AN APPLICATION OF THE AERIAL GAMMA MONITORING TECHNIQUES FOR MEASURING SNOW COVER WATER EQUIVALENTS ON THE GREAT PLAINS[1]

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ABSTRACT. During the winter of 1974-75, the Office of Hydrology of the National Weather Service in cooperation with personnel from the Canadian government, the Soil Conservation Service, the National Weather Service Central Region, and EG&G of Las Vegas, Nev., performed extensive aerial gamma surveys of the Souris River Basin in North Dakota and Canada. The object was to make reliable and timely estimates of snow cover water equivalents for the entire Souris Basin.

Background flights were made along 23 selected flight lines in the basin during October 1974 in order to measure natural background gamma radiation with no snow conditions. Similar flights and measurements were made in February and March 1975 with the existence of snow cover. The existence of water in the snow cover reduces the amount of gamma flux reaching the airborne detector. By comparing the snow and no snow gamma measurements, an estimate of snow cover water equivalents can be made. These estimates are presented along with a comparison of snow cover water equivalents obtained by extensive ground sampling along certain selected flight lines. In addition, discussions are presented on the general theory, concepts, capabilities, and limitations of the aerial gamma technique for monitoring snow cover water equivalents.

INTRODUCTION

In many areas of the country, the Great Plains for example, the snowmelt-caused flood is an annual threat. Snowmelt flood forecasts, however, constitute a direct means for the reduction of flood damage and loss of life. The formulation of a reliable river forecast requires reliable information on current hydrologic conditions over the drainage basin. The necessary data, which would include an estimate of snow cover water equivalent (W.E.), must be assembled and made available to the National Weather Service (NWS) River Forecast Centers (RFC's) in a timely and efficient manner.

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The techniques used by the NWS for making river and flood forecasts are in the process of being changed. The National Weather Service River Forecast System (NWSRFS), which includes a complete conceptual hydrologic model, will ultimately replace previously used empirical procedures at most RFC's (Monro 1974; Hydrologic Research Laboratory staff 1972). A snow accumulation and ablation model is part of this total system (Anderson 1973). This model will require timely and accurate areal snow cover W.E. information with which to check and update the snow cover simulation process. It is quite apparent that reliable and timely information on snow cover W.E.'s is of vital importance to most RFC's, especially those affected by runoff from snow cover as it exists typically in the Great Plains.

DIFFICULTIES IN OBTAINING SNOW COVER WATER EQUIVALENTS

There has always been considerable difficulty in obtaining accurate and reliable basin snow cover W.E. information (Peck 1971, Feb. 1972, Sept. 1972). Areal W.E. estimates are based on point samples obtained by ground observers. Point measurements of W.E. can be unreliable for many reasons, including errors associated with the sampling process itself and non-representativeness of the sample location. An areal estimate based on point samples is always subject to error. The magnitude of this error depends upon many factors, including the number of samples upon which the estimate is based and the algorithm utilized to make the areal estimate of W.E.

Wind redistributes snow cover, generating drifts and bare spots, and makes the choice of a representative sample location difficult. Freezing and thawing temperatures produce ice layers in the snow cover and at the snow-ground interface. Ice layers make point sampling more difficult and add to the unreliability of snow cover density estimates.

Field personnel may have to operate at reduced efficiency because of adverse weather conditions. Wind and low termperatures can make the sampling process difficult and at times even dangerous. Travel from location to location and movement along selected sampling lines can at times become quite difficult or even impossible.

GENERAL CONCEPTS OF THE AIRBORNE GAMMA TECHNIQUE

Faced with all the difficulties of obtaining current and accurate snow cover W.E.'s, the NWS RFC's would find valuable any measurement method that would be fast, independent of snow cover conditions, and give areal data rather than a series of point measurements. One such procedure currently under test by the Hydrologic Research Laboratory (HRL) of the NWS is the determination of snow cover W.E. through the airborne measurement of passive terrestrial gamma radiation (Peck 1972, 1973; Bissell 1973; Bissell and Peck 1973, Dec. 1973).

