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Scottish Universities Research & Reactor Centre

AN AERIAL GAMMA RAY SURVEY OF SPRINGFIELDS AND THE RIBBLE ESTUARY IN SEPTEMBER 1992

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The survey was commissioned from SURRC by British Nuclear Fuels plc.

SUMMARY

A short aerial gamma ray survey was conducted in the vicinity of the Springfields site and Ribble Estuary from 1st-5th September 1992, to define existing background radiation levels, against which any future changes can be assessed. A twin engine AS 355 "Squirrel" helicopter chartered from Dollar Helicopters was used for this work. It was loaded with a 16 litre NaI(Tl) gamma ray detector and spectroscopy system on the 31st August and during the following days over 2700 separate spectra were recorded within a survey area of 20 x 12 km. Gamma ray spectra were recorded every 5 seconds at survey speed and altitude of 120 kph and 75 m respectively. A flight line spacing of 0.3km was chosen for the main survey area. On the 3rd September a low altitude, high spatial resolution (flight line spacing 100m and altitude 30m) was made over Banks Marsh (an area frequented by local wild fowlers).

Survey results have been stored archivally and used to map the naturally occurring radionuclides ^{40}K, ^{214}Bi & ^{208}Tl together with ^{137}Cs and total gamma ray flux. In addition, for the first time, estimates of ^{234m}Pa in terms of deconvoluted count rate (normalised to 100m altitude) were made in the presence of ^{228}Ac interference probably in disequilibrium with its parent thorium series.

The maps provide a clear indication of the distribution and sources of environmental radioactivity in the Ribble at the time of the survey. The Ribble estuary is subject to regular and ongoing ground based studies by BNF, MAFF, HMIP, and University based groups, as a result of the authorised discharges of low level radioactivity from the Springfields site. The results of this survey complement this ground based work, and add to confidence that the estuarine system, it's associated sediments, tide washed pastures, salt marshes and river banks, have been thoroughly examined. There is support for earlier conclusions that the Cs on the salt marshes is the dominant source of external gamma exposure, and that the Springfields contribution to these locations is minor in comparison with this, Sellafield derived, signal. Upstream the situation is more complex, particularly where the dynamic sources of beta radiation are considered. As far as critical group assessments are concerned the survey provides clear evidence that the areas affected by ^{137}Cs, where external gamma dose and possible food chain effects are of greatest interest, are in the lower reaches of the Ribble, whereas, at the time of the survey the ^{234m}Pa distribution was in the upper reaches of the river. This not only confirms the findings of ground based work, but provides some assurance that the different exposure paths (external gamma dose, skin dose) are not entirely synergistic. The discovery of possible transient sources of natural ^{228}Ac in the salt marsh environment as a consequence of Th series disequilibrium immediately following spring tides is extremely interesting. If substantiated by further studies using semiconductor detectors this provides a new insight into the dynamic radiation environment of tide washed contexts.

Aerial survey can potentially provide a rapid and cost effective means of studying environmentally dynamic sources such as ^{234m}Pa. In the case of the Ribble it would be necessary to reduce survey height to below 50m ground clearance to improve spatial resolution. Possible inconvenience to residents and property owners of such low altitude flights would have to be considered in addition to the potential value of environmental knowledge of the behaviour of short lived nuclides in a dynamic system such the Ribble estuary. There is nonetheless considerable potential for time series studies of this location.

Recent flight trials by SURRC incorporating high efficiency germanium semiconductor detectors have verified the feasibility and potential a hybrid scintillation/ semiconductor spectrometer. Such a device can resolve any ambiguities arising from overlapping gamma ray peaks. This is particularly relevant to the confirmation of ^{228}Ac in salt marshes. Ground based sampling at the time of measurement would enable concentration calibrations to be made for these dynamic sources. Further ground based measurements would be desirable to establish the extent to which low energy photons contribute to external gamma ray dose rates from sources with pronounced subsurface activity maxima.

1. INTRODUCTION

A short aerial gamma ray survey was conducted in the vicinity of Springfields from 1st-5th September 1992 as part of a continuing programme of baseline mapping for nuclear sites. The survey, commissioned by BNF, extends the baseline surveys of BNF owned nuclear sites to three (Calder Hall, Chapelcross and Springfields). The main purpose was to define the existing radiation background from aerial survey heights to enable future changes to be assessed following repeat surveys. Additional objectives were to determine the capability of aerial survey radiometrics in the mapping of ^{234m}Pa and ^{228}Ac in the Ribble Estuary, and to demonstrate the high spatial resolution capability of the aerial survey technique. For calibration purposes and to aid data interpretation, soil samples were collected from a predetermined hexagonal sampling plan and analysed in the laboratory at SURRC. At the same time, a few samples were collected simultaneously by BNF for inter-laboratory comparison.

Aerial radiation survey techniques are particularly well suited to large scale environmental surveys and are highly complementary to subsequent ground based investigations. Their main strengths derive from the mobility of the observational platform, in this case a helicopter, and the spatial response of the detector, which averages signals over a field of view which can extend to several hundred metres. By recording a sequence of gamma ray spectra in flight, interleaved with navigational data and radioaltimetry it is possible to map the total radiation fields above a survey area. This leads to a highly effective means of locating areas of enhanced radiation, especially in remote locations or difficult terrain [1-7]. The method can be applied to total area searches at regional or national level, and the remote sensing nature of such measurements minimises exposure of survey teams to contamination or radiation hazards. These considerations, together with the speed of measurement, typically more than two orders of magnitude faster than ground based approaches, lead to important potential contributions to emergency response planning and implementation.

The ability to work in a complementary manner with ground based teams is no less important, allowing limited conventional resources to be effectively directed to areas of greatest need. Ground based in-situ spectrometry is capable of high spatial resolution and sensitivity, and leads naturally to sampling for investigation of radionuclide profiles and chemical speciation. However these methods alone are not particularly effective for large scale surveys due to their inherent lack of speed and low sampling densities. The combination of aerial observations and ground based studies provides a powerful approach to comprehensive evaluation of the radiation environment.

The radiation environment of BNF sites has been under study for many years for operational, regulatory, emergency response and research purposes. The majority of this work has been based at ground or sea level. However a brief aerial survey was conducted in Cumbria in October 1957 [8,9] immediately following the Windscale Fire. Although at that time the equipment available was not capable of spectral discrimination, the dominant nuclide, ^{131}I, was estimated by scaling total counts to ground measurements. More recently SURRC has conducted some 15 aerial survey projects using fully spectrometric equipment. These have included upland areas of West Cumbria affected by the Chernobyl accident and historic Windscale discharges[10], the immediate surroundings of the Sellafield[11] and Chapelcross[12] plants, and an area 2500 km^2 of Ayrshire districts for baseline definition purposes [13], South

West Scotland[14] and searches for lost radioactive sources [15].

The BNF Springfields Works manufactures fuel and fuel products for nuclear power stations in the UK and abroad[16], and is authorised by HMIP to discharge low levels of liquid effluent into the Ribble via a continuous discharge pipeline. Authorised discharge limits have historically been applied to total alpha and beta activity , and since October 1991 to include additional nuclide specific limits for ^{232}Th, ^{230}Th, Uranium,^{237}Np and ^{99}Tc. BNF reports demonstrate that only small proportions of the authorised discharge limits have been discharged in recent years[16]. Additional solid waste have been disposed of at Clifton Marsh, where radioactivity levels are satisfactorily within authorised limits. BNF conduct regular monitoring and sampling programmes of the Ribble estuary in particular measuring external gamma dose rates in silt and sediment at 8 statutory monitoring stations, and a number of additional points. In addition MAFF Fisheries Directorate examine coastal waters and mudbanks[17], and further monitoring is conducted, particularly for Uranium in faeces, soil and grass near Springfields, but also recently of similar samples from the Ribble river bank near the Springfields outfall[18]. The radiation environment of the Ribble is both dynamic and multinuclide. Contamination arising from Sellafield discharges (particularly ^{137}Cs and ^{241}Am) is known in the area, and gives rise to the main component of external gamma dose rates to critical groups. However the Springfields derived ^{234m}Pa, a short lived U series daughter supported by ^{234}Th, may represent a local source of beta exposure during periods where the plant is operational. The increasing importance of skin dose under ICRP 60 assessments has been pointed out recently[19], and although this component of radiation exposure is expected to remain within dose limits to the public, there is increasing interest in the behaviour of such nuclides in dynamic estuarine systems.

This project therefore aims to define the distribution of both the main components of external gamma exposure, to support ground based sampling and monitoring programmes, and to examine the possibility of detecting the dynamic components associated with beta emitters. It is hoped that the production of total area maps may help not only to focus future monitoring and sampling programmes, but also may offer some assurance to the general public that the distribution of activity arising from past low level discharges is well known.

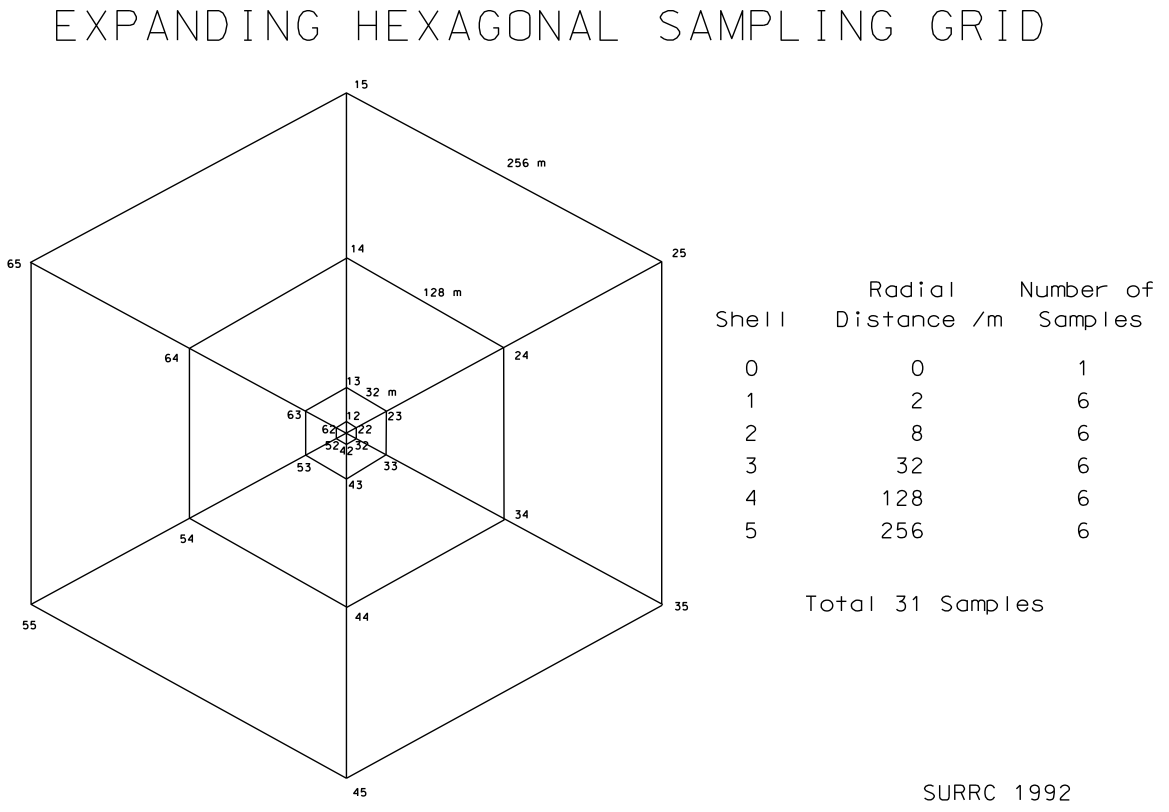
2. SURVEY PLANS

2.1 Soil Sampling Strategy

Typically a detector measuring ^{137}Cs at aerial survey altitudes of between 50m and 100 m has a field of view of 130 m and 195 m radius respectively (dependent upon the source mass relaxation depth). This typically represents a centre weighted area sampled of $6x10^6$ and $1.4x10^7$ greater than a typical 2 kg soil sample. Thus, clearly, there is a problem in spatially matching soil sample strategies with in-situ detector measurements. This in conjunction with inherent site variability requires ground verification with soil samples to take into consideration site variability and the centre weighted averaging of activity within the field of view of the detector.

Detector fields of view can be calculated with photon transport equations, which take into consideration of detector altitude and shape, the distribution of source activity within the soil or sediment column, attenuation within the soil and air path length and photon energy (Refs). Having determined the fields of view for the underlying environmental parameters a sampling plan can be developed to match these calculated fields of view.

Several sampling strategies have been developed at SURRC based on concentric circles weighted to match the field of view of ^{137}Cs at 100m [12-14]. This sampling strategy, whilst able to quantify the amount of activity within the field of view of the detector at 100 m height with an associated sampling error, it was not flexible in its ability to estimate activity for any detector height above ground for any radionuclide, nor quantify the variability within a particular field of view with sample spacing.



Shell	Radial Distance /m	Number of Samples
0	0	1
1	2	6
2	8	6
3	32	6
4	128	6
5	256	6

Total 31 Samples

SURRC 1992

Figure 2.1 Hexagonal Sampling Carried out at Warton Bank, August 1992.

The expanding hexagonal sampling plan was developed as part of PhD research at SURRC and was illustrated on the Caerlaverock salt marsh [13,14] and Wigton salt marsh [14]. For the purposes of flexible calibration and consistency, an identical sampling plan was set up on Warton Bank for Springfields calibration. Shells can be set up on a x 2, x 3 or x 4 basis.

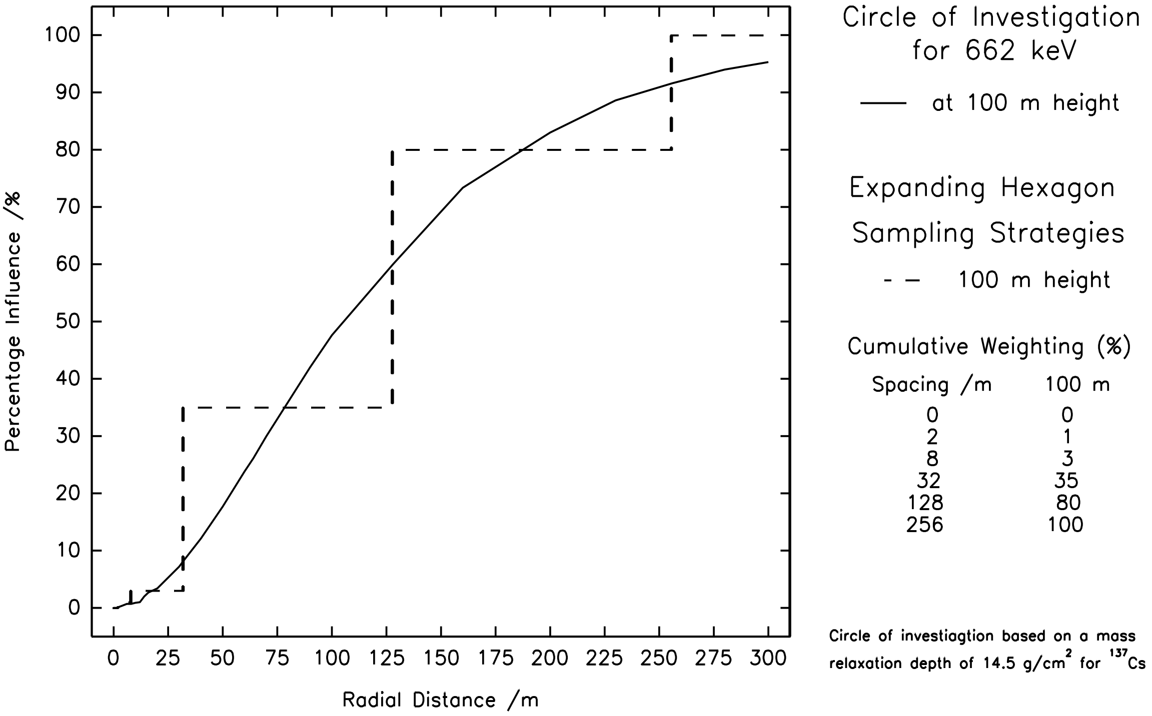


Figure 2.2 The Relationship between the Circle of Investigation for ^{137}Cs at 100 m altitude and the appropriately weighted Hexagonal Sampling Strategy.

Figure 2.1 illustrates the five shell configuration set up on Warton Bank.

By weighting the inventories associated with each shell appropriately, the sampling plan can be forced to match the circle of investigation for a detector at any appropriate height. When using this weighting in the averaging of shell inventories and sampling errors, this will provide the mean inventory associated with that detector height as illustrated in figure 2.2.

Provisional site locations were determined in the laboratory prior to field work on the basis of representability of the area of interest, access and safety both from land and air, potential activity distribution and lateral extent. With these criteria, Warton Bank was identified as the ideal site, with Banks Marsh held as a possible alternative.

