Part 3: Jabiluka

Importance of large wood for creating aquatic habitat and stable channels in the Ngarradj Creek catchment

WD Erskine, MJ Saynor, G Fox & AC Chalmers¹

Background

Recent Australian research has quantified the role of large wood (wood of any origin and length with a diameter greater than 0.1 m) in dissipating stream energy, forming various pool habitats by either local bed scour or damming, protecting river banks from erosion and damming rivers with long rafts causing avulsions or abrupt, wholesale changes of river courses (Brooks & Brierley 2002, Webb & Erskine 2003, Erskine et al 2007, 2012). Furthermore, Australian riparian tree species are often hardwoods, unlike many northern hemisphere riparian species. As a result, recruited large wood may behave differently to that reported overseas. Large wood in Australian streams is sourced by a range of processes from the nearby riparian zone, which has often been degraded by post-European settlement vegetation clearing (Brooks et al 2006, Erskine et al 2009). However, the extent of large wood loadings within the bankfull channel for different riparian plant community types is essentially unknown for most Australian rivers (Erskine et al 2009). The Ngarradj catchment (Figure 1) is an excellent location to determine the importance of large wood for creating aquatic habitat and stable river channels in the natural environment because there are long reaches which have experienced little human modifications and which have the same riparian plant community within Kakadu National Park. Information obtained on such rivers is also important for designing river restoration works in areas where riparian vegetation has been extensively cleared (Erskine et al 2012). Greater use of national parks, forest reserves and other types of protected areas needs to be made to understand natural large wood loadings and the role that living and dead trees play in stabilising rivers and their associated floodplains.

The locations of the study sites are at the former *eriss* East Tributary (ET) and upper Ngarradj (UN) river gauging stations (Figure 1) where there are riparian *Allosyncarpia ternata* ST Blake forests and meandering stream channels (Erskine et al 2001). *Allosyncarpia ternata* is an evergreen tree up to 18 m high with grey fissured, fibrous bark and ternate leaves that is endemic to western Arnhem Land, Northern Territory (Blake 1977). The riparian forest is unusual because it comprises only a narrow strip bordering the immediate river channel (Figure 2). Previous research on *A. ternata* forest has been largely confined to non-riparian locations associated with sandstone escarpments and valleys where different forest dynamics and disturbance processes occur than in riparian zones because of the lack of large floods and because of protection from strong winds and fire.

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Figure 1 The Ngarradj catchment showing the study sites at East Tributary (ET) and upper Ngarradj Creek (UN) where there is an *Allosyncarpia ternata* riparian forest

Large wood and aquatic habitat

The forested, laterally stable, unconfined, meandering rivers represented by these two sections of Ngarradj Creek are defined as sand-bed streams with a sinuous pattern (sinuosity > 1.5 which means that the channel is at least 1.5 times longer than the valley in which it is located), a continuous but narrow floodplain and a narrow, forested riparian corridor (Erskine et al 2005). Living and dead trees in rivers are important for creating large-scale roughness elements and for protecting river banks from erosion. We have previously shown that these channels are low to medium energy streams (Saynor et al 2004) that may be incapable of redistributing recruited large wood.

Methods

The surveyed reaches were 130 m (15 channel widths) long and 292 m (29 channel widths) long on the East Tributary and upper Ngarradj Creek, respectively. This follows the recommendation of Roni & Quinn (2001) in adopting study reaches at least 10 times bankfull width in length so as to include at least two complete meander wavelengths. Such reaches are long enough for meandering rivers to also include at least two pool-riffle sequences (Leopold et al 1964). The characteristics (ie loading, spatial distribution, orientation, composition, arrangement, blockage ratios, dynamics) and recruitment processes of large wood were measured along both study reaches, together with the length and depth of every aquatic habitat type (principally pools, runs and riffles) present. The recognition of aquatic habitats was based on longitudinal profile surveys by total station. Every living tree within the bankfull channel and within contiguous 5 m x 5 m quadrats aligned perpendicular to the channel through the riparian *A*. forest was identified to species level.



Figure 2 The riparian *A. ternata* forest on upper Ngarradj Creek which is the sinuous green ribbon across the brown, dry lowlands

Results

Erskine et al (2007; 2012) have published the results of the first survey which was completed in May 2002. *Allosyncarpia ternata* was the dominant tree (comprising 42–85% of all trees at each site), with *Lophopetalum arnhemicum*, *Syzygium forte* ssp *potamophilum*, *Calophyllum sil*, *Carellia brachiata*, *Erythrophlem chlorostachys* and *Xanthostemon eucalyptoides* also being present in much smaller numbers.

