Uranium mill tailings in the Pine Creek Geosyncline, northern Australia : past, present and future hydrogeological impacts

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Abstract. Uranium mining has been a principal part of Northern Australia since mineralisation was discovered at Rum Jungle in 1949. To date, 5 mills have operated at Rum Jungle, Rockhole, Moline, Ranger and Nabarlek supported by 27 adjacent or other NT mines. The tailings management at 1950s mills was through discharge to adjacent lowlands with in-pit tailings at Rum Jungle in the 1960s. Due to higher environmental expectations in modern times, Ranger and Nabarlek have used in-pit plus above ground interim storage of tailings. The environmental and hydrogeological impacts of these sites is reviewed.

Uranium mining history in the Pine Creek Geosyncline

The identification of uranium minerals at Rum Jungle in August 1949 heralded the start of a long history of uranium mining and milling in the Pine Creek Geosyncline, at the top of the Northern Territory (NT), Australia (Fig. 1). The geology is described in Ferguson and Goleby (1979) and Needham and De Ross (1990).

The 1950s saw a major mining and milling project at Rum Jungle, with additional ore sourced small mines across the NT. In the South Alligator Valley, 12 U mines were operated to support the Rockhole and Moline mills. Exploration in the early 1970s led to the discovery of new U deposits at Ranger, Jabiluka, Nabarlek and Koongarra. Due to community concerns, only the Ranger and Nabarlek projects were developed and operating by the early 1980s.

The main issues relating to uranium tailings management are climatic extremes (wet/dry), radon, permeable carbonate units and/or fractures in groundwater flowpaths and links from shallow aquifers to surface water systems (Mudd 2002).

The approach to tailings management has developed together with improved scientific knowledge of their associated hazards, such as gamma radiation, radon flux, erosion, heavy metal and water quality impacts (Mudd, 2002). The impacts from these sites will be reviewed (data in Table 1), thereby developing thematic issues for uranium mill tailings management in northern Australia.

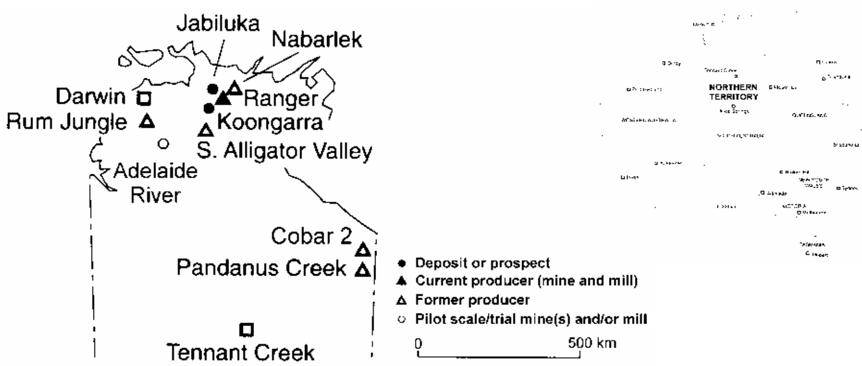

Fig. 1. Location of uranium projects in the Northern Territory, Australia

Table 1. Uranium mill tailings and waste data, Pine Creek Geosyncline (Mudd 2000, 2002)

	Rum Jungle	Moline	Rockhole	Nabarlek	Ranger [a]
Mill operating	1954-71	1956-64	1959-62	1980-88	1981-??
Ore milled (t)	1.50 Mt [b]	135,444 [b]	13,418	0.76 Mt [c]	22.91 Mt
Waste rock (Mt)	14.28	??	??	2.3	88.68
U_3O_8 t Produced	3,530	716	139.7	10.955	65,468
U_3O_8 Ore (%)	0.32%	0.46%	1.11%	1.84%	0.319%
U_3O_8 Tail's (%)	0.086%	0.065%	0.048%	0.034%	0.033%
Ore (Bq/kg)	488,868	689,272	1,672,769	2,772,878	480,696
Tail's (Bq/kg)	438,127	605,969	1,447,014	2,389,005	419,957
Initial (Bq)	$6.6x10^{14}$	$8.2x10^{13}$	$1.9x10^{13}$	$1.4x10^{15}$	$9.6x10^{15}$
Tail's (Bq/kg) ^{226}Ra	33,686	47,495	115,264	191,068	33,123
Tail's (Bq/kg) 10^3 yrs	383,519	517,447	1,209,639	1,985,616	355,879
Tail's (Bq/kg) 10^6 yrs	128,879	98,466	71,916	49,903	49,983

[a] data to March 31, 2002. [b] not including 1.11 Mt / 152,600 t of base metal ores milled.
[c] includes 157,000 t of low grade ore heap leached (not included in radioactivity calc's).