2.2 Baseline Mapping

The survey area comprised a main rectangular box 20 x 12 km approximately centred about the Ribble Estuary and River together with a single flight line up the River Ribble through Preston (figure 2.3).

The main zone, bounded by OS coordinates SD 300320, 500320, 300200 and 500200 was flown at 300 m resolution and selected to provide detailed baseline map of the distribution of anthropogenic and natural radionuclides in the area to the south and west of Springfields. This includes the towns of Lytham St Annes, Freckleton, Hutton, Longton, Much Hoole, Tarleton, Banks and the very northern part of Southport.

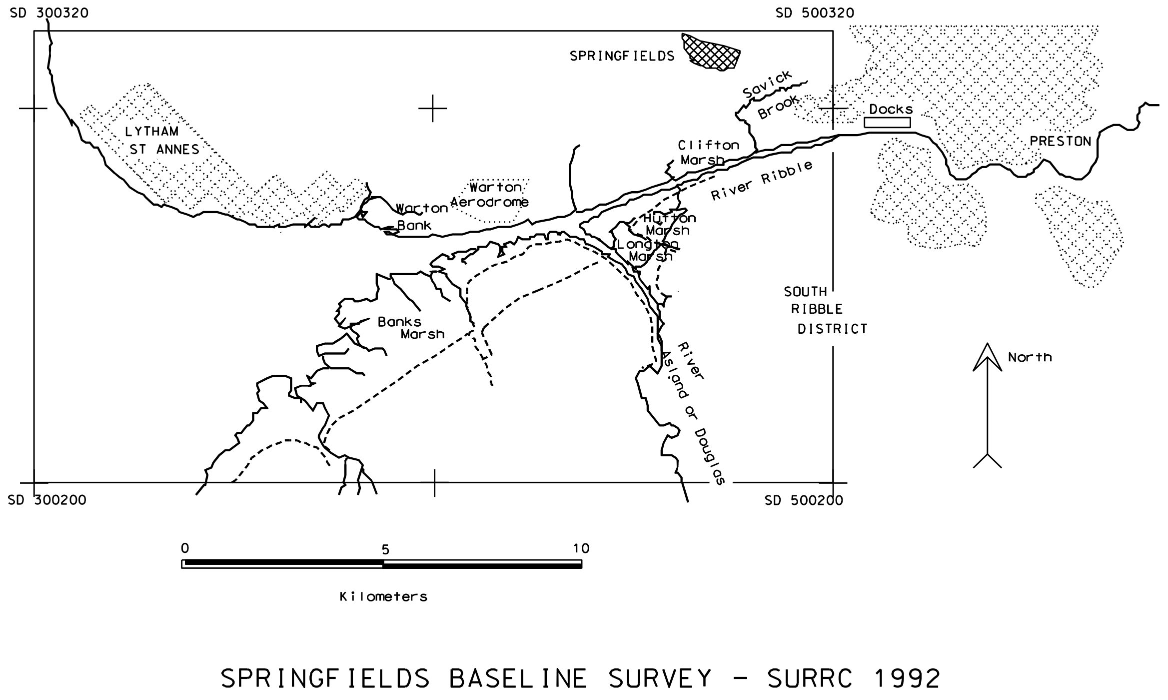


Figure 2.3 The Survey Area and River Ribble

East-West flight lines were chosen, set 300 m apart and labelled sequentially as illustrated in figure 2.4. Flight speed and integration period were selected to provide comparable spatial resolution along the flight lines. The baseline survey also included an area of detailed surveying, flown at 30 m altitude and by free flying at approximately 100 m line spacing centred around Banks Marsh, also illustrated in figure 2.4.

This flight plan was chosen to in order to aid the new and advanced development of the aerial survey technique to the mapping of ^{234m}Pa and ^{228}Ac in the environment. Banks Marsh was chosen for detailed spatial flying because of interest expressed by Springfields into critical group assessment on this site with special regard to wild fowlers.

Provision was made to conduct the survey from BAe Warton Aerodrome, which was centrally located in the survey area. Working space for data reductions and processing was provided by Flight Operations. Ground power was supplied to the survey instruments onboard the helicopter via a portable generator.

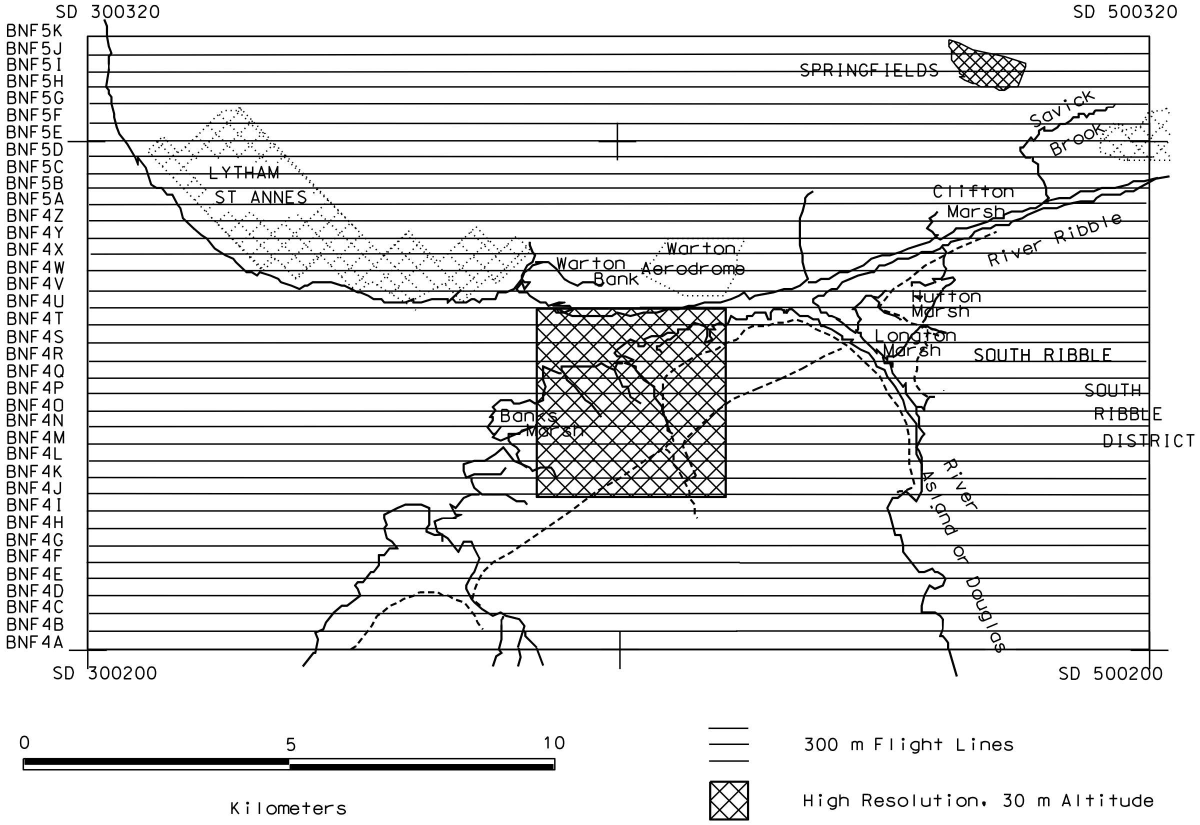


Figure 2.4 Flight lines flown in the Ribble Estuary

3. FIELDWORK

3.1 Field Sampling

On the 26th August, permission was gained by the local farmer to visit Warton Bank salt marsh. Exploratory investigations by A.N. Tyler and M. Graham (SURRC) with a 3"x3" NaI(Tl) detector coupled to a Canberra Series 10 MCA, confirmed the approximately homogeneous ^{137}Cs signals across the site. Therefore a decision was taken to proceed with sampling. The field team was then joined by M. Kerr (BNF Springfields) and M. Parker (BNF Sellafield). The sampling hexagons were surveyed rapidly using a compass, ranging rods and a pre-marked guide string. Each sampling location was marked by a wooden peg. A total of 31 sampling locations were laid out as illustrated in figure 2.1. Two transects (1 and 4, positions 1 to 5) and the central core were then rapidly sampled (figure 2.1) with a 105 mm soil corer to 30 cm depth, under extremely poor weather conditions. The samples collected were whole and intact. These were bagged and carefully labelled. A parallel set of samples was collected from 5 sites with a 71 mm diameter corer at locations 01, 12, 13, 14, 42, 45 for cross comparison between the SURRC and BNF (Sellafield) coring systems.

The following day, 27th August, the remaining 4 transects and 20 cores were collected. The centre of the hexagonal site was clearly marked to aid identification from the air, and a central in-situ gamma spectrum recorded at ground level.

3.2 Detector Description

The spectrometer comprised a standard 16 litre NaI detector coupled to an SURRC aerial radiometrics rack containing instrumentation power supplies, EHT, pulse height analyzer and data logging computer. The installation incorporates a flexible power supply capable of operation from mains, under self power for a period of roughly one hour (which may be supplemented with external batteries) and for unlimited periods when supported by the aircraft 28 V dc supply. The equipment was shock mounted to a laminated fibreboard baseplate rigidly mounted to the rear section of the helicopter floorpan. This installation was devised to ease rapid installation following the 1990 Sellafield survey with Dollar helicopters, and has been approved by CAA following brief flight trials in 1991[20]. It was used successfully during the Chapelcross baseline survey[12]. Navstar XR-4 GPS satellite navigation system was incorporated in the spectrometer, following successful functional trials in 1991, and proved extremely useful at Chapelcross. This survey also used GPS position logging. The uncertainties in stand-alone mode are typically better than 50m, but can be extend to 100m or poorer on occasions. An opportunity was taken to evaluate a real-time differential GPS facility which uses corrections from a fixed terrestrial base station, transmitted to the aircraft via a telemetry link, to compensate for error producing terms in the stand alone receiver, including the deliberate degrading signal introduced by the US Department of Defence under "selective availability". This differential system operated successfully, producing estimated precision of better that 5-10m in the aircraft, and would be useful for any future high-resolution (ie line spacing of 100m or better) surveys which might be contemplated in the future.

The detector consisted four identical 10x10x40 cm NaI scintillators, operated through a bifet summing amplifier and trimmed to give composite energy resolution of 10% at 662 keV. Resolution of better than 11% was maintained throughout the survey. The selection of a 16 litre detector for this survey was made to provide optimal sensitivity for baseline mapping. For emergency response purposes a smaller 8 litre detector would be considered in preference; both detector packs have been cross calibrated on several occasions.

3.3 Installation

The equipment was installed in a twin Squirrel helicopter at Cumbernauld Airport. The main spectrometer installation was rapid; the most time-consuming step being to mount the GPS antenna and cable on the rear of the tail boom. For rapid installation under emergency response conditions it would be desirable to have GPS antennae as permanent fixtures.

3.4 Flight Testing and fieldbase establishment

The survey was established at the BAe Warton Airfield within Flight Operations of Air Traffic Control, with kind permission of Mr. Bill Rose. A complete set of spare parts for the spectrometer and computing systems for data backup and preliminary analysis was transported there by car and an office area set up. Mains power was supplied by portable generator to the aircraft to maintain detector bias and battery levels overnight using a circuit breaker and extension cable.

Functional tests of the spectrometer were made during the flight from Cumbernauld to Warton. Spectrometer stability was confirmed by monitoring the position of the natural 40-K peak (at 1462 keV).

Flight tests were completed on 1st September with radioaltimeter calibration, and testing of position capturing routine based on GPS.

3.5 Recording

The recording technique adopted in flight followed standard SURRC procedures. Gamma ray spectra were recorded into 511 channel pulse height spectra with an integration time of 5 seconds. Full spectra and a table of 8 selected regions of interest were written directly to hard disc, labelled with time and date of acquisition, time averaged radioaltimetry data and interleaved with positional information for each spectral pair. This provides all the information needed to form maps automatically once on the ground.

A significant development was introduced during the Chapelcross survey, using the GPS satellite navigation system for automatic positional capture. On previous surveys positional information was derived from Decca navigation equipment installed on the aircraft, and input manually to the spectrometer between each spectral pair. This has been successful, and enables avionics instrumentation to be used. However precision is limited to some 200 m, the Decca facilities are not available on all possible survey aircraft, and a considerable operator workload is committed simply to track logging. The procedure adopted in this survey was to capture RS-232 data from a Navstar XR4 GPS system every 2 seconds, providing time, latitude longitude, 95% triangulation error estimates and satellite status information, when needed within the acquisition cycle. These signals were decoded within the SURRC data logging programme and appended to spectroscopy files in an identical manner to previous surveys, thus ensuring compatibility with mapping software. A parallel navigational log summary was also recorded to permit assessment of the GPS performance. Options to revert to external input or to record data for retrospective track reconstruction have been retained for use in the event of GPS failures.

The possibility of using differential GPS for high resolution aerial survey applications was investigated with assistance from Clive de la Fuente of NavStar. This proved successful, and would be useful for low altitude, high spatial resolution (<100m) radiometrics. For work with stand alone GPS, the nominal 100m or better precision is well within the detector fields of view (400-500m) at normal aerial survey altitudes.

The choices of 5 second integration time, 65 knot speed and 60-75 m nominal ground clearance were made after consideration of the spatial response of the detector, performance data for the helicopter, and the counting statistics of the 16 l. detector. The field of view of the detector varies with survey height and gamma ray energy[21-23]. There is also a slight topographic influence. However the most important feature for practical purposes is the influence of aircraft height. A static detector receives 90% of its signal from a centre weighted zone with diameter at 662 keV of roughly 4-5 times the ground clearance. At 75-100 m altitude this means an effective spatial smoothing of 300-500 m. Allowing the aircraft to transit a distance up to this circle of investigation within each reading leads to a safe and economical flight without loss of spatial detail. It is extremely important to take the spatial characteristics of these data into account when interpreting features recorded, and when making comparisons with ground based results.

The detector display during flight indicated the position, acquisition status, average height above ground and gross and net rates within 8 spectral regions of interest. This display was updated every 5 seconds in flight. All of these data plus full pulse height spectra were recorded on hard disc.

The procedures for archival backup and data transfer are described more fully in section 4. The essential feature is that duplex backup copies of all data and initial reductions were made on the aircraft and transferred to a ground based computer before clearing the primary copies and resuming survey.

3.6 Field Measurements

Each daily flight was preceded by a check on the resolution of the 662 keV line from ^{137}Cs, using a 370 kBq reference source placed beneath the aircraft. Detector gain was continuously monitored using the natural ^{40}K peak, and maintained within 1% of 6 keV per channel at all times.

4. DATA ANALYSIS

4.1 Soil Sample Analysis

On return to the laboratory the samples were cut into 15cm intervals with five samples collected from the north-south transect divided into 2 cm and 5 cm intervals in order to determine the source mass depth characteristics. These samples were then weighed and dried at about 40 ^{o}C. Once dry, the samples were reweighed and subsequently ground and homogenised in a 1 kg capacity Mixer Mill. Sub-samples were then taken and placed in standard size 150 cc polystyrene geometry containers.

Two 50% relative efficient n-type HPGe detectors were then calibrated. This was undertaken with uncontaminated soils of varying density spiked with an Amersham International mixed gamma radionuclide reference standard. Thus the calibration is density compensated and all samples are IAEA traceable. Samples were counted rapidly, with sufficient counting statistics for ^{241}Am and ^{137}Cs validation.

Also, several surface samples were counted for several days on a Ge(Li) detector soon after the field work for ^{234m}Pa measurement, paying particular interest to the 1001 keV and 766.4 keV energy lines.

4.2 General

Each full record stored by the spectrometer includes quality assurance information on acquisition time, positional fixes, radioaltimetry data, a table of integrated count rates in preselected regions of interest together with estimates of their associated poisson errors, plus the full spectra recorded over 511 channels. Gain stabilisation is achieved using the natural ^{40}K peak. A gain monitor is based on comparing the ratio of two windows (k1/k2) arranged to bisect the 1462 keV full energy peak. If this ratio is significantly different from 1 then gain adjustments can be made manually to the detector high voltage. Keeping the gain monitor between 0.7 and 1.3 is equivalent to better than ±1% gain shift, and this in turn has previously been shown to have a negligible effect on spectral characteristics.

The acquisition rate during survey was high - resulting in over 2700 gamma spectra recorded over the four survey days. The emphasis of SURRC data handling procedures has been to allow such sets to be reduced rapidly and in a manner which automatically leaves a traceable quality assurance trail. A suite of programmes has been developed in the "AERO" package, capable of flexible reduction, analysis, mapping, statistical summarisation and spectral display. Production of mapped survey data follows five main stages described below together with a brief statement on quality assurance and a summary of the present status of the calibration. Preparation of hard copies of maps and archival results was conducted afterwards at SURRC.