A total census of large wood in the bankfull channel for both reaches found that loads ranged between 184 m³/ha (upper Ngarradj Creek) and 302 m³/ha (East Tributary). At upper Ngarradj Creek, dead wood comprised 61.3% and living trees comprised 38.7% of the total large wood load, whereas at East Tributary, the percentages were 34.5 and 65.5%, respectively. Most living trees were located on the river banks within the bankfull channel. Between 94 and 97% of living trees were located on the banks, with only between 3 and 6% in the river bed. The roughness created by the dense stands of bank-side trees is responsible for low flow velocities along the channel margins and hence the zero bank erosion rates measured over four years (Saynor & Erskine 2006). At upper Ngarradj Creek there were 272 pieces of large wood at an average spacing of 1.07 m. At East Tributary there were 230 pieces at an average spacing of 0.57 m. In addition, 12.6% of the large wood in the bankfull channel at East Tributary exhibited fire scars compared with 16.2%, at upper Ngarradj Creek. This provides evidence that fire and the resultant damage to the riparian trees cause some recruitment of large wood to the channel.

Small diameter wood (<0.3 m) dominates in terms of the number of pieces, but large diameter wood (>0.3 m) dominates in terms of volume in both reaches. Debris dams were uncommon but, when present, often caused significant localised expansions in channel width because of outflanking by erosion at the extremities of the dam. Blockage ratios refer to the percentage of the bankfull channel area occupied by large wood. They are usually less than 5% but the few debris dams that are present do block a significant proportion of the bankfull channel area (>16%). Blockage ratios less than 5% usually do not impact on flood routing, but ratios of 16% would increase flood heights for the same peak discharge (Gippel et al 1996).

Most of the large wood was orientated with the long axis downstream. Downstream orientations are only possible where rivers have the stream power to reorient and transport a significant proportion of the recruited large wood from the riparian zone.

Large wood loadings within both study reaches varied greatly longitudinally with up to three orders of magnitude variation at the spatial scale of one channel width lengths down the channel. At East Tributary, the mean loading per unit channel width of length was 1.90 ± 0.46 m³ (SE)(range 0.65 to 6.8 m³). At upper Ngarradj Creek the mean large wood load was 1.87 ± 0.28 m³ (range 0.06 to 5.4 m³).

In the seasonally wet tropics of northern Australia, strong winds and tropical cyclones are important recruitment processes along with bank erosion and fire. Strong winds in February 2002 resulted in significant wind throw and branch breakage in the East Tributary study reach. Large wood recruitment equivalent to 912 m³/ha occurred in the affected area. Subsequently, the core of Cyclone Monica passed over the Ngarradj catchment on 25 April 2006, resulting in an estimated 42% loss of woodland canopy cover (Staben & Evans 2008). The maximum 3 sec wind gusts were 36–64 m/s during Cyclone Monica (Cook & Goyens 2008). A survey of the large wood inventory in the upper Ngarradj study reach was made after Cyclone Monica in October 2006. The number of individual pieces of large wood was found to have increased from 272 to 720, and the total load increased from 184 to 324 m³/ha. The number of pieces of large wood per metre channel length increased from 1.07 to 2.48 pieces per metre. High winds and tropical cyclones can clearly be a significant large wood recruitment process but are rarely discussed in the large wood literature.

A longitudinal profile survey of the bed of the East Tributary study reach before Cyclone Monica showed that there were 13 pools in the surveyed reach with an average spacing of 1.75 channel widths (Figure 3). This is much less than the 4 to 8 channel widths commonly associated with pool-riffle sequences in meandering, gravel-bed streams (Leopold et al 1964). Of these 13 pools, only two were dominantly produced by bend processes (secondary or helicoidal currents), the remainder being caused by localised bed scour due to the presence of large wood. Scour mechanisms included under scour, over scour, lateral scour and constriction scour. Each scour mechanism produced a distinctive pool type (Erskine 2005; Webb & Erskine 2005), namely transverse scour pool, log step pool, longitudinal pool and convergence pool, respectively (Figure 3).