Gamma flux near the ground surface originates from natural radioactive isotopes in the soil, primarily from ^{40}K and the decay products of the Uranium and Thorium series. The concept of airborne monitoring of snow cover W.E. is based on the premise that water placed between the source (i.e., the ground) and the detector (the aircraft) will attenuate the radiation flux arriving at the detector. If the attenuation is known, the water shielding (i.e., the snow cover W.E.) can be calculated.

Briefly, the field procedure is as follows. An aircraft with a suitable gamma detection system makes a background or pre-snow cover flight along selected flight lines in a basin. This provides a measurement of the natural gamma radiation for each particular flight line. Subsequent snow cover flights along these same flight lines will result in less flux reaching the airborne detector. The amount of flux reduction can be related to the W.E. of snow cover.

THEORY AND CAPABILITIES OF GAMMA RADIATION TECHNIQUES

The gamma ray striking a scintillation crystal interacts to produce light that is converted to a pulse by a photomultiplier tube. The magnitude of the pulse is proportional to the energy of the gamma ray. The pulses are then assigned to one of 200 channels by a pulse height analyzer. Counts are kept of gross or total pulses as well as spectral counts of certain specific energy rays.

Three components of the gamma flux are used. These are:

(1) the gross count (the total gamma flux, 0.05 MeV $\leq$ energy $\leq$ 3 MeV)

(2) the ^{40}K photo-peak area (the uncollided gamma flux due to ^{40}K having an energy = 1.46 MeV), and

(3) the ^{208}Tl photo-peak area (the uncollided gamma flux due to ^{208}Tl, having an energy = 2.62 MeV).

Both the ^{40}K and ^{208}Tl photo-peak areas are portions of the gamma energy spectrum recorded by the NaI crystals. Each of the three components is attenuated by snow cover according to a particular, but known, attenuation curve.

Some adjustments have to be made to the initial data. Cosmic radiation flux and aircraft background radiation must be separated from the total pulse count. This is rather easily accomplished. The most difficult adjustment is for radon gas in the atmosphere. The radon gas, formed by radioactive decay of Radium 226 in the soil, diffuses into the air and contributes to the measured gamma flux. The concentration of radon gas is highly variable and more difficult to take into account.

Gross count (G.C.) calculations are most reliable when radon gas is not a significant factor. The advantage of G.C. information is that it is a strong signal which can be used to give fine resolution to a flight line. The spectral peaks are useful in that, even though the signal is weaker, they are less affected by radon gas. The disadvantage of the spectral peaks is that with a weaker signal (i.e., fewer counts) it is more difficult to give a fine resolution along the flight line. G.C.'s can give a line average W.E. and/or mile by mile W.E. while spectral counts generally give only a single line average W.E.

Three equations, one each for G.C., ^{40}K, and ^{208}Tl, are used to yield three water equivalents. Variables in each equation are N_0, N (count rate over snow cover), M_0 (the no snow soil moisture), and M (the soil moisture with snow cover). The W.E. equations are:

$$\text{W.E.(G.C.)} = \frac{\ln \frac{N_0}{N} - \ln\left(1 + 0.75\,\frac{M-M_0}{1+M_0}\right)}{0.0594}\ \text{g/cm}^2$$

$$\text{W.E.}(^{40}\text{K}) = \frac{\ln \frac{N_0}{N} - \ln\left(\frac{1+M}{1+M_0}\right)}{0.076}\ \text{g/cm}^2$$

$$\text{W.E.}(^{208}\text{Tl}) = \frac{\ln \frac{N_0}{N} - \ln\left(\frac{1+M}{1+M_0}\right)}{0.064}\ \text{g/cm}^2$$

The measured errors in this system are 1.5 g/cm^2 W.E. for the G.C. method, 1.5 g/cm^2 W.E. for ^{208}Tl and 1 g/cm^2 for ^{40}K W.E., all at 68-percent confidence level.