4.3 Summary file formation.

The first stage of data reduction was the formation of compressed summary files - each containing a series of single line entries for each spectral observation. These comprise the positions, altitudes and 6 integrated count rate estimates at preselected energy windows.

Windows were chosen, to estimate ^{137}Cs, ^{234m}Pa, ^{40}K, ^{214}Bi, ^{208}Tl and the total dose rate using an integrated window above 450 keV. Each line of survey data was initially assigned a single summary file. Formation of summary files, and tabular printout was conducted during the survey in a manner which kept pace with the previous flight. Numerical assessments were therefore available on the day of flying.

4.4 Background Subtraction

The second stage of data analysis was to link the summary files forming the survey area together into area records of net count rate. Detector background count rates (recorded at high altitude or over clean water) were subtracted at this stage. A complete summary file describing the net data set was formed in the process, together with a header recording the background count rates used. This net file is also printable in tabular form, and is available for mapping or for subsequent calibration.

4.5 Spectral Stripping.

Spectral interferences occur with NaI spectroscopy due to the combined effects of unresolved full energy peak overlap (line interference) and scattering both in transport from source to detector and also within the detector. This leads to multiple contributions to net count rates within each integrated window. These are deconvoluted using a matrix inversion stripping method which depends on values for the fractional interference from pure radionuclide sources into each region of interest. A matrix of fractional interferences between each channel is assembled and inverted. Stripped counts for each channel are obtained by matrix multiplication of the inverse stripping matrix and a vector representing net count rates. Again a full file copy of the data set is produced in printable form, available for mapping or further analysis.

As with previous surveys the stripping matrix was estimated by laboratory measurements of pure nuclide sources. In this case however a set of standard 1 m^2 calibration pads, doped with potassium, U series and Th series activities was used in preference to small scale laboratory sources. The pads themselves were purchased in 1991 through the Geological Survey of Canada[24] and are an internationally traceable standard for field spectrometry. In addition, stripping matrices were experimentally derived to account for altitude dependence. The simulation of the air column between source and detector was achieved by using perspex sheets of suitable thicknesses. Monte carlo simulation of gamma-ray scattering within the environment and detector may eventually lead to the determination of a final set of corrections for stripping in standard aerial survey detectors.

The detector response to ^{137}Cs has been made from carefully fabricated doped plywood sheets, providing a surface area of 1m^2. The placement of these sheets upon a background calibration pad (a blank), provides a more realistic simulation of the physical form of the activity found in the environment, than has been previously been made.

4.6 Altitude Correction and Calibration.

The final conversions to calibrated data combined altitude corrections with sensitivity estimates. Stripped data were first converted to standardised values at 100m altitude. The form of the altitude dependence is an exponential integral, however a simple exponential approximation is adequate for survey heights over 30m above ground. Coefficients were determined in 1990 during the SURRC survey of Ayrshire [13]: the altitude dependence factor of ^{234m}Pa was determined by simple interpolation from existing data. Calibration was achieved (with the exception of ^{234m}Pa) using a set of linear equations determined by comparison of ground based readings from known sites with aerial survey data. The calibrated data set has been printed out and is stored archivally at SURRC for future reference.

4.7 Mapping

Radiometric maps were produced from the calibrated data following standard procedures. The calibrated data files were read into the AERO program, and latitude and longitude coordinates transformed to OS grid references, which were also used as plotting coordinates. This produced an implicit set of x and y values for each observation. Thereafter the calibrated level for each nuclide was sequentially selected for allocation to the z variable. A new routine to allow concatenation of "XYZ" files was used at this stage to produce complete records for each nuclide individually, covering the whole survey. These files can be read back into the package directly as a quick entry point to mapping, and can also be exchanged with standard mainframe graphics packages. Before mapping, the z values were examined statistically (histograms, summary statistics) and assigned to up to 14 colour codes using linear or logarithmic coding. Linear coding was applied to all channels except ^{137}Cs.

Once colour-coded the individual data points were plotted in their appropriate colours on a high resolution monitor and then subject to a spatial contouring procedure whereby each screen pixel was replaced by the colour code corresponding to the average value of all data points within a certain locality, weighted inversely in proportion to distance from the implied position. Screen capture routines were used to store the resulting images, which were then printed using a Tektronix 4697 colour inkjet printer. Geographical detail was added using a CAD/CAM system.

4.8 Quality Assurance

Attention was given to quality assurance at all stages of the work. The recording technique and data nomenclature are designed to enable a continuous check of spectrometer operation possible in flight, and to allow rapid traceability of full records from each reading for quality control purposes thereafter. The archive for the survey is fully retrievable, doubly backed up, and use has been made of ASCII text only files for all data storage to enable quality assurance checks to be made. The data reduction stages are all self recording, and the archive is so structured that primary data can be examined readily where any unusual features have been located. Finally the algorithms used have been tested with known data.

4.9 Status of the Stripping and Calibration Constants

The values of stripping factors and calibration constants used in this work are shown in appendix A. These represent current SURRC working values at the time of the survey. Such values are under continual review, and may therefore be subject to future change. Their status is as follows.

The stripping factors have been discussed above. Although experiments with absorbers and transport calculations are expected to lead to further revisions to stripping matrices in the future, this is only likely to effect Cs estimates close to the detection limit of approximately 1 kBq m^{-2}. For spectra where full energy photons comprise the major contribution to window count rates, stripping has a neutral effect. An error analysis of the stripping process was conducted in 1988 following the SURRC survey of West Cumbria[10]. This showed that the combined statistical errors in full energy peak estimates for ^{137}Cs at levels above 15 kBq m^{-2} were better than ±10%. In the tide washed pasture context the statistical precision of ^{137}Cs is typically better than 2%.

The gamma dose rate estimates were derived by scaling integrated spectra above a 450 keV threshold to ground based dose rate measurements on calibration sites. This high energy threshold method derives from a ground based technique designed to avoid problems associated with the low energy over-response of scintillation detectors. It is believed to be accurate within ± 10-15% for evaluating dose rates from natural media. The potential of systematic underestimation from anthropogenic sources with complex vertical distributions has been recognised, but not yet quantified.

The calibration data for nuclide inventories, and any associated systematic errors, depend on comparison between ground sites where inventories have been estimated by gamma spectroscopy of collected cores with correlated aerial survey data. The values used here derive from an analysis of data from Warton Bank and Caerlaverock where ground to air comparisons could be made, spanning a range of ^{137}Cs activities from 0-500 kBq m^{-2}. It is implicit in the calibration process that the vertical distribution of activity in the survey area is comparable with that from calibration sites. Furthermore it is vital that lateral spatial association, and spatial variability of deposition be considered when comparing aerial survey and ground measurements. Aerial survey results are spatially smoothed over 10^4-10^5 m^2 whereas soil cores typically represent sampling areas of $10^{-2}m^2$, or less. Ideally calibration experiments would be conducted over uniform areas of deposition. While this may be practicable for natural radioactivity, it rarely, if ever occurs with anthropogenic deposition in the environment.

The original calibration performed in 1988 used data obtained from 12 sites in SW Scotland selected from over 50 analysed to maximise Cs contrast. An extremely good correlation between aerial and ground based data was obtained. The resulting working calibration was concordant in West Cumbria (1988) with spatially matched results from 1400 soil samples collected by MAFF on a 200m cartesian grid, however the high degree of spatial variability exhibited by the latter, and the relatively small numbers of associated aerial survey observations limited more detailed conclusions. SURRC surveys in 1989 were calibrated by re-flying calibration sites and lines through West Cumbria using new detectors and projecting sensitivity estimates onto them, and collecting a limited number of extra cores from each survey to confirm traceability. Procedures for overlaying two or more aerial survey data sets and cross comparing their results were developed for this purpose.

Finally in 1990 a new set of local calibration sites was defined in Ayrshire with ground samples collected in a manner which attempts to overcome the problem of spatial matching. In this work each site has a pattern of 17 soil sampling locations laid out on three concentric arcs around a marked centre with an area density which approximates the field of view of a static aerial survey detector. Aerial survey readings are taken on these sites while hovering at various heights above the centre marker, thus providing better counting statistics than obtained during dynamic calibration measurements, and data to determine altitude corrections.

The unweighted mean of the 17 soil cores gives a better ground estimate of mean activity than single cores or other sampling configurations. These new sites produced a total of over 150 soil samples for high resolution gamma spectroscopy. A preliminary analysis of roughly half of these data together with old sites was used to determine the 1990 working values which were used to calibrate these data. The working values are not significantly different from those used in earlier surveys - suggesting that sensitivity estimates may be approaching final values. For ^{137}Cs they are also within error of theoretical sensitivity estimates based on laboratory efficiency determination and geometrical integration of uniform activity distributions.

The expanding hexagonal sampling plan tested at Caerlaverock extended this concept of spatial weighting of soil cores so that response functions at different altitudes could be evaluated. The results from both in-situ gamma spectrometry and soils cores at this site indicate that it had maximal ^{137}Cs activity it the centre point, with a significant fall-off at radial distances beyond 32 m. from the centre point. Natural nuclides were much more uniformly distributed. The weighted estimate for ^{137}Cs, based on high resolution gamma spectrometry, for the activity seen at 100m altitude is 50.8 kBq m^{-2}. This value compares with observed values of 49.8 kBq m^{-2} (BNWES168A , 66 m height), 41.6 kBq m^{-2} (BNWES168b, 74 m) and 39.6 kBq m^{-2} (BNWES169a, 100m) recorded above the calibration mark on 6th February, and evaluated using the "working" sensitivity values. The aerial survey results thus appear to underestimate inventory by some 20-30% on this site. Given the lateral variability (by more than 50% over the detector field of view), and the possibility that vertical activity profiles are variable throughout the tide-washed zones, it was decided to note this potential under-response but to retain earlier working values for the purpose of mapping, thus ensuring consistency with previous surveys, and avoiding over-estimation of inventories for near surface terrestrial sources.

The vertical distribution determined at Caerlaverock showed a pronounced sub-surface maximum at 10-15 cm depth, which is one obvious contributory factor for the systematic under-response in estimating inventory on the tide washed pasture. Where the lateral dimensions of tide washed pastures are smaller or comparable with the field of view of the detector, then there is further potential for compounded under-estimation of Cs inventories by aerial survey. Therefore it is recommended that the inventory estimates be interpreted cautiously as representing probable lower limits to the inventories of tide washed contexts. These factors should not be overlooked in making comparisons with ground based observations.

In light of the experience at Caerlaverock, a calibration site for the Springfields survey was required. The site had to represent an effective infinite plane source that was potentially uniform in its characteristics. Hence the site at Warton Bank was chosen. Subsequent laboratory analysis of the soil cores illustrated significant ^{137}Cs sub-surface maxima across the site which lead to a marked change in the calibration constant as illustrated in section 5.1.

5. RESULTS AND DISCUSSION

5.1 Warton Bank Sediment Analysis and Interlaboratory Comparison

The results of the soil core analysis are illustrated in Appendix B in terms of both activity per unit weight and activity per unit area. The sample location numbers are illustrated in figure 2.1. Six of the samples from the north-south transects have been selected and subdivided into 2 cm and 5 cm depth distribution portions. The remainder were divided into to 15 cm intervals. The data is summarized as integrated inventories with depth and are illustrated in table I.

Table I Integrated Inventories from the Expanding Hexagon at Warton Bank for ^{137}Cs Activities (kBq m^{-2}).

Transect	**Hexagonal Shell No (Spacing m)**					
No.	**0 (0)**	**1 (2)**	**2 (8)**	**3 (32)**	**4 (128)**	**5 (256)**
1	314.20	338.52	349.45	315.19	366.75	53.68
Error	5.13	11.49	13.24	7.70	5.88	1.17
2		301.11	285.68	230.61	189.93	132.17
Error		10.48	9.90	7.77	6.53	4.14
3		431.12	386.37	217.32	204.96	159.65
Error		14.64	13.00	7.31	7.16	5.41
4		159.89	321.19	159.87	175.13	610.94
Error		5.65	11.15	5.44	2.78	10.50
5		395.41	388.92	412.00	360.36	265.53
Error		12.88	12.99	14.28	11.02	7.63
6		334.58	364.31	226.02	110.74	138.21
Error		11.60	12.56	8.30	3.98	4.78
Mean	**314.2**	**326.77**	**349.32**	**260.17**	**234.65**	**226.70**
St. Dev.	**5.13**	**85.93**	**36.53**	**81.67**	**95.76**	**182.73**
St. Err.		**35.08**	**14.91**	**33.34**	**39.10**	**74.60**

By weighting the expected observations from each shell appropriately, the expected activity observed by the detector can be calculated and used for calibration. Table II illustrates the spatially weighted and averaged results for a detector at 1 m, 50 m and 100 m altitudes. The relatively small change in inventory estimates with detector height illustrates the relative spatial homogeneity of the site, in contrast to that experienced at Caerlaverock salt marsh. Relatively large changes in inventory estimates are observed at sample spacings of 256 m (table I), which does not contribute significantly to the error estimate of detector calibration at 100 m altitude (table II).

Table II Illustrating the Spatially Weighted Mean Activities for ^{137}Cs at Caerlaverock Sampling Site

Radius metres	**Percent Weighting**	**Cumulative Percentage**	**Activity kBq/m^2**	**St. Dev. 1 σ**	**St. Error of Mean**
Detector Height 1					
0	10	10	314.20	5.13	5.13
2	70	80	326.77	85.93	35.08
8	17	97	349.32	36.53	14.91
32	3	100	260.17	81.67	33.24
	Weighted Mean		**327.35**	**28.60**	
Detector Height 50 m					
2	2	2	326.77	85.93	35.08
8	7	9	349.32	36.53	14.91
32	47	56	260.17	81.67	33.24
128	34	90	234.65	95.76	39.10
256	10	100	226.70	182.73	74.60
	Weighted Mean		**255.72**	**93.49**	**38.12**
Detector Height 100 m					
2	1	1	326.77	85.93	35.08
8	2	3	349.32	36.53	14.91
35	32	35	260.17	81.67	33.34
128	45	80	234.65	95.76	39.10
256	20	100	226.33	182.73	73.60
	Weighted Mean		**245.33**	**107.36**	**43.63**

However, of particular importance to aerial survey observation interpretation and calibration is the source depth distribution within the sediment profile. This phenomenon is illustrated in both A.N. Tyler and J.D. Allyson's forthcoming PhD thesis'[25,26] and has a considerable control on the photon fluence rate. Source depth distribution is quantified in terms of mass depth (g cm^{-2}). Figure 5.1 illustrates the variation in source depth of ^{137}Cs across the calibration site at Warton Bank. There is a clear decrease in the sub-surface maxima with distance from the Ribble River, although over the central portions of the area (within a 128 m radius), the mean mass depth appears to remain fairly constant. Such source burial must have overriding consideration in the interpretation of aerial survey data. A significant change was observed in the calibration constant for ^{137}Cs. This is explained by the source burial characteristics; greater than that observed at Caerlaverock; and thus the new calibration constant had to be employed for this survey. However, this is likely to cause an overestimation in the ^{137}Cs activity associated with weapons testing and Chernobyl fallout on land by a factor of 2.6.

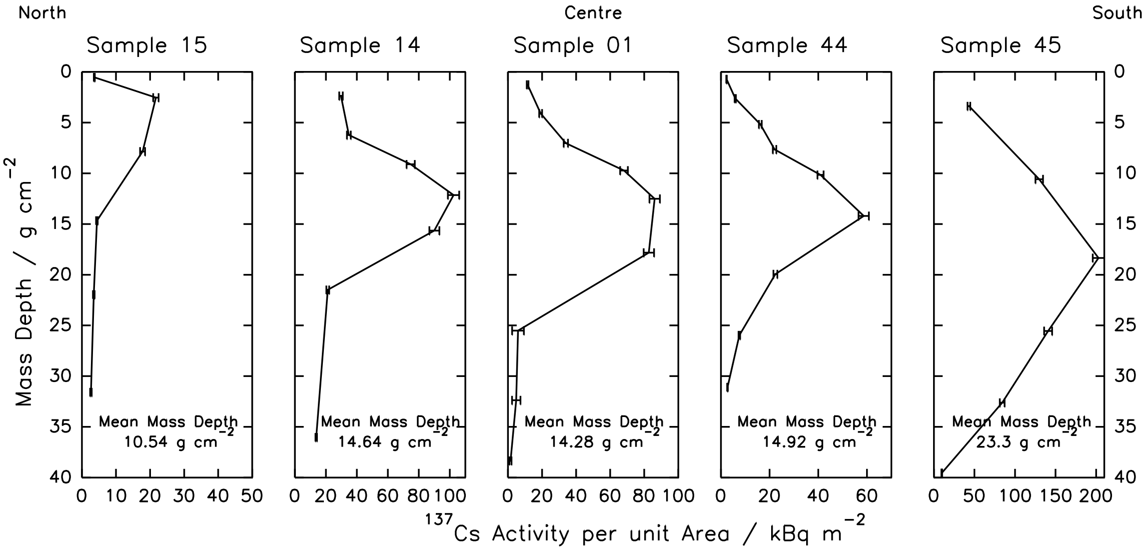


Figure 5.1 Illustrating the change in ^{137}Cs mass depth profile with position across the Warton Bank calibration site. Spacing between sampling positions = 128 m.