The close spacing of pools reflects the addition of pools between bends in sinuous streams due to localised scour induced by the high large wood load. Scour pools are important refuges in the seasonally flowing streams common to northern Australia. In some cases these pools can persist right through the dry season providing a source of recruitment when flow is re-established the following wet season. Loss of pools is known to reduce fish abundance (Erskine 2005).



Figure 3 Longitudinal bed profile of the East Tributary of Ngarradj Creek showing locations of examples of various types of pools. See text for further information.

Step structure formed by logs is important for energy dissipation, which reduces erositivity of a stream. On East Tributary, there were four log steps in the study reach which accounted for 14% of the total hydraulic head loss along that length of the stream. Two log steps have remained in the same location for the last 13 years.

Conclusions

The channels in the two study reaches have been stable over the last 13 years. Measured bank erosion rates over four years at both sites were not significantly different from zero (Saynor & Erskine 2006) and mean annual net bed scour was statistically identical to net bed fill (Saynor et al 2004). Changes in the channel cross section at 8 permanently marked locations in each study reach were minor over the 6 years between 1998 and 2003 (Saynor et al 2004). The reason for the existence of the stable meandering channel is the presence of the riparian *A. ternata* forest and the supply of large amounts of large wood to the channel by a range of recruitment processes, including strong winds, bank erosion and fire. The diversity of pool types initiated and sustained by the presence of this large wood increases aquatic habitat diversity which should also lead to increased fish species diversity.

This work has provided an important baseline data set for Ngarradj Creek which can be used to assess future changes and to determine whether any changes which do occur are either natural or man-induced. In particular, any future mining-related activities within the Jabiluka Mineral Lease should not disturb the river channels and the vegetation, especially riparian trees, growing on the bed and banks of Ngarradj Creek in order to maintain the stability of this fluvial system.

Future work

The current publications (Erskine et al 2007; 2012) largely result from the field work completed in May 2002. Another detailed field survey was done in October 2006 so as to determine the immediate after effects of Cyclone Monica, which occurred in April 2006, on large wood recruitment. A follow-up survey was done in October 2010 to determine whether

large wood recruitment continued by the supply of dead branches and trees in the years after a large tropical cyclone. The results of the last two surveys are still to be processed although all of the data have been entered into spreadsheets.

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Part 4: Nabarlek

There are no research papers this year in the Nabarlek key knowledge needs theme. The taking over of management of the site by Uranium Equities Limited and the requirement for conduct of monitoring and progressive rehabilitation activities as part of the mine management plan have meant that the involvement of SSD has been reduced following completion of the suite of projects that had been initiated to define for stakeholders the rehabilitation status of the site.

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Part 5: General Alligator Rivers Region

Empirical line calibration of WorldView-2 satellite imagery to reflectance data: using quadratic prediction equations

GW Staben, K Pfitzner, RE Bartolo & A Lucieer¹

A systematic remote sensing capture, incorporating full ground control and coincident collection of ground spectral data was undertaken for the Magela floodplain and Ranger uranium mine in May 2010. Three World-View 2 images covering 730 km² of the Magela Creek catchment were acquired. Project work in 2010–11 focused on orthorectification of the imagery and atmospheric correction to provide the basis for producing high resolution maps of vegetation and habitat types. This paper is a summary produced from Staben et al (2012), where full details are included.

Introduction

Before multispectral satellite imagery can be utilised for quantitative applications, a number of pre-processing steps, including geometric and radiometric corrections need to be undertaken. To reliably quantify extents of change from time series acquisitions and to accurately match remote sensing data to field-based measurements (such as plant biophysical parameters) a high degree of radiometric accuracy is required. Radiometric accuracy in this context can be defined as the degree of scaling of the pixel values (in digital numbers) to actual radiance values emitted from the earth's surface.

To obtain quantitative information from multispectral satellite sensors such as WorldView-2, factors affecting the raw digital numbers (DN) such as sensor characteristics, illumination geometry and atmospheric effects need to be removed (Smith & Milton 1999). Effects of the atmosphere, such as scattering and absorption, vary across the optical spectrum by either adding to, or diminishing the surface radiance values recorded by the satellite sensor (Hadjimitsis et al 2009, Karpouzli & Malthus 2003). A number of different methods have been developed to correct for the effects of the atmosphere on satellite imagery including: image based methods (Chavez 1996); radiative transfer models (Vicente-Serrano et al 2008); and empirical line method (Smith & Milton 1999, Karpouzli & Malthus 2003).