Gamma flux primarily originates in the top 4 to 6 inches of soil cover. Thus, a determination of W.E. by the change in gamma flux actually provides a measurement of snow cover W.E. and the increase in soil moisture content. Currently, the change in soil moisture content is accounted for by taking soil samples during the background and operational flights. The actual change in soil moisture is determined by the gravimetric process, and this information is used to determine how much of the total increase in water is in the snow cover and how much is in the upper soil layers.

It is expected that reasonable results can be obtained with the spectral method at snow cover W.E.'s up to 12 inches. A standard error of about 6 percent at 3.5-inch W.E. and 4 percent at 12-inch W.E. has been determined from previous research (Bissell and Peck 1973). This would mean that over the relatively flat terrain of the upper Midwest, snow cover W.E.'s can be determined by airborne gamma measurements to within 0.2 to 0.5 inch of the true amount (Peck Oct. 1971).

It is most important to note that W.E.'s obtained by airborne measurements represent areal measurements and are not just areal estimates based on point measurements. The aircraft samples an area of about 1,500 feet wide and the length of the flight line. For a typical 10-mile flight line, this is an area of approximately 4 square miles as compared to a point sample made with an Adirondack snow sampling tube having a sampling area of about 7 square inches.

SOURIS RIVER PROJECT

Background

An application of the aerial gamma technique for determining snow cover W.E.'s was made in the Souris River Basin of North Dakota and Canada during the winter 1974-75. The project had two primary goals. First, to evaluate the operational capabilities of the airborne gamma technique in the upper Great Plains areas of the United States. Second, to provide snow cover W.E. information to the Kansas City RFC to aid in their snowmelt runoff forecasts of the Souris River.

The Souris River originates in Saskatchewan, Canada, loops southward into North Dakota at Sherwood, continues south past Minot, and then flows back north into Canada at Westhope (figs. 1 and 2). In years past, it has been a serious trouble spot during the spring flood season, especially at Minot. It is difficult to forecast because of the problems associated with obtaining adequate, reliable, and timely snow cover W.E. information. A summary of discharge data for the Souris River in North Dakota is presented in table 1.

Flight Line and Mission Description

Twenty-three flight lines were selected for aerial monitoring (fig. 2 and table 2). Each flight line was 6 to 10 miles in length and each was chosen from a separate sub-basin of the Souris. Twelve lines were in North Dakota (ND50-61) and 11 were in Canada (CA1-10). Four of the flight lines, ND51-52 and CA6-7, were designated "ground true" lines. Each flight line was carefully chosen so that it could be easily identified from the air (i.e., parallel to a highway or railroad, etc.).

Three missions were flown in the Souris Basin. The first was a background flight performed from September 30 to October 3, 1974. The purpose of this mission was to determine the pre-snow natural background radiation profile for each line and also to determine the initial soil moisture conditions. Operational flights for determining snow cover water equivalents were performed February 3-9 and March 5-6, 1975.

Sampling Techniques

Each gamma monitoring mission consisted of an airborne and a ground phase. In the airborne phase. the aircraft flew each line at an elevation of 500 feet at least once. The ground true lines were flown two or more times depending upon available time, weather conditions, etc.

Concurrent with the airborne phase a ground sampling process occurred. This was accomplished by ground crews who heavily sampled the ground true lines for soil moisture and snow cover W.E. information. In addition, other lines were spot-sampled by ground crews where accessible.

In general, on the North Dakota ground true lines, snow depths were sampled each 100 feet, and snow cover W.E. measurements were made each 600 feet. In special situations, drifting, etc., sample spacing was reduced. Soil samples were obtained at preselected locations on the ground true lines, generally one location in each line mile. Lines other than ground true lines were spot-sampled for W.E. and soil moisture data at one or two locations per line.

