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AIRBORNE GAMMA RADIATION MEASUREMENTS OF SOIL MOISTURE DURING FIFE; ACTIVITIES AND RESULTS

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ABSTRACT

Soil moisture measurements were obtained during the summers of 1987 and 1989 near Manhattan, Kansas, using the National Weather Service (NWS) airborne gamma radiation system. The research was in support of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE), sponsored by the National Aeronautics and Space Administration (NASA).

A network of 24 flight lines were established over the FIFE research area. The flight lines were calibrated by conducting multiple airborne surveys with simultaneous extensive ground measurement of soil moisture. Airborne surveys were flown daily during two IFCs (intensive field campaigns) periods during 1987 and one in 1989. The data collected were sufficient to modify the NWS standard operational method (for flight lines averaging 16 km in length) for estimating soil moisture for the FIFE flight lines (average length of 6.2 km). The average root mean square error of the soil moisture estimates for the shorter FIFE flight lines was found to be 2.5 %, compared with a reported value of 3.9 % for the NWS flight lines. Techniques were developed to compute soil moisture estimates for portions (sections) of the flight lines.

Results of comparisons of the airborne gamma radiation soil moisture estimates with those obtained using the NASA Pushbroom Microwave Radiation (PBMR) system and a hydrologic model are presented.

The airborne soil moisture measurements, and areal averages computed using all remotely sensed and ground data, have been used in support of the research of the many FIFE investigators whose overall goals were the upscale integration of models and the application of satellite remote sensing.

INTRODUCTION

Soil moisture measurements were obtained for an area south-east of Manhattan, Kansas, during the summers of 1987 and 1989, using the National Weather Service (NWS) airborne gamma radiation system. The research was in support of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE), sponsored by the National Aeronautics and Space Administration (NASA). The FIFE research area included the Konza Prairie National Reserve, owned by the Nature Conservancy and supported by the NSF with the participation of Kansas State University. The Konza reserve area was the focus of the FIFE study.

The FIFE experiment plans for the 1987 [Sellers and Hall,1987] and 1989 [Sellers and Hall,1989] field operations present information on the Konza study area. The FIFE investigations included seven soil moisture data experiments. Preliminary analyses and results of many of the soil moisture and other FIFE investigations were reported earlier [American Meteorological Society, 1990].

The primary objectives of this project were to; (1) obtain estimates of the soil moisture conditions for the FIFE study area during periods of intensive field campaigns (IFCs), (2) develop techniques for using the airborne gamma radiation system to obtain soil moisture estimates for short flight lines, and (3) provide soil moisture information for validating and calibrating other remote sensing methods for measuring soil moisture and for use by other FIFE investigators.

This report is a summary of the activities conducted during the FIFE 1987 and 19/89 field experiments and the results of the research.

AIRBORNE GAMMA RADIATION TECHNIQUES

The NWS airborne gamma radiation system consists of five downward, and two upward looking, sodium iodine (NaI) thallium (Tl) detectors, an associated pulse height analyzer, a mini-computer system, and temperature, pressure and radar altitude sensors as described by Carroll and Vadnais (1980). The spectral radiation data obtained by the system are used to compute the gamma fluxes for three radiation windows; the ^{40}K window (1.26 - 1.56 MeV), the ^{208}Tl window (2.41 - 2.81 MeV) and the gross count (GC) energy spectrum (0.41 - 3.0 MeV).

The concentration of radioisotopes in the ground is essentially constant with time [Zotimov, 1968]. Therefore, it is necessary to measure the ground soil moisture and establish background radiation by airborne surveys for the three radiation windows only once to calibrate a specific flight line. The airborne flight line measurement of soil moisture is considered to be a measurement of an area rather than a single line. The width of a flight line measurement has been accepted as 305 m; thus a measurement for a single FIFE flight line of 6.2 km represents an areal measurement for an area of 1.9 km^2.

The NWS's soil moisture estimates for a flight line are the weighted average of estimates determined using data from the three spectral radiation windows. The weights are; (1) 0.346 for the ^{40}K window, (2) 0.518 for the ^{208}Tl window, and (3) 0.136 for the GC. These weights were derived from a 10-year historical data base of simultaneous ground measurements of soil moisture and airborne radiation data [Carroll and Allen, 1988]. The techniques used by the NWS system to measure soil moisture are discussed by Carroll and Allen [1988] and by Jones and Carroll [1983].

There are a number of possible sources of random and systematic errors in the airborne soil moisture measurements. One error results from random fluctuations in the radiation data as a result of the nature of the radioactive decay process [Knoll, 1979], resulting in "counting statistics errors." Two other sources of error are; (1) those associated with the ground measurements of soil moisture data used for calibration, and (2) those accounting for the airmass between the aircraft and the ground which absorbs a large portion of the emitted gamma radiation. A fourth source of error results from calculations to compensate for extraneous sources of radiation and scattering with the gamma spectrum, as discussed by Fritzsche [1979].