^{234m}Pa concentration estimation for the Warton Bank site was calculated to be of the order of 40 kBq m^{-2}. This estimate is prone to considerable analytical error for statistical reasons, and represents an upper limit to the activity, decay corrected to the time of sampling. This is significantly lower than observed in samples collected by BNF in other upstream areas of the Ribble, with typical ^{234m}Pa/^{137}Cs values of about 100 (Wilson pers comm). However this is consistent with the observed distributions of ^{234m}Pa and ^{137}Cs found by the aerial survey.

^{228}Ac levels on Warton Bank are estimated to be in the region of 12 kBq m^{-2} and ^{40}K, ^{214}Bi and ^{208}Tl are of the order of 170 kBq m^{-2}, 8.8 kBq m^{-2} and 4.5 kBq m^{-2} respectively (20 % error). These provide calibration coefficients consistent with the Caerlaverock calibration site. From these levels measured at Warton Bank, it would appear that ^{208}Tl was approximately in equilibrium with ^{228}Ac at the time of measurement. Therefore any excess ^{228}Ac which had been present at the time of sampling, or which was present the following week during the aerial survey (after a high spring tide had flooded the salt marsh) was probably unsupported by ^{228}Ra.

The results of the inter-laboratory comparison of samples collected by BNF and SURRC at Warton Bank are illustrated in figure 5.2. The random distribution about the 1:1 comparison line suggests that the small discrepancies are controlled by sampling error. Current verification of this is underway with each laboratory measuring the others samples.

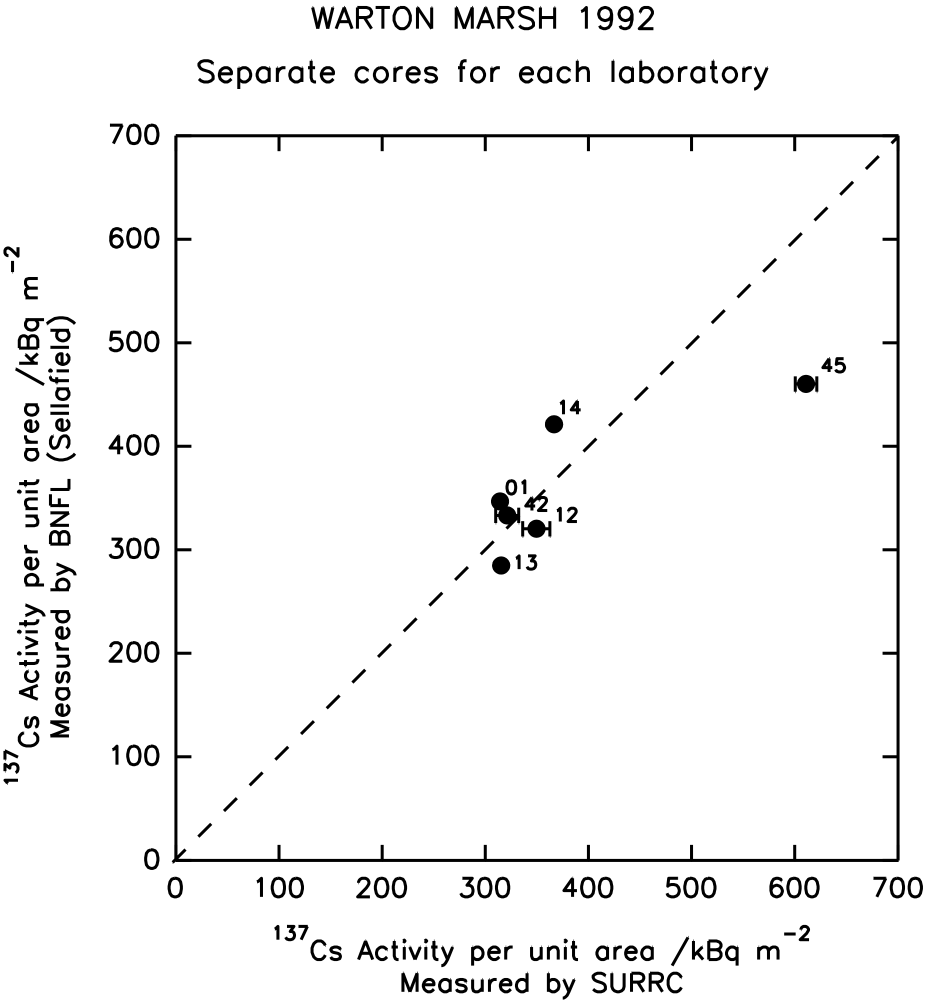


Figure 5.2 Illustrating the results from corresponding samples collected by BNF and SURRC at Warton Bank.

5.2 Aerial Survey Results

A frequency histogram of survey gain stabilisation (k1/k2 ratio) is shown in figure 5.3. From this data and figure 5.4, it is possible to estimate the average and range of percentage gain drift during the entire survey. A mean of 1.11 corresponds to a gain of -0.45% and is likely to be easily within the experimental accuracy of figure 5.4.

The baseline maps for ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl, gamma dose rate and estimates of stripped ^{234m}Pa & ^{228}Ac are presented in figures 5.7 to 5.17. In interpreting these maps the spatial averaging of the aerial measurements and the contouring process should be taken into account, together with the comments on underresponse from buried sources above. This leads to a slight tendency to broaden spatial features and to reduce maximum values particularly for boundaries less than the spatial resolution (500m) of the survey. Small scale features will also be underestimated.

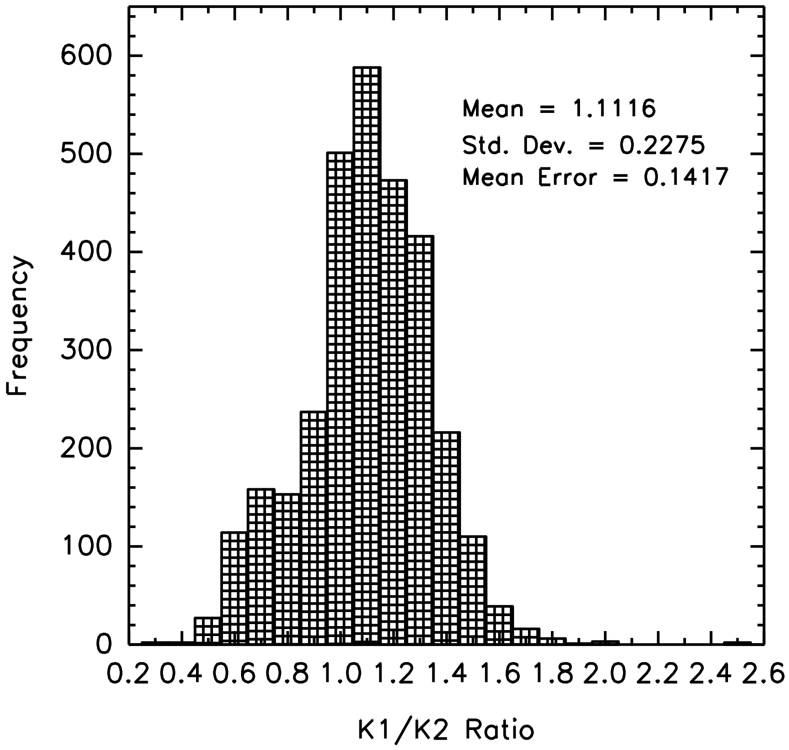


Figure 5.3 Variation in k1/k2 ratio.

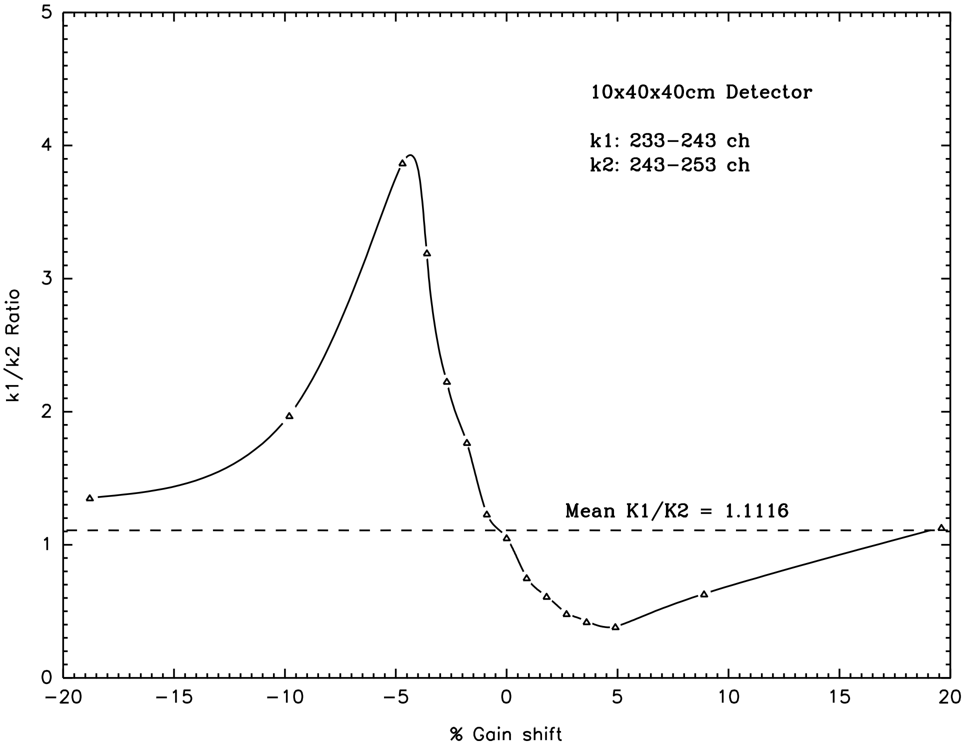


Figure 5.4 k1/k2 ratio as a function of percentage gain shift.

The ^{137}Cs map shows a number of features associated with the Springfields site and the liquid effluent from Sellafield discharges accumulating in the tidal waters of the River Ribble. The most significant levels of ^{137}Cs are found in the salt marsh regions near the entrance of the estuary, where inventories up to and over 500 kBq m^{-2} are observed, both from the aerial survey and from the calibration measurements undertaken by SURRC and BNF. The upstream signal does not extend much further than 1km east of Savick Brook to any degree, however small source geometry may have led to the underestimation of signals from narrow mudbanks in these areas. It would appear that the historical development of land reclamation at Hesketh Out Marsh and Hesketh New Marsh, is reflected in the variation of deposition. For the latter the tidal barrier may have been breached at high tide during the past or redistribution of soil may have occurred through farming practices (as indicated by the corresponding variations of the natural emitters).

Weapons fallout and Chernobyl derived Cs contamination is below 14 kBq m^{-2}, and will be overepresented due to the calibration factor used.

Geologically the area is predominantly represented by Permian and Triassic sandstones and mudstones. However, the natural radionuclides (^{40}K, ^{214}Bi & ^{208}Tl) show variations which reflect the local soil types and sedimentation processes. Saltmarsh deposits appear to have elevated levels of potassium and thalium, although land management have altered any characteristic features (also seen in the bismuth map). Estuarine sediments have lower associated natural radioactivity due to relatively higher water content and tidal inundation. Terrestrial soils show enhanced bismuth levels; this may indicate potential radon emission from these soils and underlying sandstones.

The gamma dose estimates correspond strongly with ^{137}Cs deposition. Thus occupancy of the Banks Marsh region, and other salt marsh areas identified by the survey, is of particular significance, and should be taken into consideration with respect to critical group assessments. MAFF has identified the critical group to be a small number of people who live on house boats moored in the muddy creeks of the Ribble Estuary [16].

High resolution mapping of Banks Marsh was conducted in response to BNF interest in the radiological implications for wild fowlers. Flights were made at approximately 30m altitude and about 100m flight line spacing. These results are shown in figures 5.15-5.17.

5.2.1 Measurement of ^{234m}Pa

The potential measurement of ^{234m}Pa was investigated at SURRC prior to the Springfields survey, by analysis of the spectral response of the survey detector from depleted uranium.
During the processing of the Springfields data and the mapping of ^{234m}Pa, it became clear that either:
a). ^{234m}Pa is distributed more widely than previously thought, or
b). an excess count-rate occurred in the ^{234m}Pa channel window owing to detector gain drifts, or
c). an unforeseen interference had been measured.

Calibration of ^{234m}Pa to equivalent concentration levels was not possible owing to insufficient ground based measurements and therefore height corrected (to 100m) stripped count rate only is displayed. Following a careful visual inspection of the full spectral measurements, ^{234m}Pa was positively identified at Springfields from data recorded during flights made around the perimeter of the plant or at greater than 500 ft altitude above the site, under the supervision of Roger Cheshire. A second observation was seen near the riverbank in Preston (BNF has documented this source during past discharges). In the Ribble estuary, a low intensity peak is observed corresponding in energy to about 930 keV, below that of ^{234m}Pa (1001 keV).

Throughout the survey and concurrently with all spectral information, a detector gain drift indicator was employed based on relative measurements of the ^{40}K peak (the detector package contains deep insulation to reduce thermally induced effects, to which the NaI(Tl) crystal is susceptible). Subsequent analysis of this showed that the observed gain drifts (typically less than +-1% at one standard deviation, although the effects of a 1.45% gain adjustment on the first survey day were detected) showed that this could not account for the energy difference described above. The gain stability is further discussed in connection with ^{208}Tl is discussed in section 5.2.2.

The possibility was examined that peak summing between 662 keV and low energy backscattered photons might be responsible for a low count rate signal at 930 keV which was spatially correlated with the presence of high environmental levels of ^{137}Cs. However laboratory investigations using multiple sources confirmed that the detector was capable of sustaining up to 10 times the count rates of ^{137}Cs observed in this survey without gross peak shape effects. Furthermore there is a possible sum peak (see figure 5.6) at approximately 800 keV, which is more consistent with the main backscatter energy, and would not supply the necessary joint count rate to account for the observed count rate from 900-1000 keV.

It is therefore postulated that an excess ^{228}Ac signal, owing to disequilibrium with respect to the parent ^{232}Th radioisotope, is seen in these regions. Three gamma-ray emission lines of ^{228}Ac occur at 911, 964 and 969 keV. The resolution of the detector is such that a single broad peak is formed by the superimposition of these lines. Figure 5.5 shows the summation of three spectra, two near Springfields and one near Preston, to accentuate the ^{234m}Pa peak. Likewise, figure 5.6 shows the accumulation of ten spectra to show the broad ^{228}Ac peak (this peak is nevertheless low in intensity). The presence of unsupported ^{228}Ac in the salt marsh environment following recent tide washing is a new suggestion. However it is in principle consistent with the expected chemical behaviour of Th series nuclides in this situation. The parent ^{232}Th is known to be relatively insoluble and particle reactive. By contrast, it's immediate daughter, ^{228}Ra is relatively soluble, and extractable from estuarine sediments. The next series member ^{228}Ac, which rapidly decays to ^{228}Th, is again an insoluble and particle reactive species. The presence of ^{228}Ra in estuarine waters, and depletion of ^{228}Th relative to ^{232}Th in sands and muds have both been observed in the near shore marine environment. The possibility that ^{228}Ac can be preferentially deposited on salt marshes, while postulated here for the first time, seems to be geochemically quite credible.