Rum Jungle uranium/copper project

The Rum Jungle U/Cu project was developed between its discovery in 1949 and 1954 when commercial operations began. All uranium was sold to the Combined Development Agency for the USA-UK nuclear weapons programs until 1963. The project was owned by the Commonwealth Government through the Australian Atomic Energy Commission (AAEC), with the project being operated on a special contract by a dedicated subsidiary of CRA Ltd (now Rio Tinto Ltd). The uranium produced from 1963-71 was stockpiled by the AAEC in Sydney, NSW.

The area was discovered to contain several small to moderate U deposits, with base metal ores (Cu, Pb) often present (about 20,000 t Cu was produced). Mining data for all deposits is given in Mudd (2002). Rum Jungle also processed custom ores from numerous small U mines across the NT.

The Rum Jungle site has become a major source of acid mine drainage pollution of the Finniss River system to the west, with significant quantities of radium and heavy metals (eg. Cu, Mn, U, Zn) impacting an area of some 100 km^2 (Kraatz 1998). The ore and waste rock contained about 3% sulfides (Richards et al. 1996).

Between 1954-61 tailings were discharged onto lowlands adjacent to the mill, later known as Old Tailings Creek, and proved to be highly erodible (Richards et al. 1996). About 1 million L of liquid wastes were discharged daily, at a pH of 1.5 containing heavy metals and radionuclides. The 640,000 t of tailings that settled out covered 35 hectares. By 1984, about 10% or 10 mm per year (~3,000 t/yr) had been eroded into the Finniss River (Mudd 2002). In 1961-62, a hole appeared in the ground near the copper cementation launders (presumably due to dissolution of dolomite by acidic liquid wastes) (see Davy 1975).

In 1961 tailings were dumped in the former Dyson's open cut, and to White's open cut from 1965 until closure in 1971. The use of pits and adjacent flood control dams were part of an attempt to improve water quality in the Finniss, though later estimates in the mid-1970s showed that the dilution ratios were not sufficient.

The radon flux from the Old Tailings area averaged about 2 $Bq/m^2/s$ (Ritchie, 1985). Other sources of radon include waste rock dumps, which were studied prior to rehabilitation in the 1980s. For the White's and Rum Jungle Creek South (RJCS) dumps, the average radon fluxes were 1.1 and 2.7 $Bq/m^2/s$ with uranium grades of 0.01% and 0.054% U_3O_8, respectively (Mason et al. 1982). Given that the RJCS deposit was 'blind', the additional radon load from the dump would be well in excess of pre-mining conditions (Mudd 2002). The target set for radon flux during rehabilitation was 0.14 $Bq/m^2/s$ (Allen and Verhoeven 1986).

Due to public pressure, the Rum Jungle site was rehabilitated at a cost of ~$20 million between 1983-86, with the open cut at RJCS rehabilitated over 1991-92. The main works involved relocation of the 'Old Tailings' and unsuccessful copper heap leach pile to Dyson's open cut, re-diversion of some surface water features, water treatment, covering dumps and re-vegetation.

The main approach used for reducing acid mine drainage was the construction of multi-layered soil covers, designed to limit infiltration of rainfall and thereby oxygen ingress. As the site was among one of the earliest to employ this technique, the ongoing monitoring is important in assessing its efficacy.

The annual loads of heavy metals and radium prior, during and after rehabilitation are summarized in Table 2. The water quality downstream in the Finniss River, as measured over the 1992/93 wet season, is summarized in Table 3.

Prior to rehabilitation, up to 50% of rainfall would infiltrate into the various dumps. The post-rehabilitation target was set at 5%. After rehabilitation the rates of infiltration into White's dump was reduced to 1.4-3.7% (1984-93). For the Intermediate dump, infiltration rates were reduced to 3.5-5.9% (1985-89). Recent monitoring has shown infiltration at both dumps increasing to about 10%, which is likely to lead to increased metal loads (Mudd 2002).

Although water quality and metal load reduction targets were set for the rehabilitation works, they were not based on eco-toxicological criteria and still allow metal concentrations downstream many times higher than upstream (Mudd 2002).