The empirical line method has been used to convert at-sensor radiance values to surface reflectance for numerous multispectral satellites (Clark et al 2010, Hadjimitsis et al 2009, Karpouzli & Malthus 2003) and airborne hyperspectral sensors (Smith & Milton 1999). The technique is based on establishing a relationship between atmosphere sensor radiance (L_{TOA}) values (in $W \cdot m^{-2} \cdot sr^{-1} \mu m^{-1}$) and surface reflectance (P_S) values (dimensionless). Surface reflectance is defined as the ratio of incoming solar radiation that is reflected from the Earth's surface and is measured from calibration targets located within the image area using a field spectrometer. The measurements should ideally cover the range of albedo (the fraction of solar energy reflected from the Earth's surface) values found within the imagery. The L_{TOA} values are then extracted from the imagery and compared with the field measured P_S values to define predictive equations that can be used to convert image-derived L_{TOA} to P_S values for each

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waveband (Smith & Milton 1999). The relationship between radiance and reflectance across the whole data range (0-100%) is quadratic (Moran et al 1990). However, correction of imagery using empirical line methods is typically based on a linear relationship. This is due to the fact that the relationship between radiance and reflectance between 0-70% has been found to be essentially linear, allowing interpolation with minimal error (Clark et al 2010, Baugh & Groeneveld 2008, Moran et al 1990).

The aim of this work was to assess the ability of the empirical line method to convert very high spatial resolution multispectral WorldView-2 imagery from L_{TOA} to P_S values using quadratic prediction equations. Correction of imagery using empirical line methods is typically based on a linear relationship due to the design characters of the sensor used (sensing elements and electronics), and in this instance a quadratic relationship provides a better fit when examining the entire data range (0 to 100%), rather than the known linear relationship between 0 and 70%). The results for two of the three images are reported here.

Methods

Image pre-processing

Orthorectification of the imagery was undertaken using the sensor's Rational Polynomial Coefficients (RPC) combined with an array of accurately geo-referenced ground control points (GCPs). The one second Shuttle RADAR Topography Mission (SRTM) Digital Elevation Model (DEM) was used as part of the orthorectification process. Coordinates for 24 GCPs distributed evenly across the imagery were acquired using a DGPS (Differential Global Positioning System) with an overall average positional accuracy of 10.6 mm for the X and Y coordinates. Nine GCPs were used in the orthorectification of Image 2 while ten GCPs were used for Image 1. The overall accuracy assessment of the orthorectification based on six independent GCPs resulted in an average Root Mean Square Error (RMSE) of 1.82 m. To account for sensor characteristics, the images were converted from DN to L_{TOA} spectral radiance (Updike & Comp 2010) using Eq. 1:

$$L_{\lambda Pixel, band} = \frac{K_{Band*}Q_{Pixel, Band}}{\Delta_{\lambda Band}}$$
(1)

Where: $L_{\lambda Pixel, band}$ represents TOA spectral radiance image pixels (W-m⁻²-sr⁻¹-µm⁻¹); K_{Band} is the absolute radiometric calibration factor (W-m⁻²-sr⁻¹-count⁻¹) for a given band; $Q_{Pixel, Band}$ represents the radiometrically corrected image pixels (DN); and $\Delta_{\lambda Band}$ is the effective bandwidth (µm) for a given band. The absolute calibration (K_{Band}) and effective bandwidth ($\Delta_{\lambda Band}$) parameters for each band are obtained from the metadata supplied with the imagery.

Field spectra

A combination of both calibration panels and field targets were utilised to convert L_{TOA} values to P_S . Smith & Milton (1999) suggest that field targets used for empirical line correction should ideally have the following characteristics: be spectrally homogenous; near Lambertian and horizontal; devoid of vegetation; cover an area several times the pixel size of the sensor; and cover a range of reflectance values. A total of 24 targets were measured for their reflectance in the field along with two calibration panels. The two calibration panels and five selected pseudo-invariant features (PIFs) (Table 1) were used to derive the prediction equation between L_{TOA} and P_S for each waveband, while the remaining 19 targets (Table 2) were used to assess the accuracy of the prediction equations. Spectra were collected according to SSD's field sampling methods (Pfitzner et al in press).