The counting statistics errors of the airborne soil moisture estimates can be reduced if the data acquisition time is increased. The acquisition time for a flight line is dependent on the speed of the aircraft and the length of the line. Since the air speed of the aircraft is nearly constant, the length of the line is a major factor in determining the acquisition time. Repeated flights over the same line is one way to increase the acquisition time and to improve the accuracy of the airborne estimates.

The gamma radiation measured in the ^{208}Tl radiation window is less subject to extraneous sources of radiation and scattering within the gamma spectrum than the measurement in the ^{40}K radiation window [Carroll and Allen, 1988]. Both of these windows are much less subject to these sources of error than the GC window. The total count in the GC window, however, is typically an order of magnitude greater than the counts experienced in the ^{40}K and the ^{208}Tl windows, and therefore much less subject to "counting statistic errors."

FIELD ACTIVITIES DURING 1987

The 1987 FIFE field experiments were conducted during two IFCs. Nineteen flights lines were calibrated and flown during 4 days in June and 5 days in July 1987. A total of 195 airborne gamma radiation surveys were flown for the flight lines. The locations of the 19 flight lines flown in 1987 are shown by the solid lines in Figure 1. Ten of the flight lines are located within the Konza reserve area, and nine are located outside. Some of the flight lines were selected to provide as comparable data as possible for the east-west remote sensing microwave soil moisture survey flights conducted by James Wang using a NASA C-130 aircraft [Wang and Shue, 1989].

To obtain reliable calibration of the 19 flight lines, extensive ground measurements (at 288 points) were observed along the flight line at the same time multiple surveys along the flight lines were flown. Other ground measurements of soil moisture were used for calibration of the flight lines. Considerable ground soil moisture data were available from observations made daily at selected meteorological and other instrumented sites (CORE sites) operated by the FIFE NASA science staff. At each of the CORE sites, soil moisture measurements were made at five selected locations at, and surrounding each site. Soil moisture measurements at the CORE sites were obtained daily (by the gravimetric method) for the 0 - 5-cm and for the 5- to 10-cm soil depths at each of the five locations.

Additional ground soil moisture measurements, collected in the Konza reserve area in support of the microwave soil moisture measuring experiment using the PBMR system on the NASA's C-130 aircraft, were also used for calibration.

FIELD ACTIVITIES DURING 1989

Airborne surveys were conducted during the 10-day period, August 1-10, 1989. The flight direction of the NASA's microwave aerial surveys by the C-130 aircraft were changed from west-east to north-south for the 1989 experiments. For this reason, four additional gamma radiation north-south survey lines were established in the area in of, and south of, the Konza reserve area, as shown by the dotted lines on Figure 1 (Flight lines KS120, KS121, KS122 and KS123). An additional line (KS124), shown on Figure 1, was established in the southern portion of the FIFE area to provide data for a special FIFE instrumented site 926 (8739-ECB).

Approximately 500 ground soil moisture measurements were obtained during FIFE 1989 for calibration purposes.

ANALYSES OF 1987 AIRBORNE MEASUREMENTS

An initial analysis was made to determine the accuracy of the 1987 FIFE airborne flight line estimates computed using the standard NWS weights for the three radiation windows [Carroll et al.,1988]. The airborne estimates were based on the combined daily radiation data for all surveys made for each flight line. Average ground soil moisture data from the CORE stations, not used in calibration of the flight lines, were used to compute average line values for each flight line and were compared with the airborne estimates. This analysis, using completely independent data, which in many cases were not obtained near the flight lines, showed the root mean square error (rms) for the 97 flights during FIFE 1987 to be 3.02 % soil moisture, with a bias of less than 0.5 % soil moisture [Carroll et al. 1988]. This rms error is smaller than the rms value of 3.90 % reported as the accuracy of soil moisture measurement in the User's Guide for the NWS airborne gamma system by Carroll and Allen [1988]. The decrease in rms error was expected since the airborne gamma and ground soil moisture measurements for each flight line during FIFE were much more controlled than were these data during the operational program of the NWS on which the standard weights for the three windows were based.

REVISION OF WEIGHTS FOR RADIATION WINDOWS

Since the investigation of the 1987 airborne estimates showed an improvement in the rms error, an investigation was made to determine if revised weighting factors would be of value. Unlike the operational flight data used by the NWS in determining the weights for the radiation windows, multiple flights were flown each day that a flight line was calibrated during FIFE 1987 and FIFE 1989. The radiation data for the three radiation windows (^{40}K, ^{208}Tl and GC) were combined to determine revised weighting factors for use with the shorter FIFE flight lines. The independent CORE soil moisture values discussed previously were used in conjunction with the airborne radiation data for all flight days for deriving soil moisture estimates using radiation data from the three radiation windows [Peck et al. 1990]. Some of the flight lines were much shorter than others and therefore the acquisition time for the collection of the radiation data varied. In order to determine the acquisition time required for best results, the FIFE flight data were divided into three groups: (1) data acquisition times from 1 to 2 min; (2) data acquisition between 2 and 3 min; and (3) data acquisition greater than 3 min.