Table 2. Range of annual heavy metal and radium loads from Rum Jungle (Mudd 2002)

Period	Rain (m)	Flow (GL)	Cu (t)	Zn (t)	Mn (t)	SO_4 (kt)	^{226}Ra [a] (GBq)
54-61	nd	nd	~43	nd	~114	nd	~914
61-67	nd	nd	~100	~6.7	~167	nd	~1,011
67-74	0.90-2.00	7.0-69.0	40-106	20-30	46-110	3.3-13.0	~703
82-84	1.12-1.70	9.5-48.0	23-28	5-9	6-21	1.52-3.6	~23
84-90	0.90-1.60	3.1-35.0	1.8-9.1	1.6-4.4	3.9-19.2	0.76-4.4	0.35-1.6
90-93	1.00-1.56	7.1-40.5	3.8-14.9	2.7-7.4	9.1-30.5	1.26-4.0	nd

[a] Estimates based on ^{226}Ra in liquid wastes of 1,480 GBq (1954-61); 1,850 GBq (1961-67); and ^{226}Ra in tailings of 14,060 GBq (an annual average of 703 GBq). The data from 1954-74 does not distinguish between dissolved and sediment-bound radium. (nd - no data).

Table 3. Finniss River water quality, downstream of Rum Jungle, 1992/93 (Kraatz 1998)

	mg/L			μg/L								
	Al	Ca	Fe	As	Ba	Co	Cr	Cu	Ni	Pb	Th	U
Ave.	3.6	9.9	1.71	4.1	37	176	5	485	169	76	3.3	33
Min.	0.21	4.2	0.096	0.6	21	53	0.7	180	53	2	0.02	6
Max.	9	29	14	41	120	480	33	1100	430	880	26	63

The rehabilitation design life was 100 years, although as the water quality and infiltration data show, deficiencies are evident after 15 years (likely to be related to either the construction or design thickness of the covers). A major failure of the rehabilitation works was to not remediate groundwater, which receives saline seepage from the dumps and contributes significant metal loads to the Finniss River, especially during the dry season and early wet season (Parker, 1999).

The tailings, now all below-grade in White's and Dyson's open cuts, appear to have been stabilized, though the extent of groundwater contamination remains uncertain. If the covers continue to deteriorate, then it is likely that pollution loads will increase again in the Finniss River. It is clear that the Rum Jungle site is far from stable environmentally, with continuing metal and radionuclide loads (eg. U) discharging into the Finniss River every wet season derived mainly through seepage from the various dumps and groundwater.

Upper South Alligator Valley - Rockhole, Moline projects

The 1950s saw considerable exploration in the Upper South Alligator Valley (SAV) leading to the development of numerous U mines (0.13-2.5% U_3O_8) which supplied two mills at Rockhole within the SAV and Moline 60 km to the south-west (some ores also had gold). The practices of both were similar and are presented jointly (see Mudd (2002) for detailed data and analysis).

The discharge of non neutralized acidic tailings was onto lowlands adjacent to and downhill from each mill, with no serious attempt to retain tailings (Waggitt 1994). Observers at the time noticed that tailings were easily eroded into the river during the intense rain and flooding of the wet season (Waggitt 1994). The metal concentrations and radiation rates from the tailings sites are given in Table 4. By the mid-1980s, up to 10% (~1,500 t) and 25% (~63,000 t, including later base metal tailings) of the Rockhole and Moline tailings had eroded into creeks and the South Alligator and Mary rivers, respectively (Fig. 2) (Mudd 2002).

Table 4. Radiation rates and heavy metals in Rockhole/Moline tailings (Mudd 2000, 2002)

		Rockhole (R)		Moline (M)	
		Ave.	Range	Ave.	Range
Gamma [a]	μGy/hr	18	<2.5 to 65	~5	<2.5 to 24
Radon	$Bq/m^2/s$	~6	<5 to 21.1	~2	<1 to 17.9
	Bq/m^3	??	52 to 9,586	??	50 to 1,654
	Bq/m^3	190	wind >2 m/s [b]	135	wind >2 m/s [b]
	Bq/m^3	1,895	wind <2 m/s [b]	395	wind <2 m/s [b]