KKN 5.1.1 Develop a landscape-scale ecological risk assessment framework for the Magela catchment that incorporates, and places into context, uranium mining activities and relevant regional landscape

ID	Target description	CoV*
C1 [°]	(~95%) Tyvec® calibration panel	0.97
C2 ^c	(~67%) White calibration panel	2.77
C3 ^c	Sports field grass	6.96
C4 ^d	Synthetic bowling green	15.58
C5 ^d	Asphalt road	17.13
C6 ^e	Open Water – Jabiluka billabong	9.29
C7 ^e	Open Water – Jabiluka billabong	9.31

Table 1 Description and mean coefficient of variation (CoV) for targets used to derive predictionequation to convert between L_{TOA} and P_S

* Mean CoV (σ/\bar{x} *100) of each target based on field spectra. Wavelength 400–1040 nm; Spectra collection date: (° = 11/5/10), (° = 13/5/10), (° = 27/5/10)

ID	Target description	CoV*
V1 ^a	Sports field grass	13.23
V2 ^a	Open Water – Jabiru Town Lake	14.10
V3 ^a	Open Water – Jabiru Town Lake	55.82
V4 ^b	Asphalt road	5.52
V5 ^b	Sports field grass	9.42
V6 ^c	Sports field grass	4.31
V7 ^c	Sports field grass	5.91
V8 ^c	Sports field grass	7.88
V9 ^c	Sports field grass	12.25
V10 ^c	Golf green	8.86
V11 ^d	Builders Sand	6.89
V12 ^d	Sand / blue stone	31.86
V13 ^d	Sand / concrete slab	9.83
V14 ^d	Native grass	17.43
V15 ^d	Rock outcrop	39.28
V16 ^d	Bare earth (scrape)	13.59
V17 ^e	Open Water – Jabiluka billabong	10.18
V18 ^e	Bare earth	13.76
V19 ^e	White road base	14.64

Table 2 Description and mean coefficient of variation (CoV) for targets used to test prediction equation between L_{TOA} AND P_S

* Mean CoV for each target based on field spectra. Wavelength 400–1040 nm

Spectra collection date; (a = 6/5/10), (b = 7/5/10), (c = 11/5/10), (d = 13/5/10) (e = 27/5/10)

Empirical line calibration and accuracy assessment

The very high resolution averaged field spectra (P_S) were re-sampled to provide spectral bandwidth data corresponding to each WorldView-2 waveband. The average L_{TOA} values corresponding to each calibration panel and field target were then extracted from the imagery. A non-linear quadratic relationship was fitted between L_{TOA} and P_S .

The overall accuracy of the empirical line calibration was assessed by comparing image derived P_S values with field measured P_S for the 19 validation targets. Summary statistics

were obtained to assess the performance of each spectral band, and each individual validation target, using the Root Mean Square Error (RMSE) and the Mean Absolute Percent Error (MAPE), which enable the assessment of the relative error for each target.

Results

The combination of calibration panels and field targets enabled the development of a nonlinear relationship between L_{TOA} and P_S . A total of seven targets were used to derive the predictive equations, resulting in statistically significant relationships for each waveband ($R^2 = 0.99$, P < 0.0001, 99% confidence level). Figure 1 shows the non-linear regression line and prediction equation for WorldView 2 blue waveband.



Figure 1 Non-linear regression and prediction equation for WorldView-2 blue waveband

Summary statistics for each band are presented in Table 3. The overall RMSE values for each band show that there was a high degree of agreement between the satellite-derived P_S values and field-measured P_S values for the 19 validation targets. Five of the eight bands recorded RMSE values less than 1.5% with the coastal band recording the lowest value of 0.94%. The red-edge and two NIR bands recorded the highest RMSE values. However, the MAPE values (which assess relative error of the predition) show that the red-edge band recorded similar errors to the bands in the visible portion of the electromagnetic spectrum.

Band	RMSE%	MAPE%
Coastal (1)	0.94	18.39
Blue (2)	1.05	14.01
Green (3)	1.20	11.48
Yellow (4)	1.29	13.75
Red (5)	1.36	16.78
Red Edge (6)	1.86	16.02
NIR 1 (7)	2.13	25.97
NIR 2 (8)	2.14	44.83

 Table 3
 Summary statistics derived from the validation targets for each waveband

Conclusions and future work

The combination of both calibration panels and image targets enabled the development of prediction equations covering the full range of albedo values within the image. The high accuracy achieved in the geometric correction of the imagery and the spatial and radiometric resolution of the WorldView-2 sensor enabled calibration targets to be easily identified in the imagery.