The airborne gamma radiation soil moisture estimates for each of the three data acquisition time groups were correlated with average soil moisture values, as computed from the independent ground observations at the CORE sites. The weighting factors determined for the radiation windows for the three acquisition time groups are shown in Table I.

TABLE 1. Weights for Flight Line Estimates Using K, Tl and GC Windows

	Window (weight)			
Acquisition Time, min	K	TL	GC	rms Error % *
1 - 2	0.252	0	0.748	2.42
2 -3	0.299	0.342	0.359	2.24
OVER 3	0.585	0.435	0	2.54

* Percent soil moisture.

The weights determined for the three windows are in agreement with those that would be expected from consideration of the "counting statistics errors." For the shortest time period, 1 - 2 min, the GC window receives most of the weight, primarily because the greater number of counts tends to reduce the "counting statistic errors" in comparison to the Tl and K windows. With acquisition time of 2 - 3 min, the effect of "counting statistics errors" on the Tl window is reduced and the Tl window receives about a third of the weight. For times greater than 3 min, the K and Tl windows apparently have sufficient counts to overcome the effects of the "counting statistics errors" and together receive all of the weight. The rms errors for all three groups are less (2.24 % to 2.54 %) than the 3.02 % soil moisture found in the analysis reported by Carroll et al. [1988] and less than the 3.90 % reported by Carroll and Allen [1988].

AIRBORNE ESTIMATES FOR SMALL AREAS

The FIFE experiments relating climatologically important land-surface parameters to satellite radiances often require knowledge of the average soil moisture over relatively small areas (of the order of 0.25 km^2); less than the 1.90 km^2 areal measurement for the average FIFE flight line.

To provide areal soil moisture estimates for smaller areas, each flight line was divided into sections. To accomplish this, sufficient ground observations of soil moisture are required when a flight line is calibrated to adequately represent the average soil moisture for each section. The number of sections into which each line was divided depended upon the number and distribution of the ground-based soil moisture measurements along the flight line. Sufficient ground soil moisture data were collected for many of the flight lines in the Konza reserve area to permit the lines to be divided into six or seven sections, with each section being approximately 500 m long. The airborne measurement for each of these sections therefore represents an area of 0.15 km^2. The 24 flight lines were divided into 142 sections.

The data acquisition time of a single survey of a section of a flight line was not long enough to compute a reliable soil moisture estimate for the section. A method was required to insure that the soil moisture values for the sections are consistent with the soil moisture estimates determined for the entire flight lines (using the revised weights for the three radiation windows).

Soil moisture estimates, using the revised weights in Table 1 for the three radiation windows and the average of the radiation data from the multiple surveys, were computed for all flight line sections for the day a flight lines was calibrated. The average of these sections estimates were adjusted to agree with the average soil moisture estimate for the entire flight line as determined using the revised weights of Table 1. For these same calibration days, three sets of soil moisture estimates (one for each of the three radiation windows) were computed for each individual survey for the same flight line sections. The three radiation windows flight line estimates for the individual surveys were correlated with the estimates for the sections as determined using data from the multiple surveys. The correlations were made for three groups based on the acquisition times for the individual sections of the flight lines. The three groups were: (1) less than 16 s; (2) 16 -30 s; and (3) 31-60 s. The results are shown in Table 2.

TABLE 2. Results of Correlation Analyses to Determine Weights for Obtaining Line Sections Estimates Using K, Tl and GC Windows Data

	Window (weight)			
ACQUISITION TIME, s	K	TL	GC	r^2
1 - 15	0.161	0	0.846	0.55
16 - 30	0.379	0	0.621	0.83
31 - 60	0.423	0	0.577	0.96

As expected when the "counting error" factor is considered, the Tl window, which has the smallest number of counts, received no weight for any of the short acquisition times. The weight for the GC window in Table 2 is high (0.846) for the acquisition time of less than 16 s and decreases as the acquisition time increases. The increase in the weight for the K window, with increase in acquisition time, is an indication of the increase in the number of counts in the K window with longer acquisition time and consequently a less effect of the "counting error" factor.

The weights given in Table 2 are not the same as those in Table 1. The weights in Table 2 are used to distribute the soil moisture along a flight line into sections values with the average of the sections values equal to the soil moisture estimate determine for the entire flight line using the weights in Table 1.