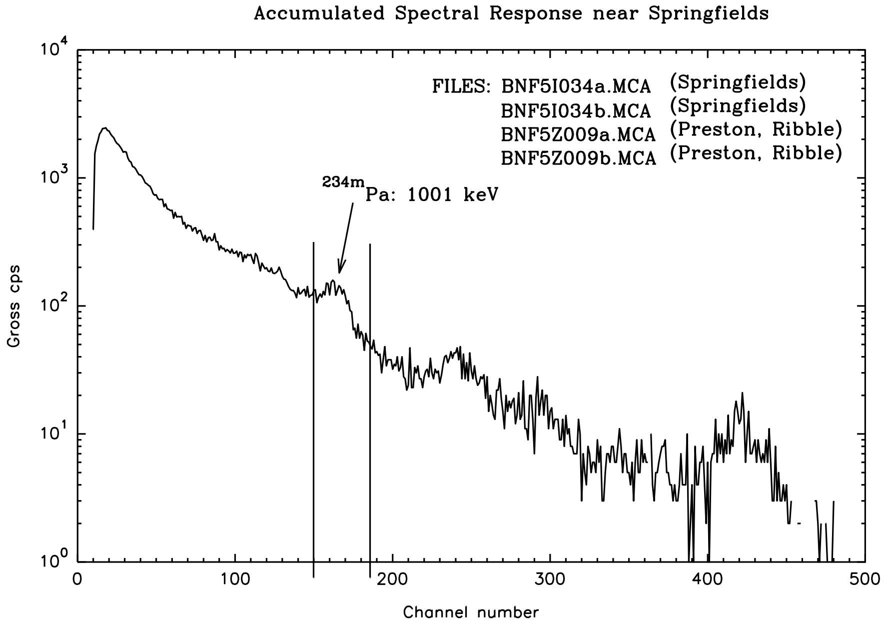


Figure 5.5 ^{234m}Pa Accumulated Spectra

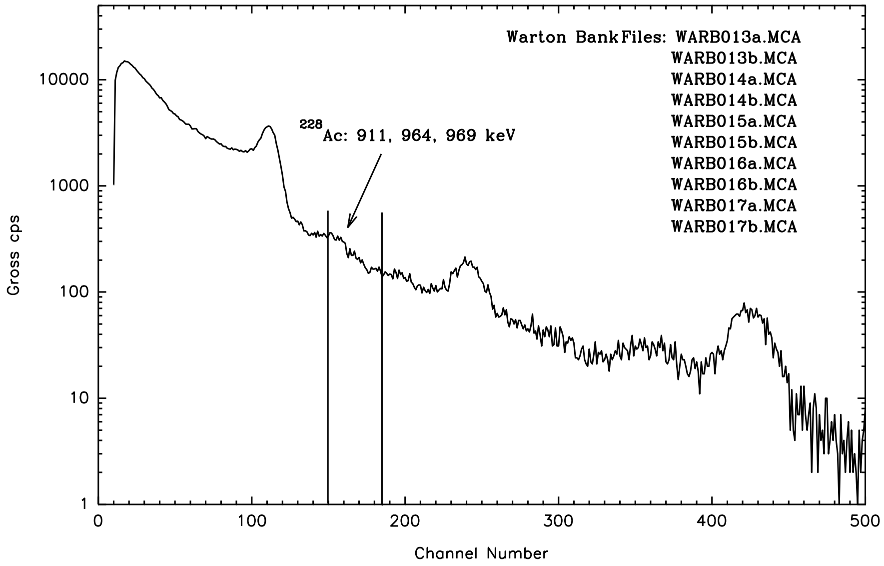


Figure 5.6 ^{228}Ac Accumulated Spectra.

5.2.2 Analysis of ^{234m}Pa & ^{228}Ac

Attempts have been made to separate the ^{234m}Pa/^{228}Ac pair, using an extension of standard SURRC data processing procedures. This has been particularly difficult owing to the almost overlapping nature of the observed peaks. Excessive overlapping of spectral windows is undesirable, therefore two narrow and adjacent windows (140-160ch, 160-180ch) were tentatively chosen instead of the single 150-185 channel window as used during the survey. It must be noted that each peak contributes to some extent into its neighbouring window.

A 6x6 stripping matrix was formed using experimental and monte carlo based results. Since an experimental gamma-ray measurement of a pure source of ^{228}Ac is not presently available, an estimation of its spectrum was calculated at aerial survey heights and with full simulation of the detector package.

Upon reintegrating the entire dataset, and producing new summary, net and stripped count-rates, the full survey area was remapped. Comparison with the previous preliminary stripped count-rates showed near identical results for ^{137}Cs, ^{40}K, ^{214}Bi and ^{208}Tl. Analysis of ^{234m}Pa and ^{228}Ac stripped data showed a very strong correlation between the two, likely caused by inadequate separation due to overlapping peaks and poor deconvolution. However, the probable interpretation from this advanced processing provides a reasonable indication of the distribution of the two radioisotopes: ^{234m}Pa is clearly seen at Springfields and at the upper reaches of the Ribble, with some elevated levels at grid references 436272, 456278, 478287, 490288 and 504292; ^{228}Ac is estimated to be in regions of the salt marsh and Springfields. Other spuriously high estimates, particularly of ^{234m}Pa in the more inland regions, can only be explained in terms of processing limitations.

Recent flight trials by SURRC incorporating a high efficiency (50% rel.eff.) semiconductor detector into the aerial survey package have proven the feasibility of operation and would enable the study of complex or interfering multi-energy gamma ray fields.

5.2.3 Analysis of ^{208}Tl

Post flight data processing revealed that for flights BNF4B, BNF4E, BNF4F, BNF4G, BNF4H, and BNF4I, an unusually low k1/k2 ratio had existed (approximately 1.3% gain increase). Since a choice of IAEA recommended channel windows had been chosen for the survey, which are somewhat narrower than SURRC windows by 5-20 channels, it was reasoned that detector drifting may have had more significant affects than previously experienced.

The preliminary mapping of ^{208}Tl showed an unusually linear feature corresponding to the area in which these measurements were taken. An investigation into the possibility that drifting may have introduced errors into the estimation of this radionuclide was made. A correction was conceived by means of averaging (2 successive pairs) the k1/k2 ratio, to reduce statistical effects. Upon remapping ^{208}Tl, the same attribute remained.

