwin Region, vol. 2. Bureau of Mineral Resources, Canberra, ACT, pp. 171–295.

Davy, D.R. (Ed.), 1975. Rum Jungle Environmental Studies. Australian Atomic Energy Commission (AAEC), Lucas Heights, NSW.

DEWHA, 12 May 2009. Environment Budget Overview 2009–10. Department of the Environment, Water, Heritage and the Arts (DEWHA), Australian Government, Canberra, ACT.

DNT, April 1978. Rehabilitation at Rum Jungle: Report of the Working Group. Department of the Northern Territory (DNT), Darwin, NT, p. 117.

Fox, R.W., Kelleher, G.G., Kerr, C.B., 17 May 1977. Ranger Uranium Environmental Inquiry – Second Report. Australian Government, Canberra, ACT, p. 415.

Fraser, W.J., June 4–8, 1979. The geology and exploration of the Rum Jungle uranium field. In: Proc. "International Symposium on Uranium in the PineCreek Geosyncline". International Atomic Energy Agency (IAEA), Bureau of Mineral Resources, Geology & Geophysics (BMR) and Institute of Earth Resources, Commonwealth Scientific & Industrial Research Organisation (CSIRO), Sydney, NSW, pp. 287–298.

Gale, S.A., Smith, S.V., Lim, R.P., Jeffree, R.A., Petocz, P., 2003. Insights into the mechanisms of copper tolerance of a population of black-banded rainbowfish (*Melanotaenia nigrans*) (Richardson) exposed to mine leachate, using 64/67Cu. Journal of Aquatic Toxicology 62 (2), 135–153.

GE, 2009. Google Earth. Google Earth (GE). http://earth.google.com/.

Gowing, M., 1974. Independence and Deterrence: Britain and Atomic Energy, 1945–1952. In: Policy Making, vol. I. Macmillan Press, London, UK.

Griffiths, M., 1998. Of Mines and Men: Australia's 20th Century Mining Miracle 1945–1985. Kangaroo Press, East Roseville, NSW, p. 200.

Hagen, M., Jakubick, A.T., 2005. Returning the WISMUT legacy to productive use. In: Proc. "Uranium Mining and Hydrogeology IV (UMH-4) – 4th International Conference". Springer, Freiberg, Germany, 11–16 September 2005, pp. 11–26.

Kraatz, M. (Ed.), 1998. Rum Jungle Rehabilitation Project Monitoring Report 1988–93. Land Resources Division, NT Dept. of Lands, Planning & Environment (NTDLPE), Palmerston, NT, p. 180.

Kraatz, M., Applegate, R.J. (Eds.), 1992. Rum Jungle Rehabilitation Project Monitoring Report (1986–88). Land Conservation Unit, Conservation Commission of the Northern Territory (CCNT), Darwin, NT, p. 298.

Kuo, E.Y., Ritchie, A.I.M., 1999. The impact of convection on the overall oxidation rate in sulfidic waste rock dumps. In: Proc. "Mining and the Environment II". Centre in Mining and Mineral Exploration Research, Laurentian University, Sudbury, Ontario, Canada, pp. 211–220.

Kvasnicka, J., Li, C.-C., Robinson, R., 1992. Rum Jungle Creek South Abandoned Uranium Mine: Radiation Fields before, during and after the Site Rehabilitation. Mines Environment Directorate, NT Department of Mines & Energy, Darwin, NT, Environmental Technical Report 92/2, p. 18.

Lichaz, W., Myers, S., 1977. Uranium mining in Australia. In: Elliott, M. (Ed.), Ground for Concern – Australia's Uranium and Human Survival. Penguin, Melbourne, VIC, pp. 25–63.

Lottermoser, B., 2007. Mine Wastes – Characterisation, Treatment, Environmental Impacts, second ed. Springer-Verlag, Berlin, Germany, p. 291.

McKay, A.D., Miezitis, Y., 2001. Australia's Uranium Resources, Geology and Development of Deposits. Geoscience Australia (GA), Canberra, ACT, p. 210.

Menzies, N.W., Mulligan, D.R., 2000. Vegetation dieback on clay-capped pyritic mine waste. Journal of Environmental Quality 29 (2), 437–442.

Pidsley, S.M. (Ed.), 2002. Rum Jungle Rehabilitation Project Monitoring Report 1993–1998. NT Dept. of Infrastructure, Planning & Environment (NTDIPE), Palmerston, NT, p. 247.

Rafferty, P.J., 1982. Licensing and Regulation of Uranium Mining and Milling 1944–1981. School of Nuclear Engineering, University of New South Wales (UNSW), Kensington, NSW, p. 284.

Raggatt, H.G., 1968. Mountains of Ore: Mining and Minerals in Australia. Lansdowne Press, Melbourne, VIC, p. 416.

Richards, R.J., Applegate, R.J., Ritchie, A.I.M., 1996. The Rum Jungle rehabilitation project. In: Mulligan, D.R. (Ed.), Environmental Management in the Australian Minerals and Energy Industries: Principles and Practices. UNSW Press & Australian Minerals and Energy Environment Foundation (AMEEF), Sydney, NSW, pp. 530–553.

Taylor, G., Spain, A., Nefiodovas, A., Timms, G., Kuznetsov, V., Bennett, J., July 2003a. Determination of the Reasons for Deterioration of the Rum Jungle Waste Rock Cover. Australian Centre for Mining Environmental Research (ACMER), Brisbane, QLD, p. 119.

Taylor, G., Spain, A., Timms, G., Kuznetsov, V., Bennett, J., July 2003b. The medium-term performance of waste rock covers – Rum Jungle as a case study. In: Proc. "Sixth International Conference on Acid Rock Drainage (6th ICARD)". Australasian Institute of Mining & Metallurgy (AusIMM), Cairns, Queensland, pp. 383–397.

Taylor, J., Pape, S. (Eds.), 2007. Managing Acid and Metalliferous Drainage. Leading Practice Sustainable Development Program for the Mining Industry. Commonwealth Department of Industry, Tourism and Resources, Canberra, ACT, p. 107.

van Dam, R.A., Humphrey, C.L., Martin, P.C., 2002. Mining in the Alligator rivers region, Northern Australia: assessing potential and actual effects on ecosystem and human health. Toxicology, 181–182, pp. 505–515.