The correlation between the soil moisture estimates based on the radiation data for an individual survey, and the estimates computed using the multiple survey radiation data for the acquisition time of 1-15 s, is small ($r^2 = 0.55$). The correlations between the estimates based on individual survey data and those based on multiple survey radiation data for the two higher acquisition times are much higher ($r^2 = 0.83$ and $r^2 = 0.96$). The weighting factors determined for the two groups with longer acquisition times were adopted for use in computing soil moisture estimates for sections with acquisition times of greater than 15 s.

It should be remembered that the radiation data for computing the soil moisture estimates for the individual flight lines were part of the total radiation data for the flight line for the day. These total radiation data were used to compute the ground estimates for the sections with which the individual section estimates were compared. In a sense, the analysis was an evaluation of how well the radiation measurements are repeated in the multiple flights over the flight line for the acquisition times indicated. When they are reasonably repeated, as indicated above for acquisition time of greater than 15 s, they can be used to distribute the soil moisture estimates to the sections of the flight line. The distribution of soil moisture by sections is not recommended when the acquisition time is less than 16 s.

Soil moisture estimates for line sections for all flight lines during FIFE 1987 and 1989, having acquisition times of greater than 15 s, were computed using the revised weights in Table 1 to obtain line averages and using the weights in Table 2 to prorate the soil moisture estimates for sections. These flight line and section estimates, along with latitude and longitude information on location of the flight lines and sections, have been placed on file in the FIFE Information System (FIS) at the NASA's Goddard Space Flight Center in Greenbelt, Maryland. Similar information and data for all of the ground soil moisture measurements collected during FIFE are available from FIS.

SPATIAL VARIATION IN SOIL MOISTURE

Analysis of only CORE measurements over the FIFE area does not provide a realistic view of the spatial variation of soil moisture for the FIFE area. The CORE measurement locations are generally in open, well exposed sites, and except for very wet periods, the CORE measurements are generally lower than the average of soil moisture measurements along a flight line.

The magnitude of the variation in soil moisture over short distances of the FIFE research area was evident from reviews of the ground measurements obtained when flight lines were calibrated. As an example, 37 ground measurements of soil moisture (shown in Table 3) were made from south to north on August 5, 1989, along the flight line KS122. The average of the soil moisture values for the 37 measurements was 27.73 % with a standard deviation of 5.29

TABLE 3 Ground Soil Moisture Measurements, Flight Line KS122 Aug 5, 1989

	SAMPLE NO.*		SM %		
South End of KS122	KS122.61		42.79		
	KS122.60		29.54		
	KS122.30		25.15		
	KS122.31		29.54		
	KS122.32		31.34		
	KS122.33		30.63		
	KS122.34		30.03		
	KS122.35		26.59		
	KS122.36		28.54		
	KS122.37		42.46		
	KS122.38		30.42		
	KS122.78		30.02		
	KS122.44		28.33		
	KS122.62		27.57		
	KS122.63		30.51		
	KS122.64		31.44		
	KS122.65		30.32		
	KS122.66		24.79		
	KS122.67		27.21		
	KS122.68		24.41		
	KS122.69		24.97		
	KS122.70		25.12		
	KS122.71		21.81		
	KS122.72		22.19		
	KS122.73		27.21		
	KS122.74		24.37		
	KS122.75		16.98		
	KS122.76		21.40	CORE 906	Avg of 3
	KS122.77		18.90	CORE 906	points closest
	KS122.43		23.58	CORE 906	to 906
	KS122.40		29.53		21.30
North End of KS122	KS122.41		29.04		
	KS122.42		28.30		
		AVG	27.73		
		STDEV	5.29		
		MAX	42.79	25.81	RANGE
		MIN	16.98		
		CORE 906	21.21		

* Some of the measurements are average of more than one sample.

Station 906 is located just to the west of flight line KS122 . The CORE soil moisture measurement at station 906 on August 5, 1989, was 21.21 % for the 0 - 10 cm depth compared with the average along the KS122 flight line of 27.73 %. However, the average of the 3 points of the ground measurements along KS122 closest to station 906 was approximately the same (21.30 % compared with 21.21 %).

TEMPORAL VARIATION OF SOIL MOISTURE

The drainage area of the Kings Creek near Manhattan, Kansas (USGS station number 06879650) covers a major part of the central portion of the Konza Reserve area (shown in Figure 1). Portions of the KS103, KS105, KS106, KS107, KS108 and KS120 flight lines transect the Kings Creek drainage area. Average daily soil moisture values for IFCs days in June and July 1987 and August 1989 for the Kings Creek Basin were computed by averaging the airborne estimates for the sections of the above flight lines that are located in the basin. Weighted averages of daily soil moisture were also computed from the CORE ground measurements. Figure 2 is a plot of the daily airborne gamma radiation estimates and CORE average soil moisture values for select days in June and July 1987 and August 1989. The plots of the two daily averages with time are fairly similar except for the last few days of August 1989 when the CORE ground values are approximately 5 % lower than the airborne measurements. This is in line with the lower value observed at CORE station 906 when compared with observed ground measurements along flight line KS122. The results, indicating that the CORE measurement during dry soil moisture conditions (less than 25 %) are lower than the average soil moisture along a flight line, are in agreement with the earlier study .