Importantly the calibration targets used ensured that the predicted P_S values were interpolated within the bounds of the prediction equations. Assessment of the prediction equations based on 19 independent validation targets show that overall accuracy was high, with RMSE values between 0.94% and 2.14% across the eight multispectral bands. The results show that the empirical line method using quadratic prediction equations can be used to successfully calibrate the eight multispectral bands of the WorldView-2 satellite image to surface reflectance. This method will enable *eriss* to routinely process very high resolution imagery for time series and quantitative analyses.

Further work will be undertaken to calibrate the third World-View 2 image where Bidirectional Reflectance Distribution Function (BRDF) effects are evident due to the differing illumination and viewing geometry. A vegetation map of the Magela floodplain is under development using the 2010 imagery. Another World-View 2 image was acquired in May 2011, and is currently being processed.

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External gamma dose rates and radon exhalation flux densities at the El Sherana airstrip near-surface disposal facility

C Doering & A Bollhöfer

Introduction

The 2009 remediation of legacy mining and milling sites in the South Alligator River valley (SARV) included the bulk removal of mining wastes contaminated with naturally occurring radioactive material (NORM) and their placement into a near-surface disposal facility ('containment') constructed at the site of the disused El Sherana airstrip (Fawcett Mine Rehabilitation Services 2009). These works were carried out as part of the 1996 lease agreement between the Gunlom Aboriginal Land Trust and the Director of National Parks which required the Director of National Parks to develop and fully implement a plan to restore mine-impacted areas in the SARV to near to natural environmental status by the end of 2015.

Engineering details of the El Sherana airstrip containment are given in Table 1. The waste material sits between a compacted clay base and a compacted clay capping layer. The capping layer is overlaid with a soil cover ('growth medium') to facilitate re-vegetation of the site. The capacity of the containment is approximately 25 000 m³ and the volume of contained waste material is about 22 000 m³. The waste material consists of contaminated mine plant and soils (including waste rock and tailings) and drums containing contaminated soils that were previously stored at the South Alligator Village.

Parameter	Dimensions
Surface footprint	8750 m² (175 m x 50 m)
Capacity	25000 m ³
Maximum excavation depth below natural ground level	5 m
Side slopes	3:1 (horizontal:vertical)
Maximum thickness of waste material	4 m
Base material	0.5 m compacted clay
Capping material	0.5 m compacted clay
Growth medium	2.5 m soil (northern side), 3.5 m soil (southern side)

Table 1 Approximate engineering details of the El Sherana airstrip near-surface disposal facility¹

¹Based on information from Fawcett Mine Rehabilitation Services (2009), Fawcett & Waggitt (2010) and G Balding (pers comm).

This paper presents the results of external gamma and radon exhalation measurements made at El Sherana airstrip before and one year after completion of the containment. The purpose was to establish environmental baseline values for these parameters and to check that there were no changes in surface radiological conditions at the site after one wet season attributable to the performance of the containment. The results of radiation measurements made at remediated mining and milling sites in the SARV have been reported elsewhere (Bollhöfer & Fawcett 2009, Doering et al 2010, Doering et al 2011a).

Methods

Gridded gamma surveys were conducted at the El Sherana airstrip on 27 June 2007 and 7 September 2010 to measure the external gamma radiation levels for the baseline and postconstruction situations, respectively. Environmental monitors of the same type were used for both of the surveys. Measurements were made of the total counts per 100 s in air at a height of 1 m above the ground surface. These measurements were later converted to absorbed dose rate using a calibration equation that related the count rate to the air kerma rate (absorbed dose rate in air) for the environmental monitors.

Charcoal-loaded canisters were used for radon exhalation measurements. The general methods of sampling, radioactivity analysis and determination of radon exhalation flux density were similar to those described in Bollhöfer et al (2006). Canisters for the baseline measurement were deployed in the field on 21 July 2009 and recovered three days later on 24 July 2009. Those for the post-construction measurement were deployed on 6 September 2010 and recovered three days later on 9 September 2010. For both the baseline and post-construction measurements, three additional canisters were carried into the field but remained sealed at all times. These canisters were controls, used to determine the background activity of the charcoal in the canisters.