Figure 5.7 ^{137}Cs /kBq m-2

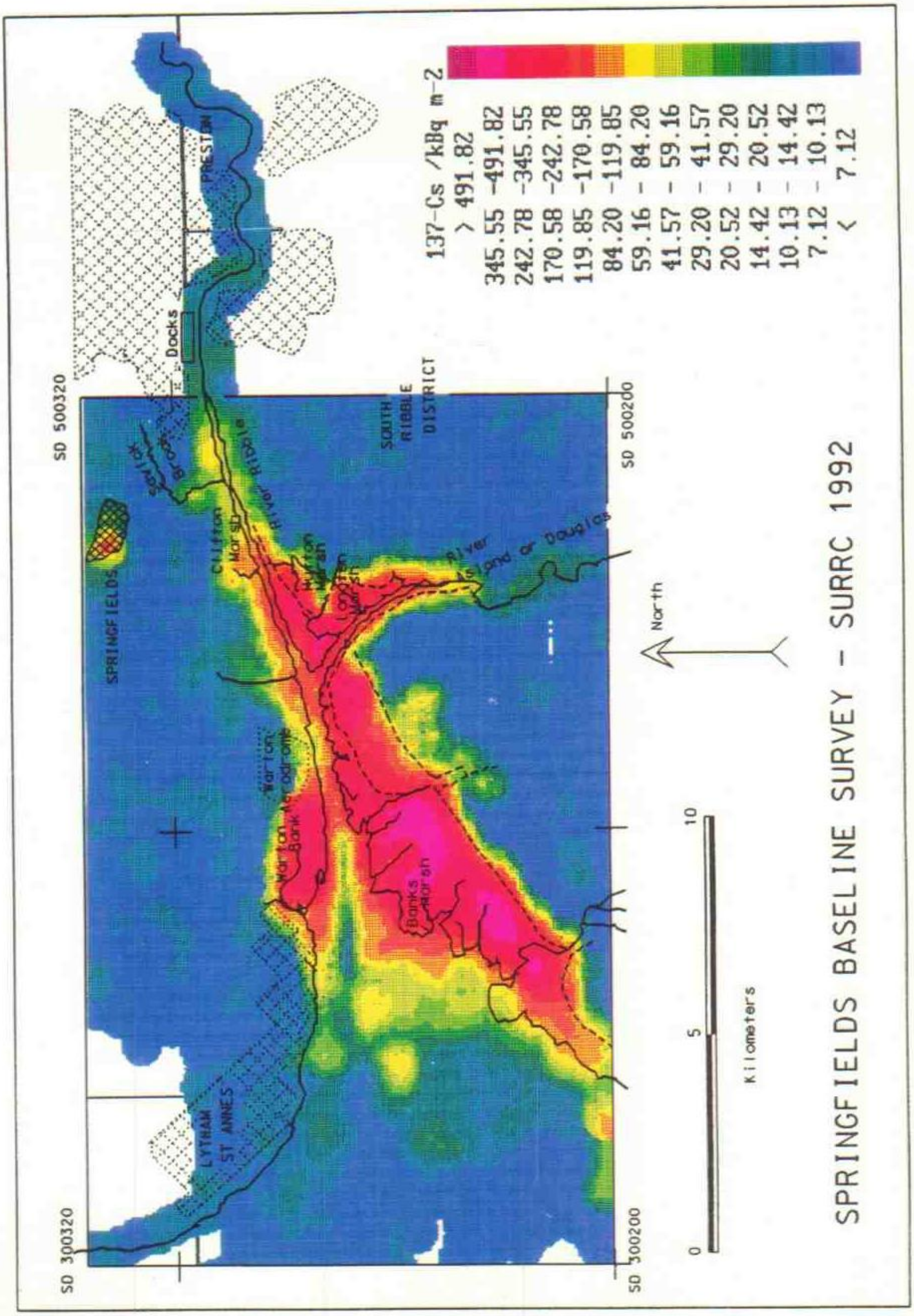


Figure 5.8 ^{40}K /kBq m-2

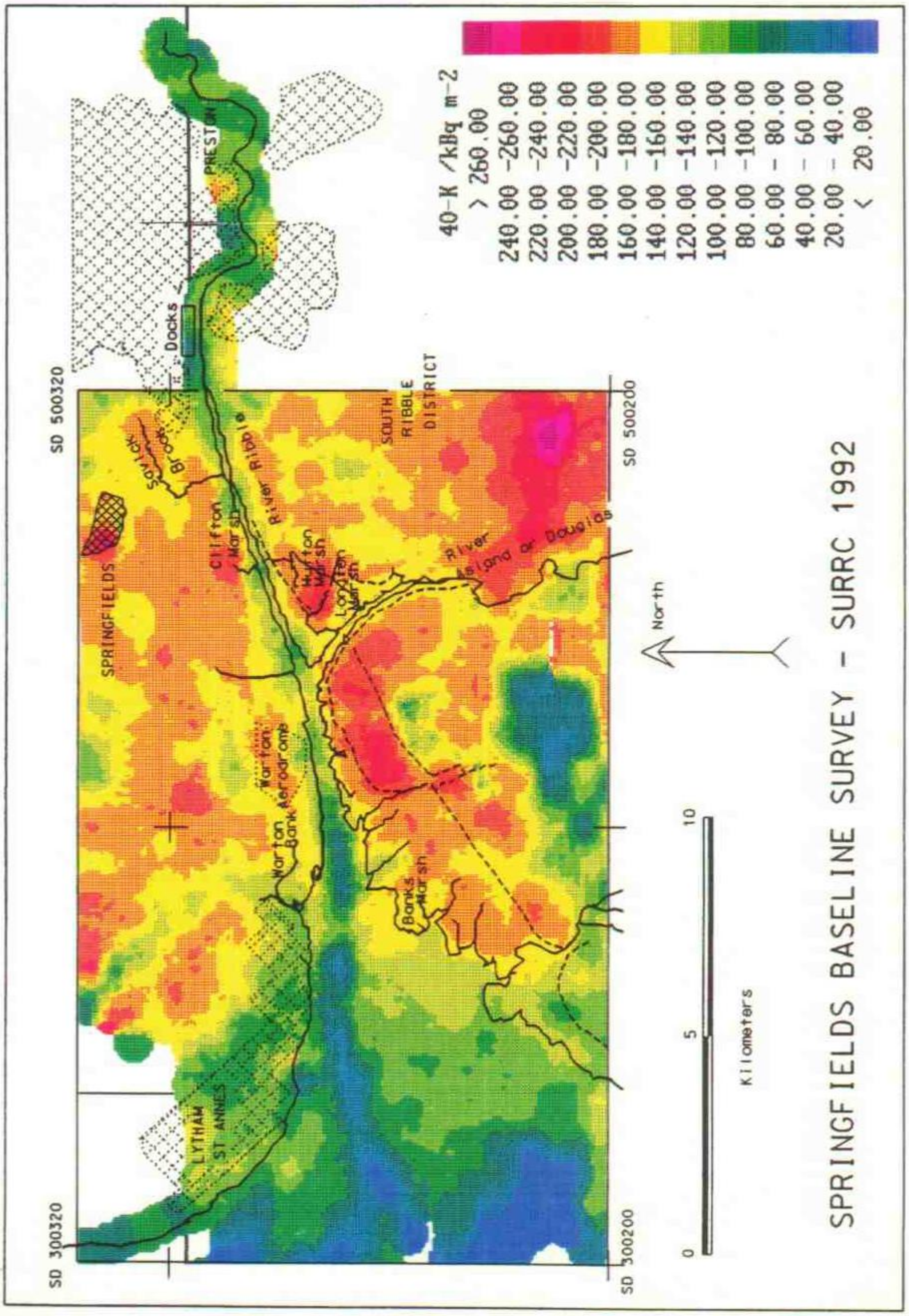


Figure 5.9 ^{214}Bi /kBq m-2

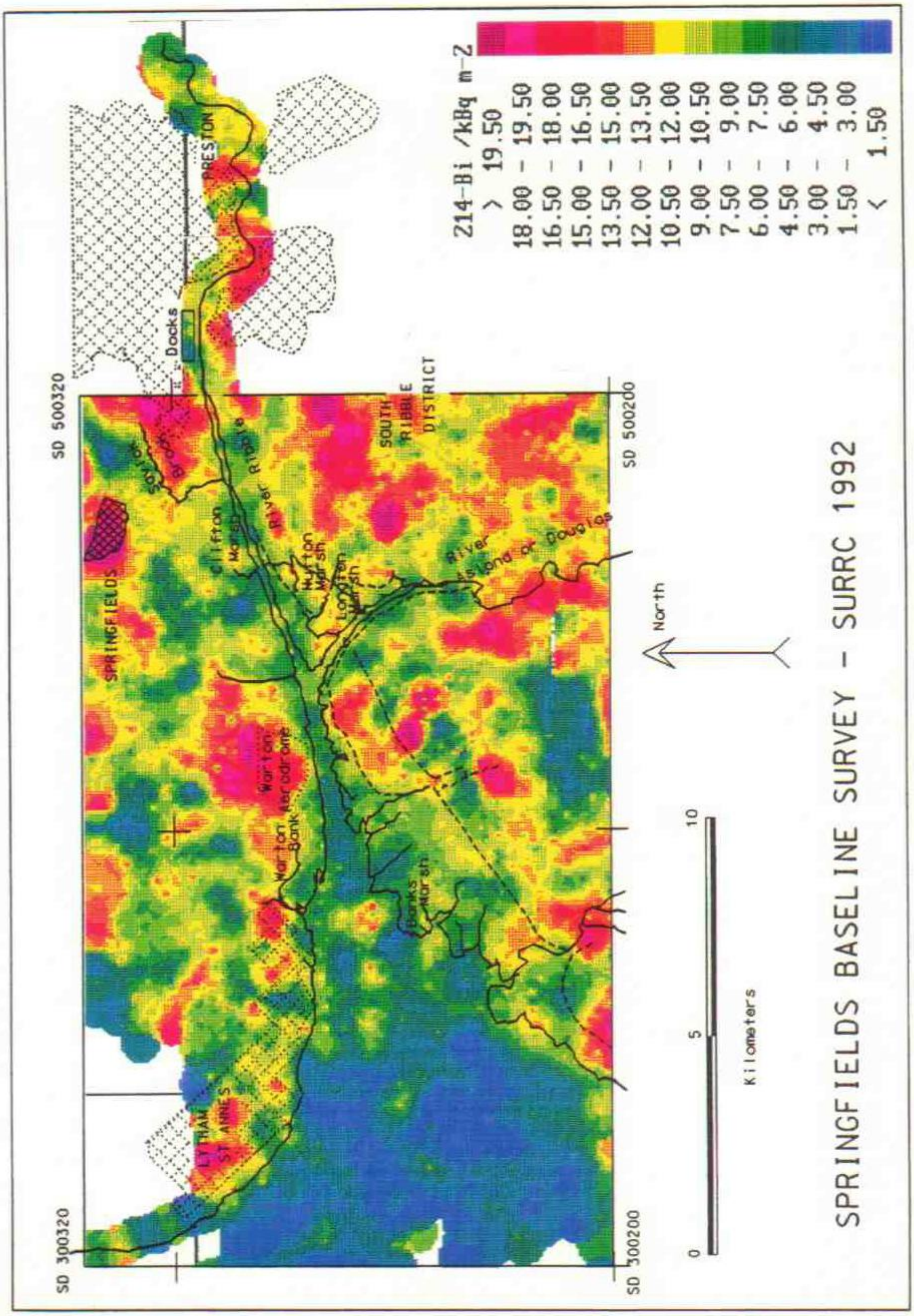


Figure 5.10 ^{208}Tl /kBq m-2

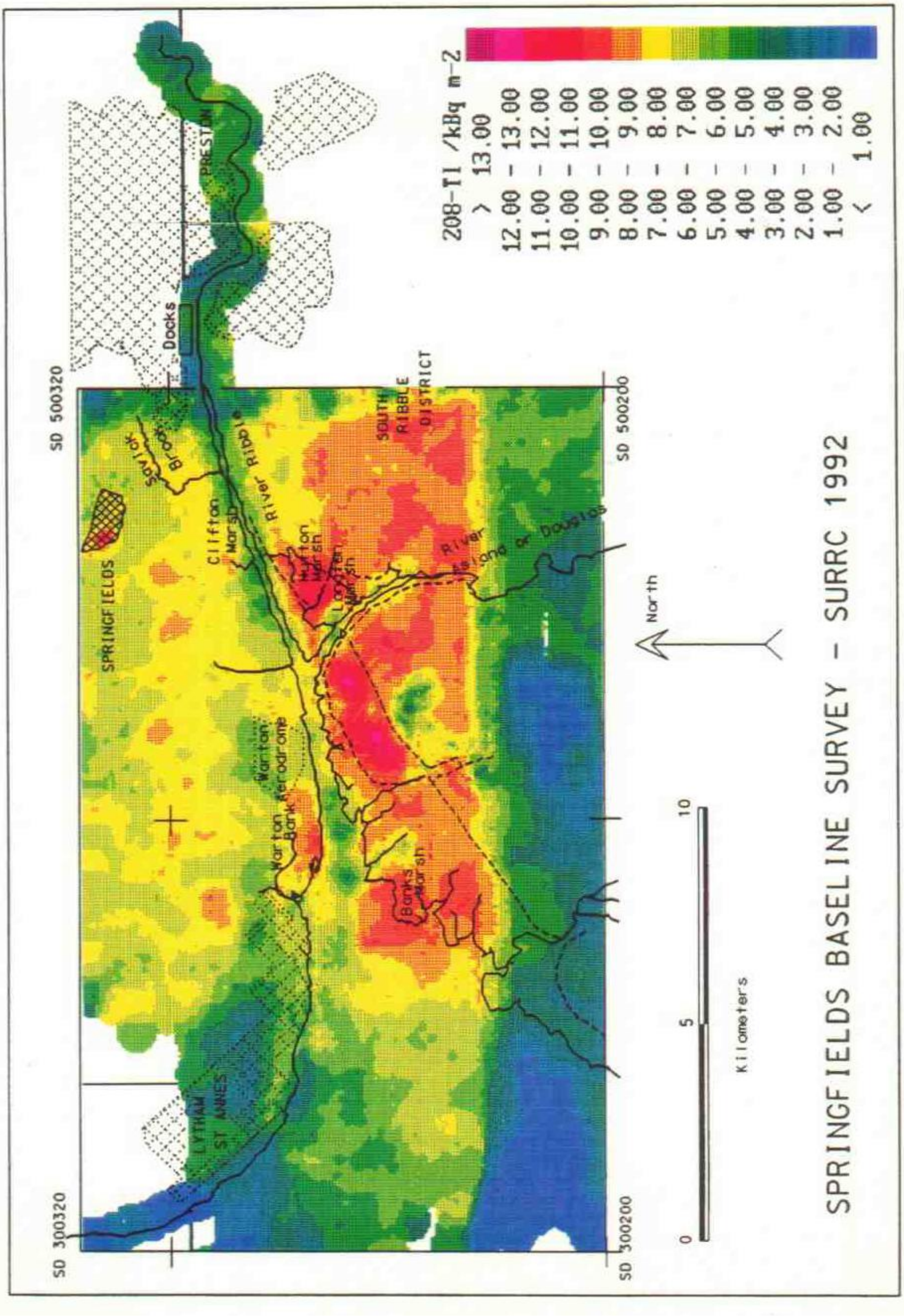


Figure 5.11 Gamma Ray Dose Rates /mGy per annum

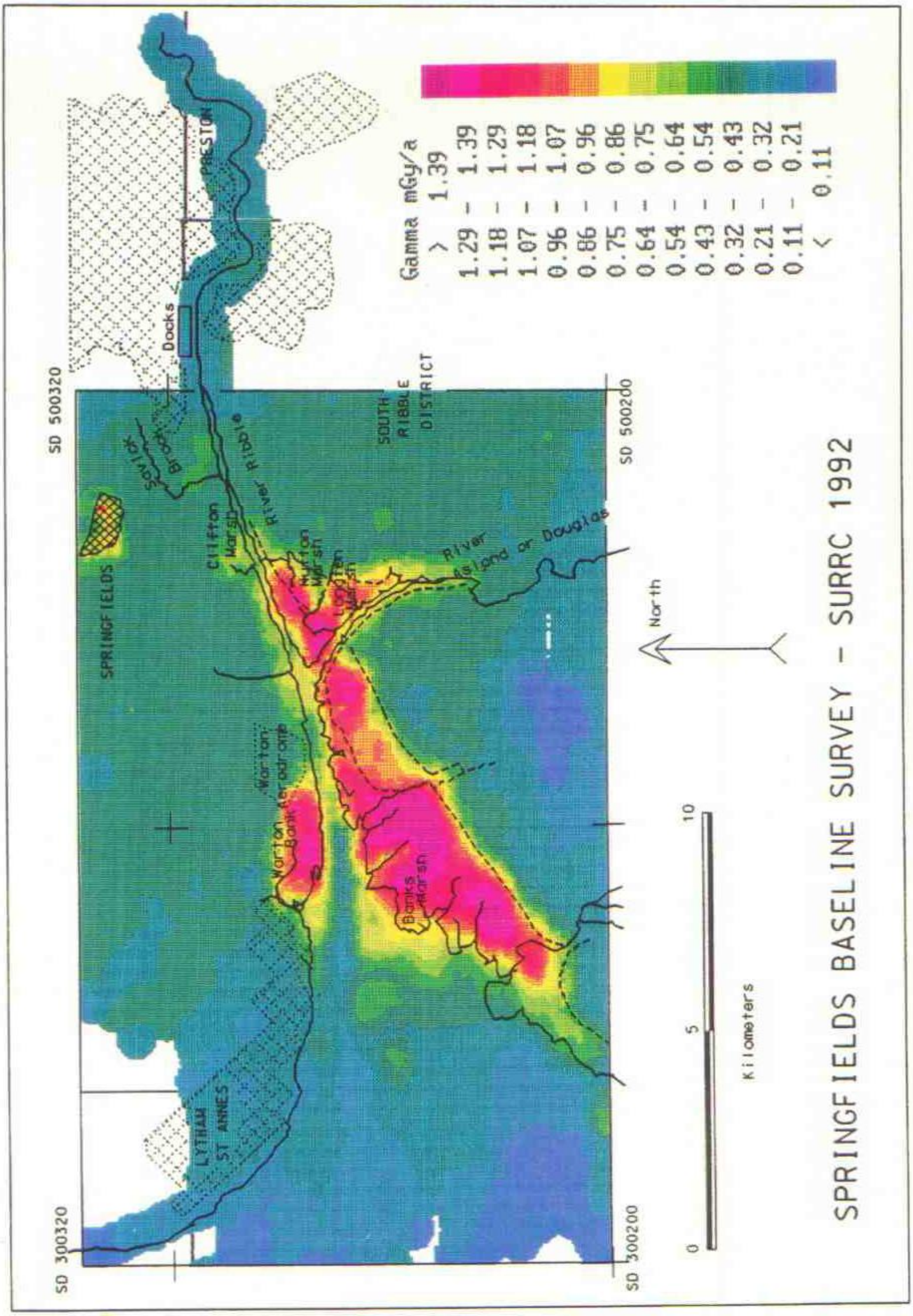


Figure 5.12 Combined ^{234m}Pa & ^{228}Ac Stripped cps (corrected to 100m)

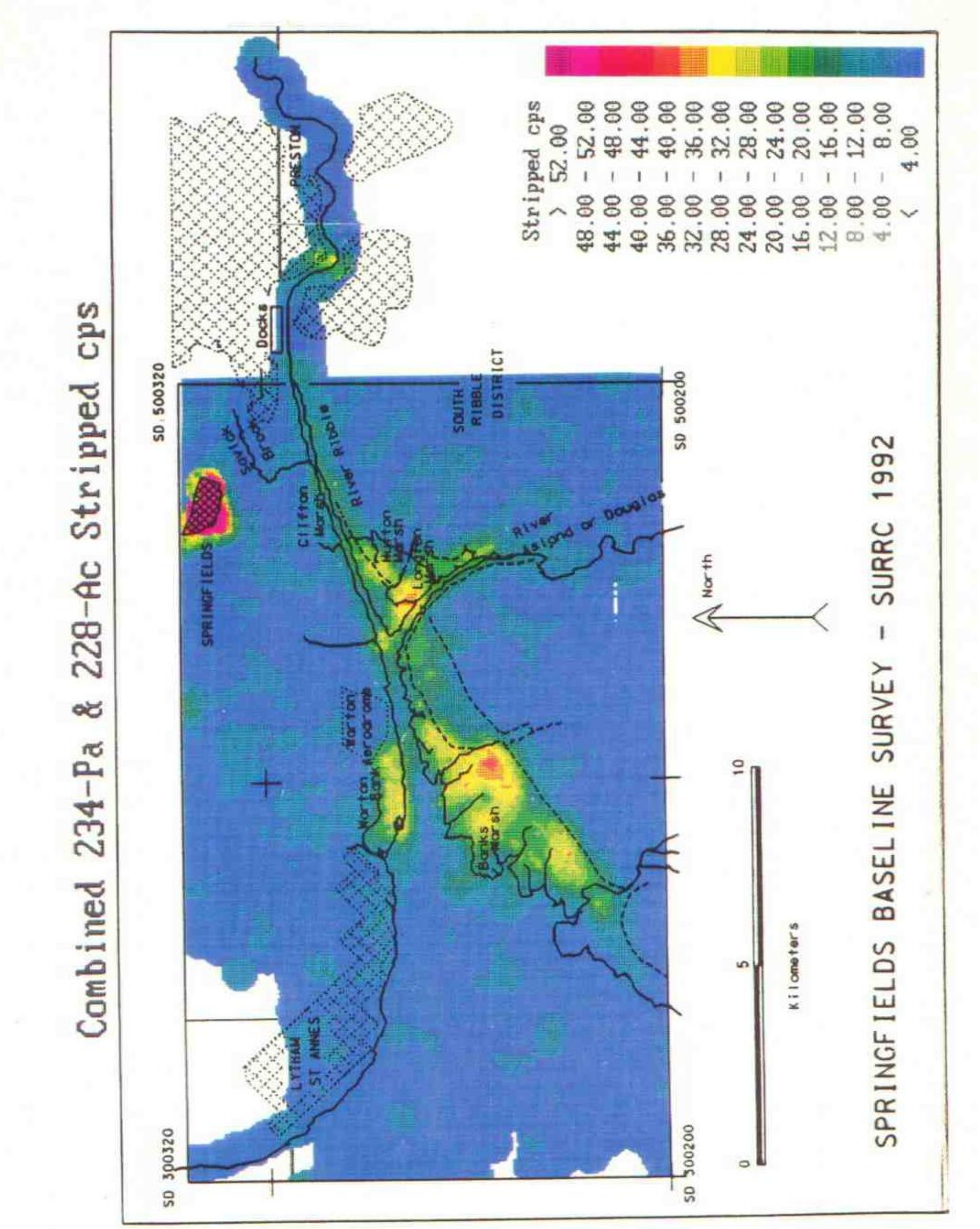


Figure 5.13 ^{234m}Pa Stripped cps (corrected to 100m)

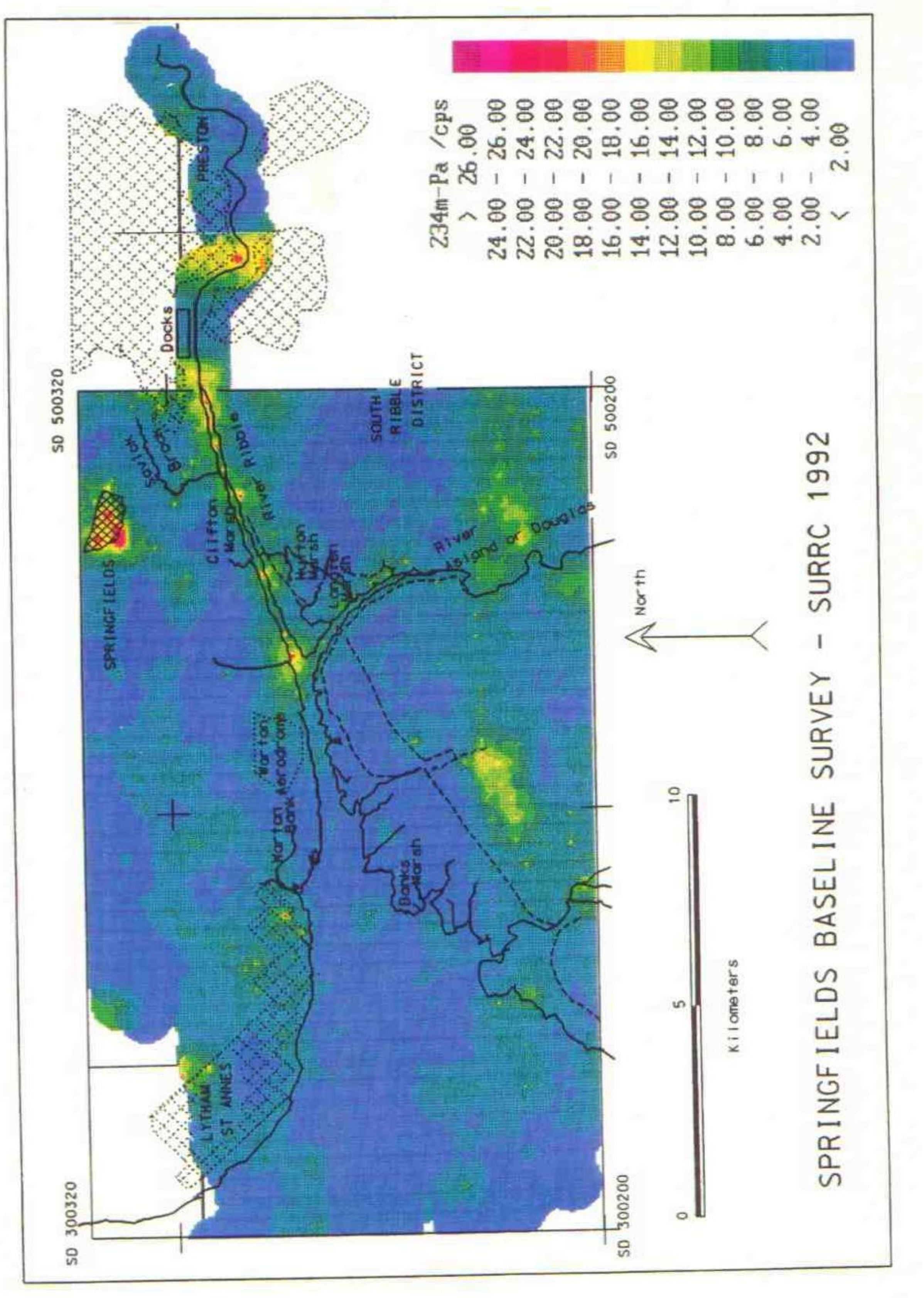


Figure 5.14 ^{228}Ac Stripped cps (corrected to 100m)