COMPARISON WITH OTHER AREAL SOIL MOISTURE ESTIMATES

With PBMR estimates

There are only a few direct comparisons of remote measurement of airborne gamma radiation and microwave measurements reported in the literature. One was made during the original development of the airborne gamma radiation method in the United States by Peck et al. [1975] which demonstrated that the estimates from the two methods were related when the vegetative cover was properly taken into account.

A preliminary comparison study was made by Peck [1990] of airborne gamma radiation soil moisture measurements obtained during FIFE 1987 with estimates obtained by Wang and Shue [1990] using the PBMR system aboard the NASA C130 aircraft. The comparisons were for sections of flight lines, some of which were only 325 in length; representing approximately 0.1 km^2 [Peck 1990]. For the preliminary study, only printouts of the microwave values were available and the line values for the microwave estimates were computed using a single line of values along the flight line (representing a measurement width of only 15 m).

The results of the preliminary study indicated that the microwave estimates were stratified over the FIFE area with alternating bands of high and low values in the north-south direction and that the microwave estimates of soil moisture were high for dryer conditions (soil moisture values of less than 25%).

A second, more complete, comparison [Peck and Carroll, 1991a] was made when digital soil moisture estimates using the PBMR system [Wang et al. 1990] became available from FIS for the entire area. These data were in imagery of 850 by 1024 pixels for 10 different days, three of which were for days during the 1987 IFCs.

The area covered by the microwave soil moisture measurements contained the same areas as measured by some sections of the airborne gamma radiation flight lines (KS107, KS112, KS113 and KS119). CORE ground sites were located along or within 500 meters of these flight lines.

The microwave estimates are in percent by volume while those for the airborne gamma are in percent of dry weight. Since a constant value near unity (0.96) is assumed for the density of the soil in the calculation of the percent by volume soil moisture values, there is not a large difference between the percent by weight and the percent by volume values.

As indicated previously, an airborne gamma radiation flight line has a cross-flight line measurement of approximately 305 m. To obtain a similar coverage for the microwave data, the averages of 21 digital PBMR data points (each pixel representing a 15 by 15 m measurement) across the entire length of the airborne flight lines were used to compute areal averages for the areas of the airborne gamma measurements.

The results of the comparison confirmed those of the previous study. The microwave estimates were found to be high for dyer soil moisture conditions (less than 25 %). The results showed an unexpected finding in that the microwave estimates were better correlated with the 0-10 soil moisture observations of the CORE stations than with the 0-5 cm values.

<u>With Estimates Based on Hydrologic Modeling</u>

A comparison study was made on relationships among the soil moisture estimates from the airborne gamma radiation system, from a hydrologic model application and from the ground measurements at the CORE stations [Peck and

Carroll, 1991b]. A hydrologic model was applied by Eric Wood [1990], one of FIFE principal investigators, to the Kings Creek Basin for the summer season of 1987. The Kings Creek Basin is located in the center of the Konza reserve area. Daily soil moisture estimates from the model study for the Kings Creek Basin were provided in a digital format by Eric Wood for the periods June 3-4 and July 6-9, 1987 (personal communication). Each pixel of the file has a resolution of 30 by 30 meters.

To compute an average value of soil moisture from the model's estimates, for each flight line section, it was necessary to determine the area measured by the sections of airborne gamma flight lines. The averages of 11 hydrologic model data points across the flight line section were used to compute average model soil moisture values for each airborne gamma radiation flight line section located in the King Creek Basin.

The soil moisture values from the hydrologic model are those for the near surface layer of the model (soil moisture in the unsaturated zone). The soil moisture values for the airborne gamma surveys are assumed to represent the soil moisture in the upper 10 to 20 centimeters of the soil.

Average daily values of the 0-10 cm soil moisture were computed for each of the CORE stations in the Kings Creek Basin. It is recognized that most of the CORE stations are located at sites that are in clear, open areas as compared with the general area and therefore the average soil moisture values from these sites may be lower on the average than the average soil moisture along a flight line. However, it has been demonstrated by earlier studies that the data are related with the average values along flight lines and can be useful in evaluating the accuracy of the remotely

The daily soil moisture values for the gamma, modeled and average CORE data were combined to compute average daily values for the three different sets of estimates for the entire Kings Creek Basin. These are compared in Figure 3 [Peck et al., 1992]. It is clear that the model soil moisture values for the Kings Creek Basin are about two percent lower than those for the gamma and CORE data during the two days in June, with a much larger difference in July. The model apparently did not properly model the moisture in the upper portion of the soil even though the modeled and observed runoff were well correlated [Eric Wood 1990]. The gamma radiation and average CORE values have much greater variability for the period. During the wet period starting July 6, the gamma and average CORE values increased considerably (about six percent) from their values on June 4th, while the modeled soil moisture values decreased.