Results

External gamma dose rates

Figure 1 shows the location and magnitude of the external gamma measurements from the baseline and post-construction surveys overlaid on a multispectral Quickbird image of the area acquired in 2004. Whereas the measurements from the baseline survey extended beyond the containment boundary, owing to fact that the exact construction location was not known at the time of this survey, all measurements from the post-construction survey were made inside the fenced area.

Table 2 provides a statistical summary of the baseline and post-construction external gamma dose rates at El Sherana airstrip. The average baseline and post-construction values were $0.12 \,\mu\text{Gy} \,h^{-1}$ and $0.10 \,\mu\text{Gy} \,h^{-1}$, respectively, indicating that there has been effectively no change in the external gamma dose rates at the site after one wet season.

Statistic	Baseline value	Post-construction value
Arithmetic mean	0.12	0.10
Standard deviation	0.01	0.01
Median	0.12	0.10
Geometric mean	0.12	0.10
Minimum	0.09	0.08
Maximum	0.14	0.13
Count [n]	100	230

Table 2 Statistical summary of baseline and post-construction external gamma dose rates at ElSherana airstrip (in μ Gy h-1)

Radon exhalation flux densities

Figure 2 shows the location and magnitude of the baseline and post-construction radon exhalation measurements overlaid on a multispectral Quickbird image of the area acquired in 2004. The baseline radon exhalation measurements were made approximately 250 m east-southeast from where the containment was built and were taken at the time of construction. Twenty one charcoal-loaded canisters were deployed for the baseline measurements, grouped in seven lots of three as indicated by the white connecting lines in Figure 2. The post-construction radon exhalation measurements were made predominantly on the top of the growth medium, with the charcoal-loaded canisters deployed individually, not grouped.

Table 3 provides a statistical summary of the baseline and post-construction radon exhalation measurements. The range in individual radon exhalation flux densities was from 5 to 25 mBq m⁻² s⁻¹ for the baseline and from 6 to 166 mBq m⁻² s⁻¹ for the post-construction measurements. The average (geometric mean) radon exhalation flux density for the baseline and post-construction measurements was 13 and 18 mBq m⁻² s⁻¹, respectively.



Figure 1 Location and magnitude of baseline (left) and post-construction (right) external gamma measurements at EI Sherana airstrip overlaid on a 2004 multispectral Quickbird image of the area. The white line indicates the approximate fenced boundary of the containment.

External gamma dose rates and radon exhalation flux densities at the El Sherana airstrip near-surface disposal facility (C Doering & A Bollhöfer)



Figure 2 Location and magnitude of baseline (left) and post-construction (right) radon exhalation measurements at El Sherana airstrip overlaid on a 2004 multispectral Quickbird image of the area. The white line indicates the approximate fenced boundary of the containment.

 Table 3
 Statistical summary of baseline and post-construction radon exhalation flux densities at El

 Sherana airstrip (in mBq m⁻² s⁻¹)

Statistic	Baseline value	Post-construction value
Arithmetic mean	14	27
Standard deviation	6	37
Median	12	15
Geometric mean	13	18
Minimum	5	6
Maximum	25	166
Count [n]	21	39

While the average post-construction radon exhalation flux density was greater than the baseline value, it is similar to average values measured elsewhere in the Alligator Rivers Region. For example, Bollhöfer et al (2006) reported average radon exhalation flux densities at undisturbed sites in the Nabarlek district of 31 ± 15 mBq m⁻² s⁻¹. Lawrence et al (2009) and Todd et al (1998) reported averages of about 40 and 64 mBq m⁻² s⁻¹, respectively, for undisturbed areas in the vicinity of the Ranger uranium mine.

Frequency distribution analysis of the El Sherana airstrip radon exhalation measurements was performed by Doering et al (2011b). The results of this analysis indicated that both the baseline and post-construction measurements followed a lognormal distribution. Lognormality of radon exhalation measurements has been reported for other sites in the Alligator Rivers Region (Bollhöfer et al 2006, Lawrence et al 2009). The 'Theory of

successive random dilutions' (Ott 1995) can be used to theoretically explain this behaviour. It indicates that a lognormal distribution will result from independent random variables having a multiplicative effect on the measurement. The independent random variables that can influence radon exhalation from the ground surface include temperature, rainfall, atmospheric pressure, wind speed, soil moisture content, soil porosity and soil radium concentration (Porstendörfer 1994). A combination of these factors may partly explain the difference between the average baseline and post-construction values.