(mg/kg)		As	Au	Ag	Cu	Pb	Zn	^{226}Ra [c]	U
M	Min.	88.8	0.026	<1	40.5	205	32	270	3.7
M	Max.	9,800	9.49	40	7,770	5,800 [d]	6,300	87,900	740
M	Ave.	1,438	1.5	12.5	661	1,227	1,107	40,290	88
M	Area [e] (18 ha)	30% >500	20% >2	20% >10	20% >500	40% >500	40% >500	-	similar
R	Min.	12	0.107	-	13	28	10	28,500	3
R	Max.	570	23.7	-	1,030	1,090	87	222,000	830
R	Area (~2 ha)	30% >100	60% >2	-	1% >500	30% >500	uni-form	(2 sam-ples)	60% >100

[a] Typical background gamma radiation is about 0.1 μGy/hr. [b] Wind speed.
[c] Bq/kg. [d] El Sherana ore had up to 5% Pb in places. [e] Area greater than conc'n.

By the 1980s, tourist numbers had increased in the former mining province, and the SAV was being considered for inclusion in Stage 3 of Kakadu National Park. As the gold industry was going through a major expansion, the tailings were tested for reprocessing. After assessment, approval was given for excavation of all the Rockhole tailings to be transported to Moline for gold extraction. Waggitt (1994), however, only lists 6,000 t or about half being transported.

The reprocessed Moline/Rockhole tailings (producing ~10,000 oz Au) were discharged into a new engineered dam (and later became the site of a major dam for 3 Mt of gold tailings from the Moline gold mine, 1988-92; see Mudd 2002).

In 1991-92, a series of 'Hazard Reduction Works' were undertaken throughout the SAV, including the erection of fences, warning signs and the redirection of roads (Waggitt 1996). Although localized areas of gamma radiation could be found (eg. El Sherana camp), radon progeny were considered low at 4.6 mWL, although a gully area of elevated gamma and radon was detected and not included in works at this time (the site was monitored).

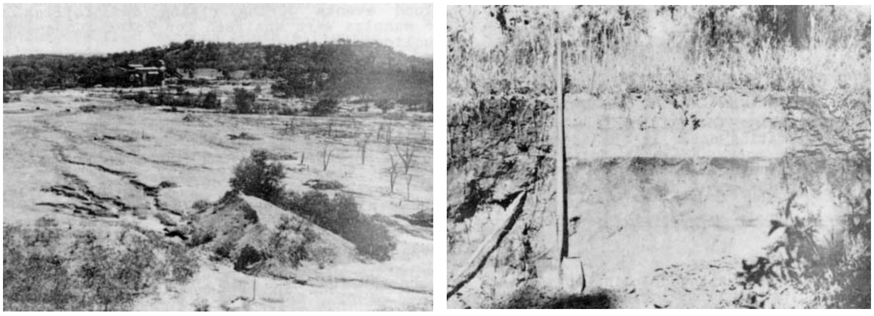

Fig. 2. Erosion of Moline U/Au tailings (Cull et al. 1986).

In 1999, the gully containing elevated radiation was found to be the source of uranium tailings dispersed onto the SAV tourist road. It is likely that this is the remaining 6,000 t of tailings not transported to Moline during the mid-1980s.

There are many continuing management issues with the former uranium mines of the SAV and their associated tailings. This includes acid drainage from adits at Rockhole, erosion problems at shallow burial and most mine sites, bat colonies in underground shafts, re-vegetation difficulties and further areas of elevated gamma rates. The continuing acid drainage in particular highlights the difficulties of interpreting and predicting groundwater flowpaths and the efficacy of rehabiliaition.

Nabarlek uranium project

The Nabarlek uranium deposit was discovered in 1970 and was found to be ~1.9% U_3O_8 in 606,000 t of ore. After the environmental, land rights and nuclear debates of the mid-1970s (the Ranger Uranium Environmental or 'Fox' Inquiry; Fox et al. 1977), the project was approved and began in 1979.

The ore was mined in 4 months of the mid-1979 dry season with the high and low grade ores and waste rock stockpiled separately. The mill began operation in June 1980, allowing the unique situation where the tailings, neutralized with lime, could be discharged to the former open cut. Between 1984-88, ~157,000 t of low grade ore (~0.05% U_3O_8) was heap leached. After the exhaustion of primary ore, the mill formally closed in late 1988.

The pre-mining radon fluxes were measured in September 1978 and June 1979 to range from 3.7 to 44.0 and 11.5 to 164.0 Bq/m^2/s, respectively, with the latter including the effects of cleared vegetation due to mining (Clark et al. 1981).