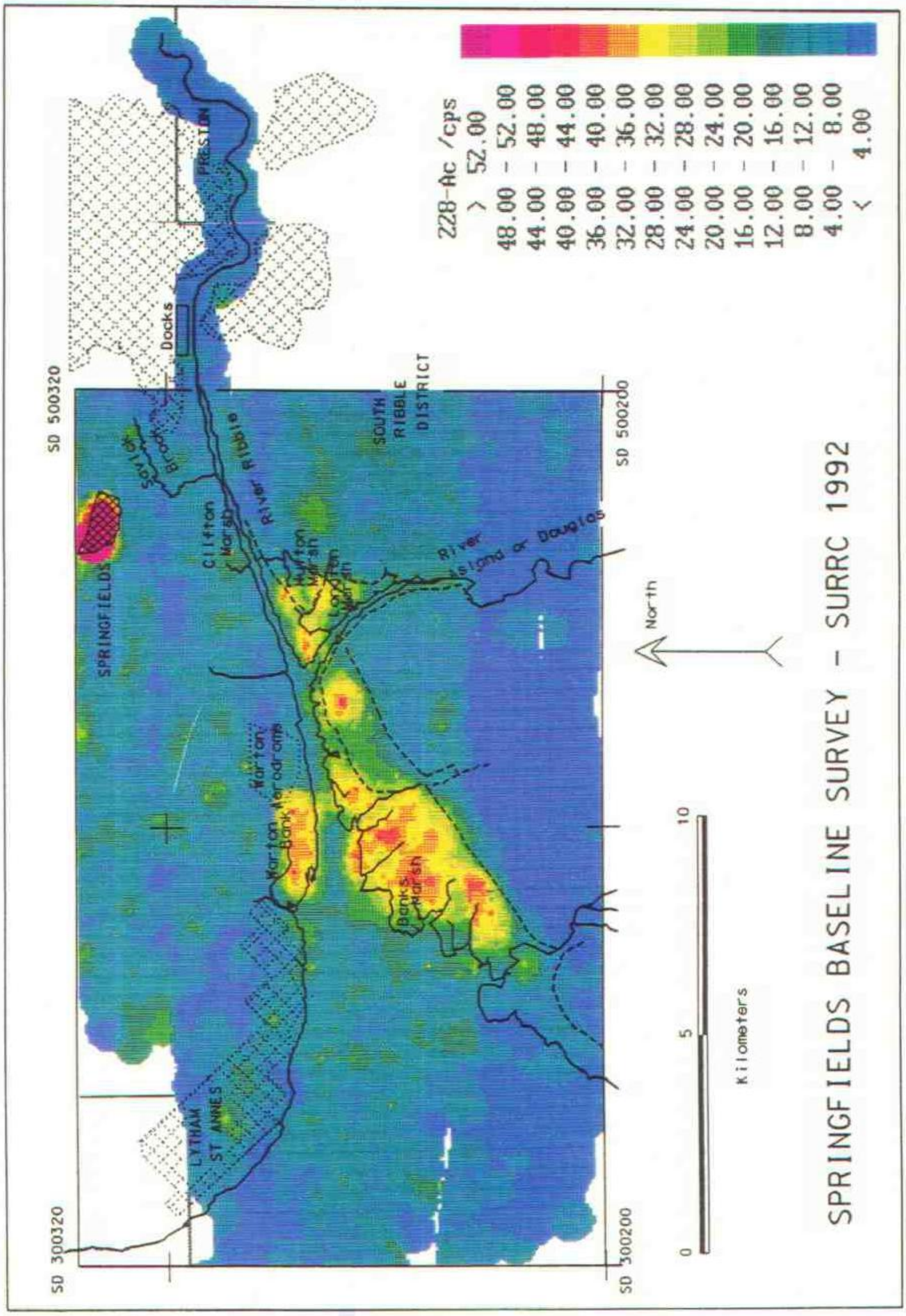


Figure 5.15 Banks Marsh: ^{137}Cs /kBq m-2

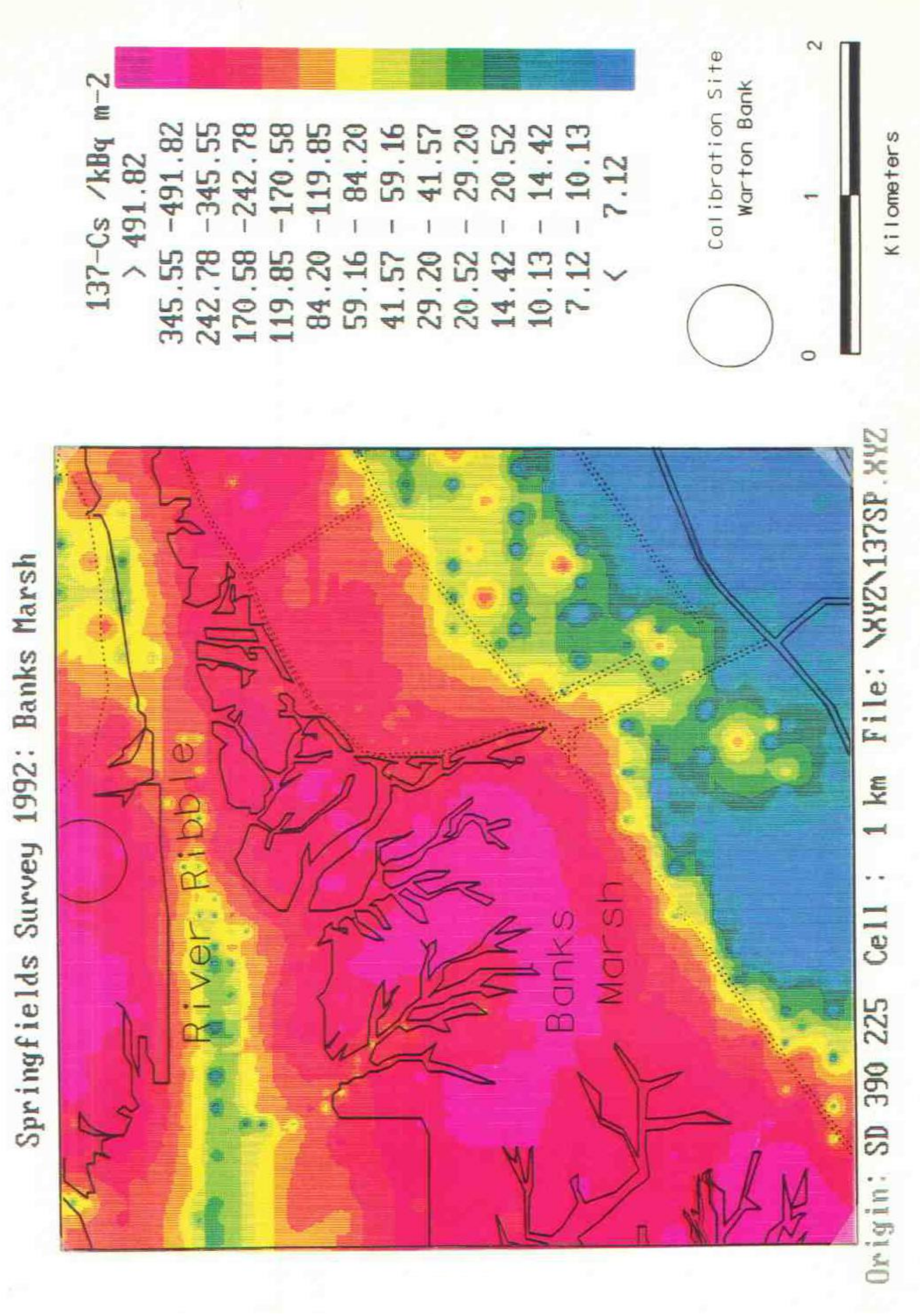


Figure 5.16 Banks Marsh: Combined ^{234m}Pa & ^{228}Ac Stripped cps (corrected to 100m)

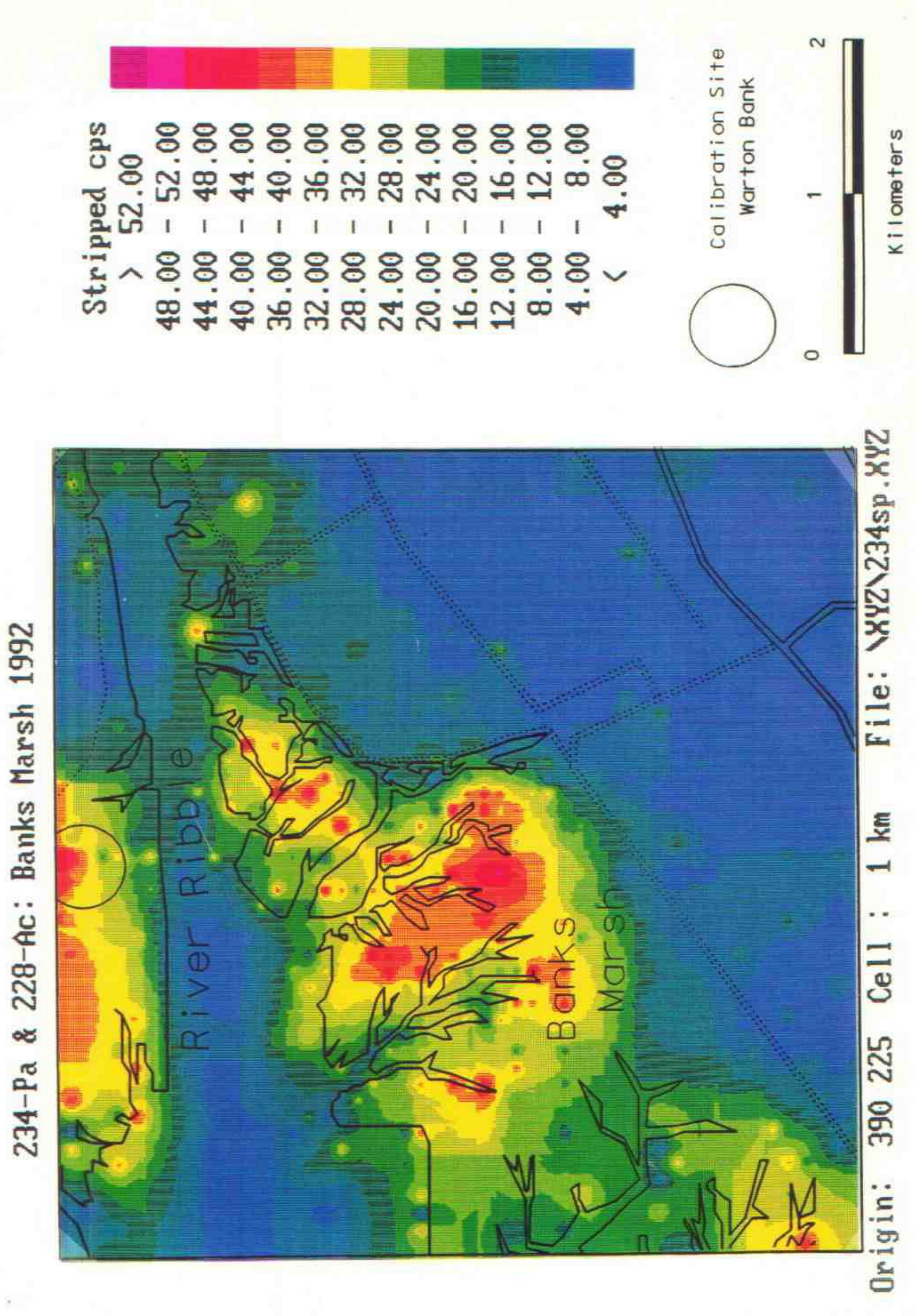
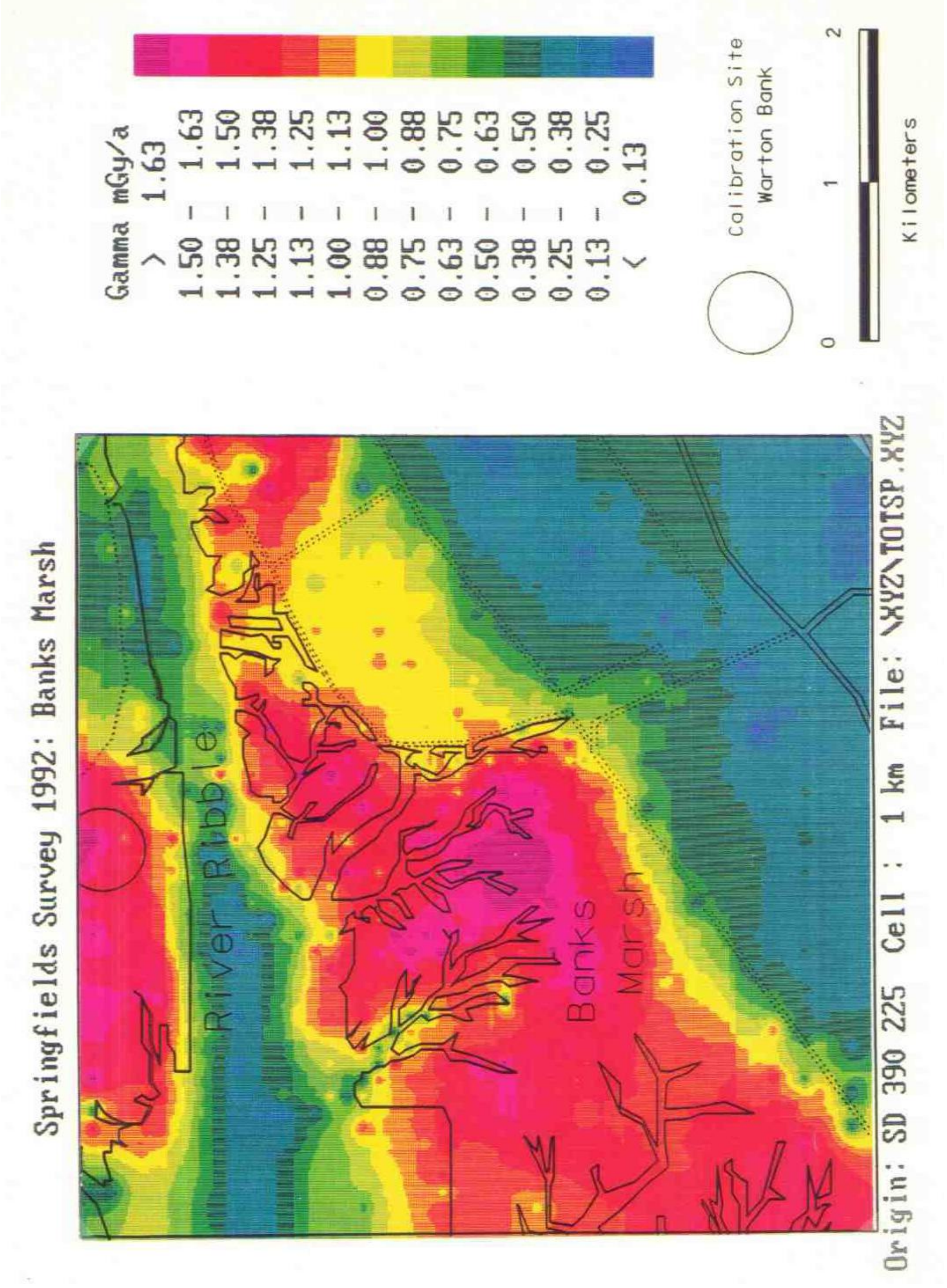


Figure 5.17 Banks Marsh: Gamma Ray Dose Rates /mGy per annum



6. CONCLUSIONS

The survey has defined the gamma radiation environment of the Springfields and Ribble Estuary in unprecedented detail. The off site contributions to environmental dose rates are modest, although the gamma dose rates due to ^{137}Cs in the tide washed areas represent a significant fraction of the total gamma dose rates. These results can form the basis for critical dose assessments. Further ground based gamma dose assessments would be beneficial, in establishing the contribution of low energy gamma rays to the total gamma ray field.

The maps provide a clear indication of the distribution and sources of environmental radioactivity in the Ribble at the time of the survey. The Ribble estuary is subject to regular and ongoing ground based studies by BNF, MAFF, HMIP, and University based groups, as a result of the authorised discharges of low level radioactivity from the Springfields site. The results of this survey complement this ground based work, and add to confidence that the estuarine system, it's associated sediments, tide washed pastures, salt marshes and river banks, have been thoroughly examined. There is support for earlier conclusions that the Cs on the salt marshes is the dominant source of external gamma radiation, and that the Springfields contribution to these locations is minor in comparison with this, Sellafield derived, signal. Upstream the situation is more complex, particularly where the dynamic sources of beta radiation are considered. As far as critical group assessments are concerned the survey provides clear evidence that the areas affected by ^{137}Cs, where external gamma dose and possible food chain effects are of greatest interest, are in the lower reaches of the Ribble, whereas, at the time of the survey the ^{234m}Pa distribution was in the upper reaches of the river. This not only confirms the findings of ground based work, but provides some assurance that the different exposure paths (external gamma dose, skin dose) are not entirely synergistic. The discovery of possible transient sources of natural ^{228}Ac in the salt marsh environment as a consequence of Th series disequilibrium immediately following spring tides is extremely interesting. If substantiated by further studies using semiconductor detectors this provides a new insight into the dynamic radiation environment of tide washed environments.

The significant development in the application of aerial survey to the studies of a dynamic source, ^{234m}Pa, has been demonstrated. Owing to the limitations of detector energy resolution, the ^{228}Ac signals inferred in the salt marsh environment can only be partially separated from ^{234m}Pa. Nevertheless aerial survey remains the only practical and cost effective means of mapping such dynamic sources. The technique is rapid, crossing all geographical obstacles and boundaries and therefore enables time series measurements to be made of the total estuarine system, which would not be possible using ground based approaches. In the case of the Ribble it would be necessary to reduce survey height to below 50m ground clearance to improve spatial resolution. The possible inconvenience to residents and property owners of such low altitude flights would have to be considered in addition to the potential value of environmental knowledge of the behaviour of these nuclides which could be obtained in further studies. There is nonetheless considerable scope for time series studies of this location.