DISCUSSION AND CONCLUSIONS

The NWS Airborne Gamma Radiation System, normally used to measure soil moisture along flight lines that average 16 km in length, was used to measure soil moisture over the FIFE research area during 1987 and 1989. The airborne system measures the radiation fluxes received by a detector in a low flying aircraft in three radiation windows (^{40}Km, ^{208}Tl, and gross count). Airborne soil moisture estimates are computed using data from each of the three radiation windows by comparing observed radiation data for each window with background data collected over the same flight line with known ground soil moisture (calibration data). The NWS uses a weighted average of the three independent estimates in its operational program to calculate the soil moisture values.

A network of 24 flight lines (average length 6.2 km) were established in the FIFE study area. In addition to the airborne measurements, numerous ground measurements of soil moisture were made using the gravimetric method. The FIFE airborne and ground soil moisture data sets were used to compute revised weighting factors for the airborne gamma radiation system for use with short flight lines. These airborne soil moisture estimates for the FIFE flight lines, when correlated with the independent ground soil moisture observations, have a rms error of approximately 2.5 %, which is smaller than the error of 3.9 % which has been established by the NWS for soil moisture measurements by the airborne gamma system. The airborne gamma and ground soil moisture measurements during FIFE were much more controlled than were the same data during the operational program of the NWS on which the standard weights for the three windows were determined.

The revised weights were used to compute airborne soil moisture estimates for the 24 flight lines and for 142 sections of the flight lines for all days surveys were flown during FIFE 1987 and FIFE 1989. Estimates for sections of flight lines having airborne acquisition time of more than 15 s were found to be unreliable.

A major source of soil moisture data for the study area was the daily ground measurements made by the FIFE science staff at special instrumented sites (CORE stations). The CORE measurement locations are generally in open, well exposed sites, and except for very wet periods the CORE measurements are generally lower than the average soil moisture along a flight line. Comparison of ground soil moisture measurements collected for the calibration of the airborne gamma flight lines,with ground CORE measurements has brought out theimportant fact that analyses of only

CORE measurements will not provide realistic information on spatial or temporal variations of soil moisture for the FIFE area.

Comparisons of the airborne gamma radiation soil moisture estimates with those obtained using the PBMR microwave system, estimates from the use of a hydrologic model, and ground CORE measurements, indicate that the gamma radiation system provides the most consistent and accurate assessments of the spatial and temporal variations of soil moisture in the FIFE research area.