The principal issue affecting tailings during operation was water management, due to the need to store large quantities of contaminated waters in the former pit. This led to low settled tailings densities, which would create difficulty at the time of rehabilitation. In mid 1985, the use of sub-aerial deposition was authorised, which led to higher settled densities. After mill closure in 1988, a series of vertical drainage wicks were installed to aid tailings consolidation, the first use of this approach in the mining industry and thought successful (Waggitt and Woods 1998).

During operation, it was decided to trial the irrigation of contaminated pond waters in 1984 on a small region adjacent to the airstrip (see Akber 1991). The main solutes of concern were perceived to be NH_4 and SO_4. After further trials in 1985, the irrigation was expanded to a nearby forest area. The total water irrigated by the end of 1987 was 701 ML. The high NH_4/SO_4 concentrations in the pond water (~1,040 / 5,340 mg/L) led to significant impacts on groundwater quality, exacerbated by oxidation of the NH_4 to NO_3 and the release of acidity, as well as tree deaths in the forest irrigation area (Mudd 1999). The impacts on shallow ground waters were detected within months of irrigation, which discharged to the adjacent creek (see Akber 1991; Waggitt and Woods 1998).

Further complexity in groundwater behavior was demonstrated by monitoring down gradient of evaporation pond 2 (EP2). Three bores each 50 m from EP2 showed SO_4 concentrations of 488, 12 and 1,260 mg/L, respectively, demonstrating the importance of fracture zones or high permeability preferential flow paths (Waggit and Woods 1998; Mudd 1999).

After prompting by government authorities, decommissioning began in late 1994 and the site was rehabilitated by late 1995. The main works involved disposal of the remaining contaminated water and removal of the evaporation ponds, backfilling of the former pit/tailings with wastes from the mill and other contaminated materials and re-contouring and re-vegetation of the area. A review of Nabarlek's rehabilitation is given in Klesaa (2001) and Mudd (2002). Environmental and some radiological monitoring has been ongoing since 1995.

A major radiological study of the rehabilitated Nabarlek site is given by Martin (2000). The gamma surveys showed that current dose rates average 0.27 μGy/hr over the 98 hectares of the former site, and clearly outlines features such as the evaporation ponds, waste rock dumps and the pit/tailings area. The pre-mining gamma dose rate was estimated to average 0.18 μGy/hr over the same area.

The radon fluxes from the various areas at Nabarlek have also been studied since rehabilitation, reviewed in Martin et al. (2002) and (Mudd 2002). Although pre- rehabilitation estimates suggested a reduction of some 10^{22} in the radon flux from the former ore zone, recent field measurements have shown that the cover over the tailings and former pit has an average radon flux of 1.03 $Bq/m^2/s$, which is only 10-100 times reduced. This was thought to be related to the use of waste rock in the final cover instead of soil, since the topsoil had become sterile during the 16 years since mining (Mudd, 2002).

Ranger uranium project

The Ranger uranium project has been a controversial focal point for the complex issues of Aboriginal land rights, uranium mining (reflecting community concerns on nuclear issues) and national parks / environmental protection. The deposits were discovered by Noranda in 1969 on Peko-EZ leases and proved by mid-1970.

The Ranger project was located within land originally intended for a national park proposed in 1965, and spirited national debate led to the Ranger Uranium Environmental Inquiry being established in July 1975. It handed down 2 reports, the final in May 1977 concentrating on the Alligator Rivers Region and the Ranger Project (in which the Commonwealth held a 50% stake) (Fox et al. 1977). It remains one of the most quoted inquiries on nuclear issues and uranium mining and made several wide-ranging recommendations regarding Ranger (as well as other proposed mines at Nabarlek, Jabiluka and Koongarra).

Primarily it supported land rights for Aboriginal people, the creation of Kakadu National Park and urged caution and best practice for all proposed uranium mines, including final below-grade tailings and 'no-release' water management systems as well as different waste rock and stockpile locations. The distinction was also made that low grade ore be considered as the same environmental risk as tailings and also be placed below-grade. When the Ranger project was authorized by the federal government in January 1979, 'Environmental Requirements' (ER's) were included covering water management, radiation protection, tailings and the like.

In the short-term, until pit #1 was mined out, an above ground storage dam has been used for tailings management, built to the west of pit #1 and the mill. The original ER's modified the Fox Inquiry recommendation to state that, after 10 years from the date of approval, Ranger may apply for an alternative to below-grade tailings management if it can be demonstrated that the environment is no less well protected. Despite considerable research, however, Ranger finally stated publicly their commitment to final below-grade tailings management in late 1997.