Ground based sampling at the time of measurement would in principle enable concentration calibrations to be made for these dynamic sources. It may however be necessary to incorporate corrections derived from Monte-Carlo simulations to account for the finite source geometries of some of the deposition sinks identified in this survey. Further ground based measurements, in conjunction with Monte-Carlo simulations would be desirable to establish the extent to which low energy photons contribute to external gamma ray dose rates from sources with pronounced subsurface activity maxima. The vertical activity distributions found on these salt marshes give rise to variable and enhanced levels of low energy scattered photons, whose associated photon fluence spectra may influence the critical region for detector response where the transition between photoelectric and compton interactions takes place. The effects which this has on the calibration of routine dosimetry instruments and systems has yet to be determined, and is important, along with extended habit survey in critical group dose analyses.

Recent flight trials by SURRC incorporating high efficiency germanium semiconductor detectors have proven the potential of their inclusion into the aerial survey package. Such a device would solve any ambiguities with regard energy resolution, especially of near overlapping gamma ray peaks. Surveying at low altitudes (30-50m) would be required to enable small localised ground features to be spatially resolved and also offer low energy gamma ray detection capability (array of LOAX detectors) eg. ^{241}Am (59.5 keV), ^{234}Th (63.93 keV). Differential GPS would be the favoured choice to positively identify the location of discrete sources. This survey was undertaken at less than optimal survey parameters (altitude, speed). It would be desirable therefore to fly lower and slower for semiconductor application. This could be achieved safely using twin engined aircraft, as deployed for this work. Nevertheless in addition to CAA exemptions to permit low altitude survey, which were obtained prior to this survey, further cooperation from local authorities and local residents would be needed to exploit the full potential of this approach.

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APPENDIX A.

SUMMARY OF DETECTOR CALIBRATION : SPRINGFIELDS BASELINE SEPTEMBER 1992

1). Detector

16 l NaI detector - box of 4 10x10x40cm NaI crystals
Resolution 9-10.5% at 662 keV
SURRC 19" RACK INSTALLATION
Recording with MCA28ca/cb software
Radalt 10 mV/ft output

2). Spectral Window Parameters

a). Springfields Aerial Survey Parameters (16 litre detector)

Spectral Windows	**Channel Number**	**Equivalent Energy /keV**	**Background /cps**
^{137}Cs	95-128	544-761	43.9
^{234m}Pa	150-185	885-1102	28.8
^{40}K	228-260	1370-1570	14.4
^{214}Bi	275-307	1660-1860	6.5
^{208}Tl	396-460	2410-2810	9.6
Total	75-500	>450	178

Note. Windows for the natural emitters are recommended by IAEA.

Stripping Matrix (at 60m):

	^{208}Tl	^{214}Bi	^{40}K	^{234m}Pa	^{137}Cs
^{208}Tl	1.0	0.35	0.42	1.66	3.09
^{214}Bi	0.17	1.0	0.76	1.77	4.35
^{40}K	0	0.015	1.0	0.502	0.72
^{234m}Pa	0	0.07	0.103	1.0	1.6
^{137}Cs	0	0	0	0	1.0

b). Speculative Windows used for ^{234m}Pa/^{228}Ac Separation (16 litre detector)

Spectral Windows	Channel Number	Equivalent Energy /keV	Background /cps
^{137}Cs	95-128	544-761	43.9
^{234m}Pa	160-180	947-1071	12.3
^{40}K	228-260	1370-1570	14.4
^{214}Bi	275-307	1660-1860	6.5
^{208}Tl	396-460	2410-2810	9.6
^{228}Ac	140-160	823-947	16.0
Total	75-500	>450	178

Stripping Matrix (at 60m):

	^{228}Ac	^{208}Tl	^{214}Bi	^{40}K	^{234m}Pa	^{137}Cs
^{228}Ac	1.0	0	0.025	0.132	0.62	1.11
^{208}Tl	1.419	1.0	0.348	0.42	0.813	3.085
^{214}Bi	1.159	0.167	1.0	0.756	0.967	4.35
^{40}K	0.312	0	0.015	1.0	0.279	0.718
^{234m}Pa	0.819	0.011	0.10	0.153	1.0	2.165
^{137}Cs	0	0	0	0	0	1.0

c). SURRC Windows used in previous surveys

Spectral Windows	Channel Number	Equivalent Energy /keV
^{137}Cs	95-128	544-761
^{134}Cs	125-150	730-885
^{40}K	220-270	1319-1629
^{214}Bi	270-318	1629-1927
^{208}Tl	390-480	2370-2932
Total	75-500	>450

3). Calibration Constants

a: exponential altitude coefficient (m^{-1})
b: slope of calibration line (kBq m^{-2} per cps, at 100m)
c: calibration intercept

Window	Nuclide	a	b	c
1	^{137}Cs	0.00962	0.5337	0
2	^{234}Pa	0.00775	-	0
3	^{40}K	0.006	3.941	0
4	^{214}Bi	0.0066	2.48	0
5	^{208}Tl	0.004	0.3477	0
6	>450 keV	0.0062	0.0007	0

4). Mapping Coordinates

Latitude and Longitude of Grid Origins (SD 300 150), 5km scale & (SD 390,225), 1km scale.

53.488°, 3.532°
Grid Angle 0.4°

APPENDIX B

WARTON BANK - RIBBLE ESTUARY, SAMPLE ACTIVITIES

Sampling Date, August 1992

Sample Name	^{241}Am Bq/g	1 σ Error	^{137}Cs Bq/g	1 σ Error		^{241}Am Bq/m^2	1 σ Error	^{137}Cs Bq/m^2	1 σ Error
WART 01 0-2	0.2501	0.0126	0.909	0.041		3177	160	11553	521
WART 01 2-4	0.3090	0.0154	1.261	0.056		4711	235	19226	854
WART 01 4-6	0.4303	0.0243	2.164	0.079		6758	381	33987	1241
WART 01 6-8	0.725	0.032	4.373	0.144		11303	499	68178	2245
WART 01 8-10	0.7301	0.0390	4.783	0.170		13153	703	86177	3070
WART 01 10-15	0.3413	0.0195	1.727	0.063		16355	937	82745	3021
WART 01 15-20	BDL		0.121	0.007		BDL		5934	342
WART 01 20-25	BDL		0.126	0.006		BDL		4885	244
WART 01 25-30	BDL		0.040	0.002		BDL		1516	59
					TOTAL	**53924**	**1359**	**314199**	**5130**
WART 11 0-15	0.4993	0.0277	2.884	0.104		55179	3057	318739	11469
WART 11 15-30	BDL		0.134	0.005		BDL		197774	706
					TOTAL	**55179**	**3057**	**338517**	**11491**
WART 12 0-15	0.4724	0.0085	2.955	0.118		52920	952	331026	13219
WART 12 15-30	BDL		0.125	0.005		BDL		18428	667
					TOTAL	**52920.39**	**952.1885**	**349454**	**13235**
WART 13 0-5	0.2888	0.019	1.120	0.04		8658	570	33587	1199
WART 13 5-10	0.5970	0.0324	4.430	0.158		23899	1298	177309	6323
WART 13 10-15	0.4349	0.0250	2.481	0.090		14795	851	84405	3079
WART 13 15-30	BDL		0.148	0.005		BDL		19885	714
					TOTAL	**47353**	**1654**	**315186**	**7170**

Sample Name	**^{241}Am Bq/g**	**1 σ Error**	**^{137}Cs Bq/g**	**1 σ Error**		**^{241}Am Bq/m^2**	**1 σ Error**	**^{137}Cs Bq/m^2**	**1 σ Error**
WART 14 0-2	0.2639	0.011	1.074	0.04		7314	305	29765	1109
WART 14 2-4	0.3848	0.0211	1.856	0.0671		7222	396	34825	1259
WART 14 4-6	0.5322	0.0290	4.031	0.1438		9871	538	74760	2667
WART 14 6-8	0.6936	0.0371	4.927	0.1753		14418	772	102425	3644
WART 14 8-10	0.6764	0.0366	3.936	0.1408		15466	838	90010	3220
WART 14 10-15	0.0880	0.0075	0.456	0.0186		4086	349	21192	866
WART 14 15-30	BDL		0.0992	0.004		BDL		13771	493
					TOTAL	**58376**	**1400**	**366749**	**5879**
WART 15 0-2	0.2019	0.022	0.972	0.04		755	82	3647	150
WART 15 2-5	0.2058	0.0132	1.413	0.0525		3147	202	21709	806
WART 15 5-10	0.0315	0.0072	0.518	0.0211		1076	245	17807	724
WART 15 10-15	BDL		0.1538	0.0081		BDL		4399	232
WART 15 15-22	BDL		0.0839	0.0056		BDL		3478	231
WART 15 22-30	BDL		0.0528	0.0049		BDL		2645	244
					TOTAL	**4978**	**328**	**53684**	**1168**
WART 21 0-15	0.410	0.0221	2.4862	0.0888		48514	2616	292652	10449
WART 21 15-30	BDL		0.0537	0.0048		BDL		8461	762
					TOTAL	**48514**	**2616**	**301113**	**10476**
WART 22 0-15	0.4719	0.0262	2.8554	0.1028		45484	2520	274048	9870
WART 22 15-30	BDL		0.0862	0.0056		BDL		11636	761
					TOTAL	**45484**	**2520**	**285684**	**9899**
WART 23 0-15	0.4357	0.0242	2.7619	0.0994		33823	1879	214407	7714
WART 23 15-30	BDL		0.1385	0.0078		BDL		16203	907
					TOTAL	**33823**	**1879**	**230610**	**7767**

Sample Name	**^{241}Am Bq/g**	**1 σ Error**	**^{137}Cs Bq/g**	**1 σ Error**		**^{241}Am Bq/m^2**	**1 σ Error**	**^{137}Cs Bq/m^2**	**1 σ Error**
WART 24 0-15	0.4390	0.0240	2.7753	0.1002		28505	1557	180190	6503
WART 24 15-30	BDL		0.1250	0.0077		BDL		9643	591
					TOTAL	**28505**	**1557**	**189833**	**6530**
WART 25 0-15	0.2256	0.0149	1.2491	0.0469		18833	1201	104264	3916
WART 25 15-30	BDL		0.2357	0.0113		BDL		27906	1333
					TOTAL	**18833**	**1201**	**132169**	**4137**
WART 31 0-15	0.4874	0.0245	3.1627	0.1110		64370	3232	417699	14633
WART 31 15-30	BDL		0.1279	0.0052		BDL		13419	546
					TOTAL	**64370**	**3232**	**431118**	**14643**
WART 32 0-15	0.4907	0.0270	2.6172	0.09439		67226	3696	358526	12931
WART 32 15-30	BDL		0.1753	0.00872		BDL		27840	1384
					TOTAL	**67226**	**3696**	**386366**	**13004**
WART 33 0-15	0.5108	0.0283	3.3751	0.12154		30518	1693	201631	7261
WART 33 15-30	BDL		0.1673	0.0091		BDL		15684	854
					TOTAL	**30518**	**1693**	**217315**	**7311**
WART 34 0-15	0.4452	0.0250	2.7722	0.1003		31651	1780	197087	7130
WART 34 15-30	BDL		0.0642	0.0052		BDL		7876	633
					TOTAL	**31651**	**1780**	**204963**	**7158**
WART 35 0-15	0.2685	0.0160	1.6174	0.0594		24382	1455	146871	5391
WART 35 15-30	BDL		0.1170	0.0043		BDL		12784	470
					TOTAL	**24382**	**1455**	**159655**	**5412**
WART 41 0-15	0.3790	0.0209	2.0065	0.07310		29166	1609	154399	5625
WART 41 15-30	BDL		0.0426	0.00376		BDL		5491	486
					TOTAL	**29166**	**1609**	**159891**	**5646**
WART 42 0-15	0.4051	0.0219	2.1737	0.07839		57468	3106	308396	11121
WART 42 15-30	BDL		0.1069	0.00624		BDL		12790	746
					TOTAL	**57468**	**3106**	**321186**	**11146**

Sample Name	**^{241}Am Bq/g**	**1 σ Error**	**^{137}Cs Bq/g**	**1 σ Error**	**^{241}Am Bq/m^{2}**	**1 σ Error**	**^{137}Cs Bq/m^{2}**	**1 σ Error**
WART 43 0-15	0.3428	0.019	2.0498	0.07444	24974	1382	149350	5423
WART 43 15-30	BDL		0.0909	0.00332	BDL		10525	385
				TOTAL	**24974**	**1382**	**159875**	**5437**
WART 44 0-2	0.1832	0.012	0.6409	0.03	662	43	2317	108
WART 44 2-4	0.2743	0.22	0.9203	0.0396	1764	1415	5920	255
WART 44 4-6	0.4603	0.1	1.892	0.0662	3939	856	16191	567
WART 44 6-8	0.4961	0.026	3.042	0.1004	3598	189	22062	728
WART 44 8-10	0.8212	0.0731	4.207	0.1304	7985	711	40909	1268
WART 44 10-15	0.6827	0.0361	3.5919	0.1289	11148	590	58656	2105
WART 44 15-20	0.1863	0.0106	1.1147	0.0407	3740	212	22373	816
WART 44 20-25	0.0390	0.0043	0.3736	0.0153	790	86	7576	311
WART 44 25-30	BDL		0.1436	0.0071	BDL		2727	135
				TOTAL	**32524**	**1918**	**175127**	**2783**
WART 45 0-5	0.271	0.011	1.056	0.042	11095	450	43233	1719
WART 45 5-10	0.448	0.024	2.620	0.094	22203	1192	129912	4663
WART 45 10-15	0.658	0.035	3.9638	0.1413	33696	1773	203019	7237
WART 45 15-20	0.7063	0.0354	3.3143	0.1161	30010	1502	140816	4931
WART 45 20-25	0.2223	0.0112	1.6114	0.0565	11618	584	84227	2951
WART 45 25-30	0.0392	0.0044	0.2309	0.0105	1651	187	9735	444
				TOTAL	**110273**	**2720**	**610943**	**10502**
WART 51 0-15	0.5002	0.0268	3.0264	0.1085	58842	3149	356009	12760
WART 51 15-30	0.0107	0.0036	0.2749	0.0120	1528	515	39400	1723
				TOTAL	**60370**	**3191**	**395409**	**12876**
WART 52 0-15	0.4786	0.0252	2.6795	0.0955	64696	3400	362176	12912
WART 52 15-30	BDL		0.1568	0.0081	BDL		26740	1379
				TOTAL	**64696**	**3400**	**388916**	**12985**

Sample Name	**^{241}Am Bq/g**	**1 σ Error**	**^{137}Cs Bq/g**	**1 σ Error**		**^{241}Am Bq/m^2**	**1 σ Error**	**^{137}Cs Bq/m^2**	**1 σ Error**
WART 53 0-15	0.4658	0.0247	2.4694	0.0885		75102	3986	398137	14272
WART 53 15-30	BDL		0.1114	0.004		BDL		13865	498
					TOTAL	**75102**	**3986**	**412002**	**14281**
WART 54 0-15	0.5252	0.0279	2.8859	0.1034		54607	2902	300083	10759
WART 54 15-30	0.1191	0.0076	0.4432	0.0176		16203	1039	60277	2387
					TOTAL	**70811**	**3082**	**360361**	**11021**
WART 55 0-15	0.4728	0.0255	3.2706	0.1171		29041	1566	200907	7192
WART 55 15-30	0.0101	0.0053	0.7796	0.0307		833	437	64627	2543
					TOTAL	**29875**	**1626**	**265534**	**7628**
WART 61 0-15	0.1655	0.0118	2.7046	0.0976		19618	1404	320501	11569
WART 61 15-30	BDL		0.0910	0.0053		BDL		14082	813
					TOTAL	**19618**	**1404**	**334583**	**11598**
WART 62 0-15	0.2639	0.0156	2.3969	0.0866		38191	2254	346843	12525
WART 62 15-30	BDL		0.1168	0.0064		BDL		17469	952
					TOTAL	**38191**	**2254**	**364312**	**12561**
WART 63 0-15	0.0990	0.009	2.0113	0.0736		10775	986	218927	8015
WART 63 15-30	BDL		0.0588	0.0040		BDL		7093	485
					TOTAL	**10775**	**986**	**218927**	**8015**
WART 64 0-15	0.0938	0.0089	1.7573	0.0649		5708	544	106930	3949
WART 64 15-30	BDL		0.0400	0.0048		BDL		3814	462
					TOTAL	**5708**	**544**	**110744**	**3976**
WART 65 0-15	0.0594	0.0077	1.4678	0.0548		5167	669	127605	4766
WART 65 15-30	BDL		0.0798	0.0030		BDL		9605	360
					TOTAL	**5166.792**	**669.0033**	**137210.8**	**4779.5**

BDL: *Below Detection Limits*