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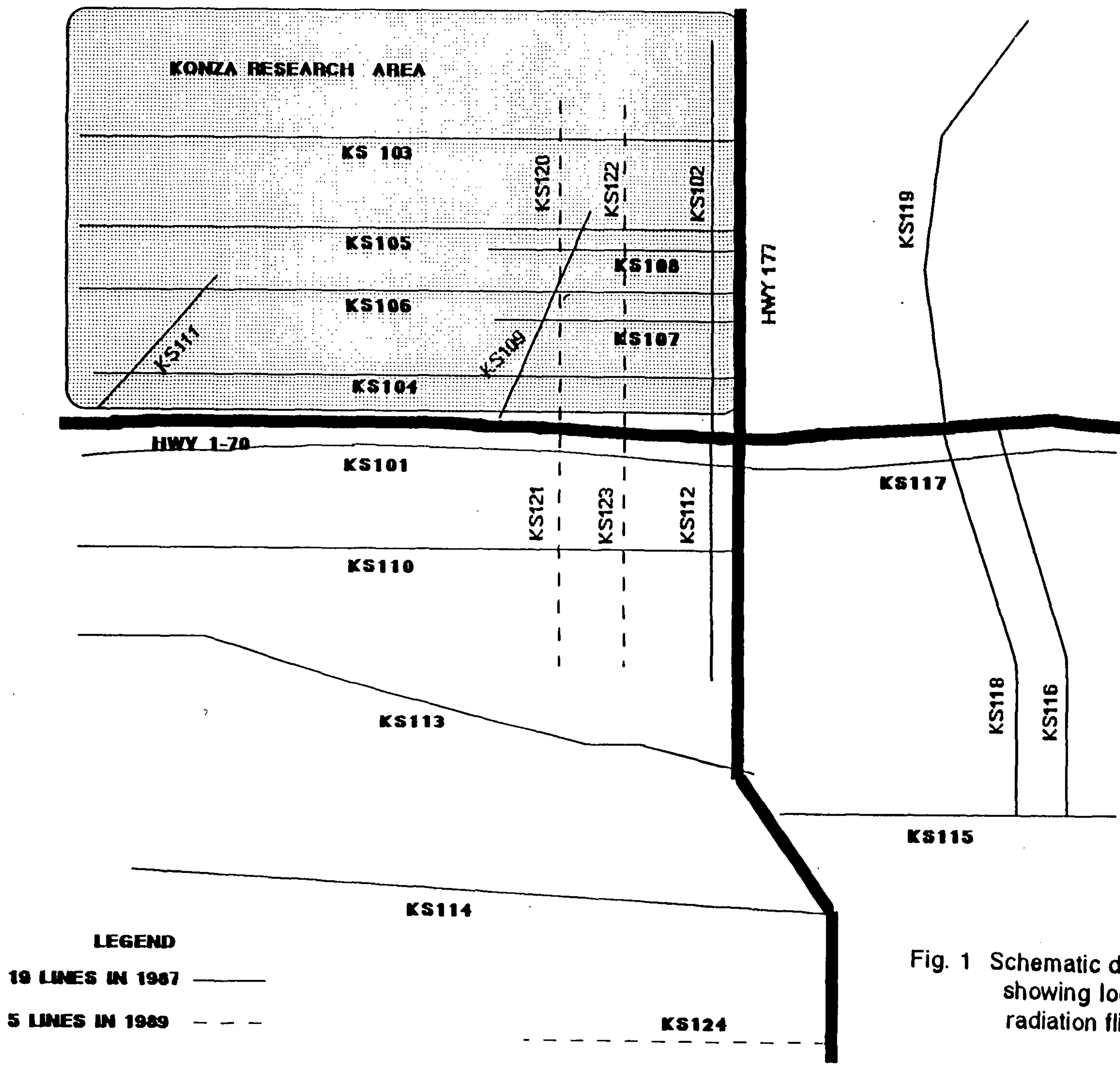

Fig. 1 Schematic diagram of FIFE study area, showing locations of airborne gamma radiation flight lines.