The difference between the average baseline and post-construction radon exhalation flux density may also result from the different surface textures on which the two sets of measurements were made. Whereas the baseline measurements were made on the surface of the old El Sherana airstrip, which consisted of compacted gravel suitable for an airstrip, the post-construction measurements were made on the soil cover comprising the growth medium of the containment. The surface of the latter was substantially less compacted to promote revegetation of the site. It has previously been shown that radon will diffuse more readily through a more porous layer, resulting in higher exhalation flux densities from the ground surface (Bollhöfer et al 2006, Lawrence et al 2009). In addition, the original El Sherana airstrip surface had large amounts of gravel (>2 mm grain size) with a relatively small area:volume ratio, whereas the area:volume ratio, and thus the surface area from which radon gas can emanate from the soil grain, was much larger (ie the grain size much smaller) for the substrate on the containment.

Discussion

The measurements presented in this paper provide information on surface radiological conditions at the El Sherana airstrip containment. They do not provide information on radiological conditions or processes at depth, such as potential seepage of radionuclides through the base layer of the containment into the groundwater. The gamma signal in air at a height of 1 m above the ground surface generally comes from radionuclides located within the top 0.5 m of the soil (ICRU 1994). Radon in dry soil has a typical diffusion length of about 1.5 m (Porstendörfer 1994). Radon coming from greater depths does not usually reach or escape the ground surface and decays within the soil layer. The implication is that the higher radon exhalation flux density at El Sherana airstrip post-construction is likely due to the different physical properties of the ground surface (ie the more porous soil cover of growth medium as compared to the compacted gravel material of the original airstrip) than due to the waste material in the containment.

Radioactive waste suitable for near-surface disposal in Australia can be separated into three categories: Category A, Category B and Category C (NHMRC 1993). The material buried in the El Sherana airstrip containment fits the description and NORM activity concentration levels of Category A waste (lightly contaminated bulk waste from mineral processing). The facility design requirements for this category of waste include suitably engineered barriers and cover to ensure the integrity of the waste and to minimise the possibility of water infiltration, and a surface water management system to control water erosion of the cover.

During the 2009–10 wet season, a number of deep erosion gullies formed in the surface cover of the containment, incising the growth medium down to the level of the compacted clay layer that caps the waste material. Gamma measurements made along the length of the gullies and at their alluvial fan did not show absorbed dose rates significantly different to elsewhere on the site, indicating that the integrity of the clay layer had not been compromised and that no radioactive waste material had been exposed. Works to repair the damage were commissioned

by Parks Australia near the end of 2010, with channels to divert rainwater around the containment installed in December of that year.

The formation of erosion gullies in the growth medium during the first wet season after construction indicates that the as-built surface conformation of the landform is not yet in a geomorphically stable condition, even for typical seasonal events. Rainwater diversion channels that have been installed upgradient of the containment coupled with the development and maturation of surface re-vegetation should help to reduce the severity of future erosion events. Regular environmental surveillance at the site, including both on- and off-site environmental radioactivity monitoring, will need to continue into the future to assess the geomorphic stability of the landform and to provide assurance that there is no unacceptable radiation risk to people or the environment from the waste material. The type and frequency of environmental surveillance and monitoring should be consistent with the requirements set out in national guidelines (NHMRC 1993) and with any conditions specified by the regulatory authority. The responsibility for environmental surveillance and monitoring rests with the licence holder, currently Parks Australia.

Conclusions

There have been no substantial changes in external gamma radiation levels or radon exhalation flux densities at El Sherana airstrip one year after construction of a near-surface disposal facility for the containment of radioactive waste materials from legacy mining and milling sites in the SARV. This finding indicates that at the time of the post-construction measurements the waste material was being effectively contained from above. Information on any downward movement of radionuclides that may be occurring, such as seepage of radionuclides through the base layer of the containment into the groundwater, cannot be elicited from the measurements presented in this paper and would require different measurement techniques to be applied. Routine environmental surveillance and monitoring at El Sherana airstrip containment is required to provide assurance that radionuclides in the waste material remain effectively isolated from the surrounding environment and that there is no unacceptable radiation risk to people or the environmental surveillance and monitoring should be consistent with requirements set out in national guidelines (NHMRC 1993) and with any conditions placed on the licence holder by the regulatory authority.

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