The hydrogeology of the Ranger site is described by Haylen (1981) and Ahmad and Green (1986). There are three main aquifer types - sands and gravels ('Type A'), weathered soils ('Type B') and fractured rocks ('Type C'), shown in Fig. 3. The relationship between the aquifers is often complex. The water quality is generally of low salinity, up to 300 mg/L, with low heavy metal and radionuclide content (except ore zones).

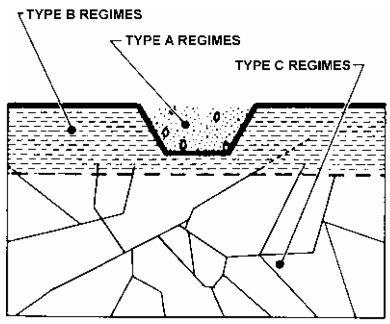

Fig. 3. Groundwater regimes at Ranger (Ahmad and Green 1986)

In 1996 Ranger began the deposition of tailings into pit #1, although no lining was constructed. The current height limit is 'RL 0 m', or the base of the weathered zone, where the tailings would come into direct contact with the permeable surficial aquifers which can connect directly to surface water systems.

A detailed analysis of the potential seepage pathways from tailings stored in both the above ground dam and pit #1 was presented by Haylen (1981), shown in Fig. 4. Essentially the critical role of permeable carbonate units, such as cherts, as well as fracture zones, are clearly highlighted as being major and potentially rapid pathways for contaminants from tailings. Haylen (1981) noted that the chert units were present downstream in the Magela Creek, which flows into world heritage-listed Kakadu National Park. Given the environmental senstivity of the region and the concerns of Aboriginal people, it is disappointing that there appears to be little follow-up research on these issues for long-term tailings management at Ranger.

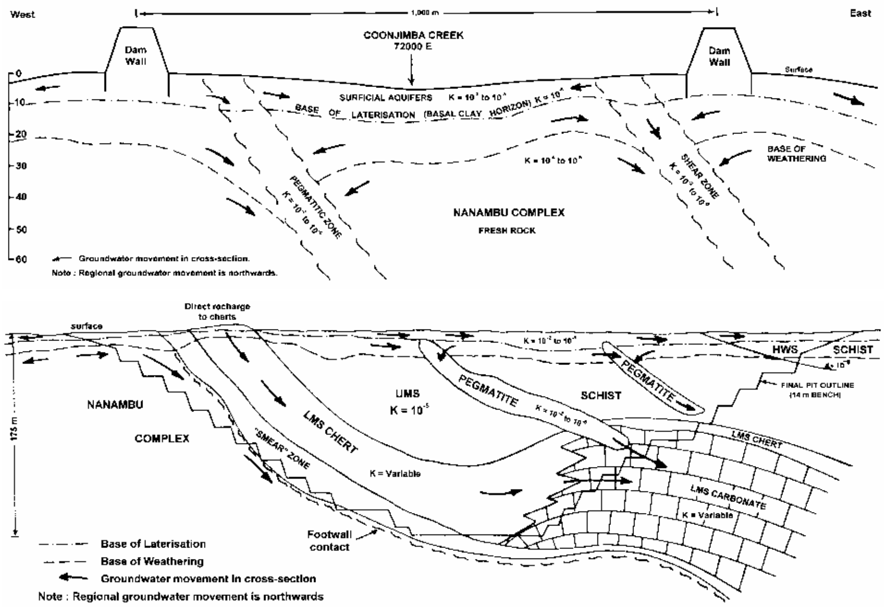

Fig. 4. Permeability (K, cm/s) zones and inferred groundwater flowpaths for the above ground tailings dam and pit #1 at Ranger (adapted from Haylen 1981)

Discussion and conclusions

The management of uranium tailings and the minimization of associated environmental and radiological impacts has improved over the last 50 years in northern Australia. The acid mine drainage problems at Rum Jungle continue to lead to groundwater pollution and metal loads to surface water systems. For Moline and Rockhole, most of the tailings appear to have been stabilized except for the residual remaining within Kakadu National Park. The use of in-pit tailings at Nabarlek was innovative, though concerns remain about the potential for fractures to transmit solutes. Ranger has managed its tailings through use of an interim above ground dam and is now using pit #1. All sites show a clear case for final below-grade tailings, links with water management and better emphasis on groundwater.

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