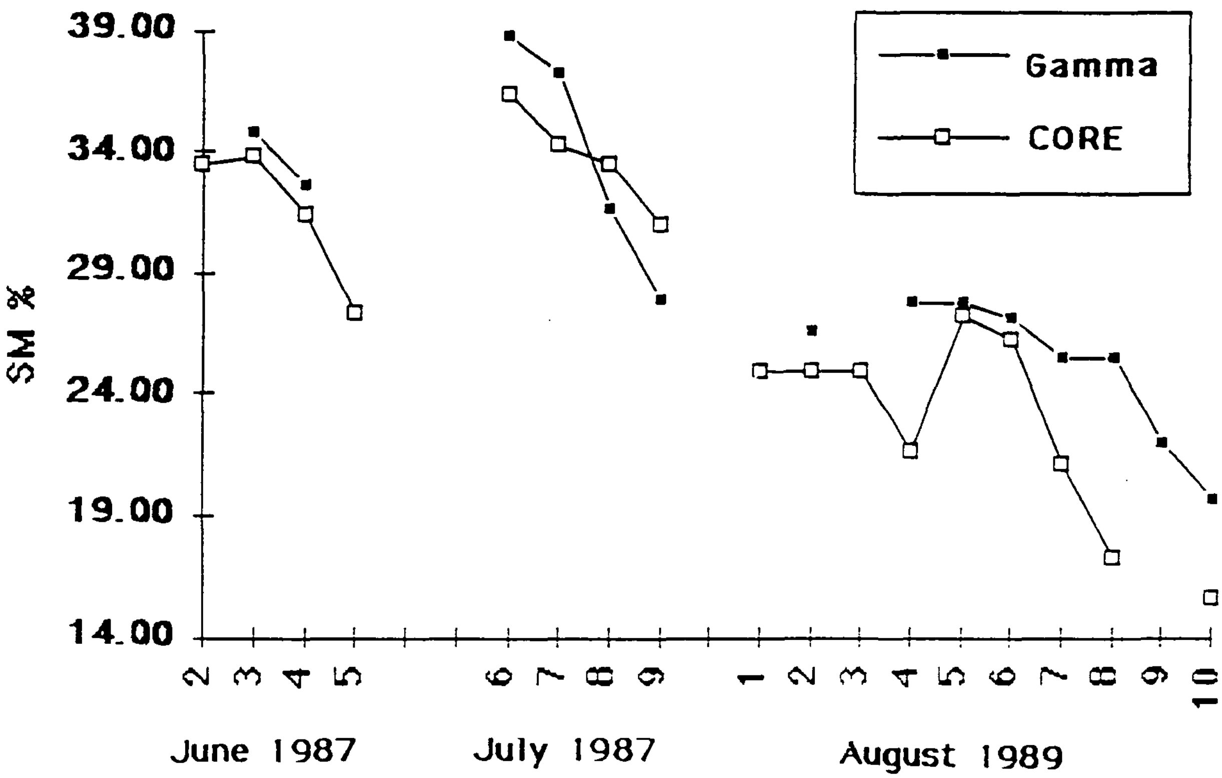

Fig. 2 Computed average daily airborne gamma and CORE ground soil moisture values for Kings Creek Basin during June-July 1987 and August 1989.

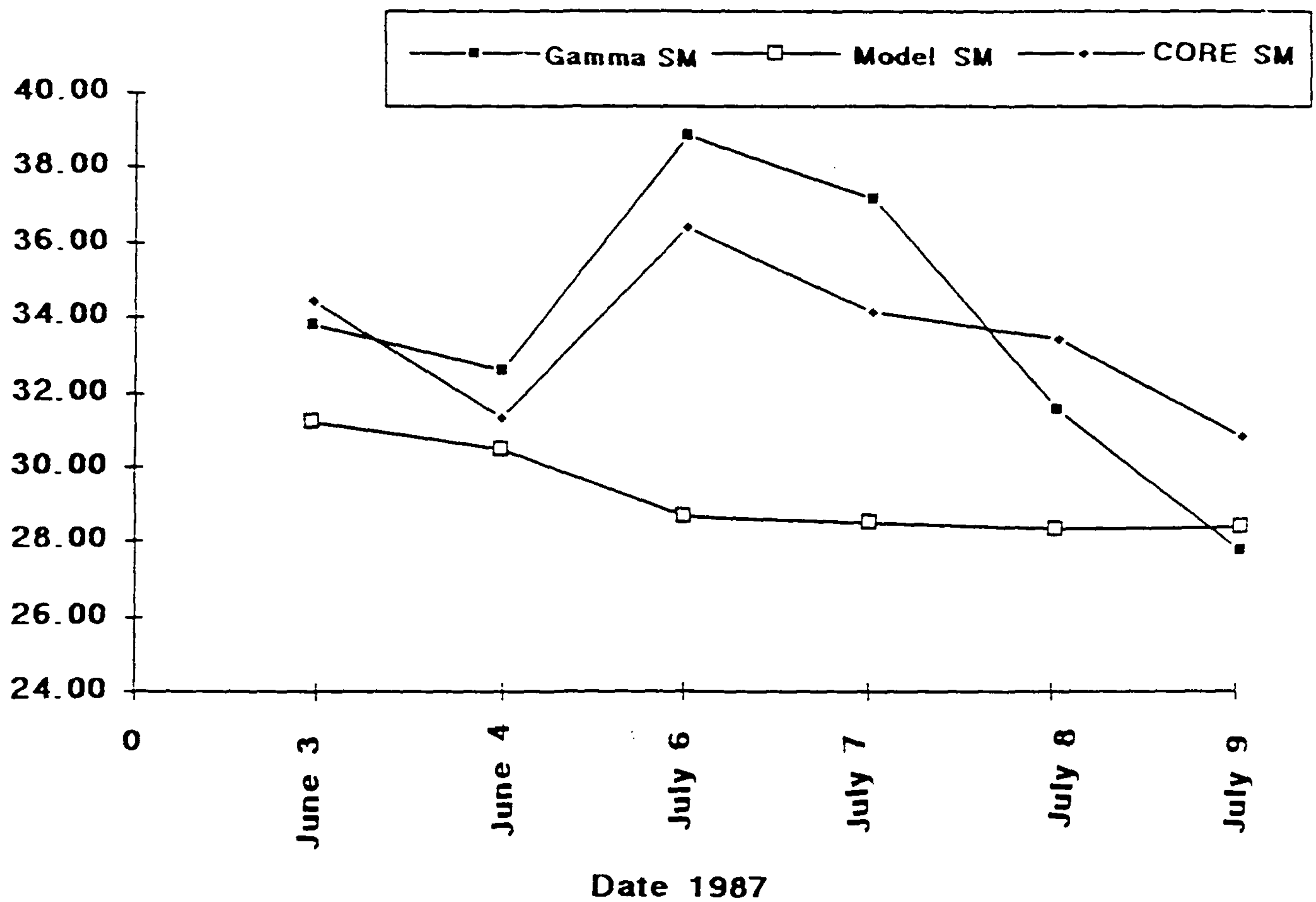

Fig. 3 Scatter diagram of average daily soil moisture for Kings Creek Basin, Gamma, Model and CORE values, June- July 1987.