Equipment Description

The aerial radiological measuring system utilized by HRL on this and other similar projects was designed and is operated for the U.S. Energy Research and Development Administration (ERDA) by EG&G of Las Vegas, Nev. The detection system consists of 14 sodium iodide scintillation crystals. This detection system is installed in a Beechcraft Twin Bonanza aircraft equipped with an accurate positioning system. An on-board computer produces a paper tape record of all flight and radiation information. A portable computer terminal and paper tape reader enabled the tapes to be processed immediately after the plane landed. W.E. information is available 4 to 8 hours after a flight is concluded.

Ground crews used Adirondack samplers to obtain most of the point estimates of snow cover W.E. A Mount Rose sampler was utilized when large drifts were encountered. Augers were used to obtain soil samples from the frozen ground.

Souris River Project Participants

U.S. participants from the NWS included the HRL, Silver Spring, Md.; the Bismarck, N. Dak., Forecast Office; and the Kansas City, Mo., RFC. Additional U.S. participants included the ERDA and the Soil Conservation Service. Canadian participants were the Inland Waters Directorate of Environment Canada and the Saskatchewan Department of Environment.

RESULTS

Snow Cover Water Equivalents

The results of the airborne and ground observations of snow cover W.E.'s are presented in tables 3 and 4. The W.E. estimates for the North Dakota times are presented in table 3, while the W.E. estimates for the Canadian lines are shown in table 4. Airborne W.E. estimates were determined by using a weighted average of the three components of gamma flux (G.C., ^{40}K, ^{208}Tl).

In February, the average airborne W.E. estimate for all four ground true lines was 1.13 inches. The ground estimate was 1.20 inches. The airborne estimate was therefore 5.8 percent low as compared to ground data. In March, the average airborne W.E. for the four ground true lines was 1.09 inches, while the ground estimate was 0.88 inch. The airborne estimate in March was therefore 23.8 percent high as compared to the ground data. For all four ground true lines, in both February and March, the average airborne estimate of line W.E. was 6.7 percent high as compared to ground estimates.

Soil Moisture Values

Soil moisture values for the Canadian and North Dakota lines are shown in tables 5 and 6. The values show a gradual but continuing increase in soil moisture from October to March. In North Dakota, the average October soil moisture for all lines was 15.2 percent, while in March it was 24.1 percent. This is equal to about three-fourths inch of water in the upper 6 inches of soil. In Canada, the average soil moisture for all lines increased from 13.8 percent to 20.6 percent during the same period of time. While the soil moisture values seemed slightly higher on the North Dakota lines, the average increase in soil moisture per line was about the same for the North Dakota and Canadian lines, 7.8 percent and 6.2 percent respectively.

The ground true lines exhibited a similar increase in average soil moisture values. In Canada, the ground true lines increased in soil moisture from 13.5 to 14.7 percent, while the North Dakota ground true lines increased from 14.7 to 21.3 percent. The soil moisture values on this particular project assumed a greater importance than normal because of the generally sparse snow cover that existed in February and early March.

DISCUSSION

An overall observation of the data is encouraging when one considers that the gamma system was utilized in a difficult low W.E. situation. On most lines, the results were consistent and reasonable. The average airborne W.E. estimates for the Canadian ground true lines were within

0.1 inch of the ground estimate in February and March. On the North Dakota ground true lines, the airborne estimate was within 0.1 inch of the ground estimate in February and was within 0.5 inch in March.

All the comparisons of airborne and ground W.E. estimates should be viewed with the following in mind. First, the expected standard error of the system is 1 cm W.E. or about one-half inch. That is, on a series of lines, about one-third of the W.E. estimates would differ from ground true by one-half inch of water or more. Second, under low W.E. conditions, a reliable ground estimate of W.E. is difficult because so much of the total W.E. on a given line may be in drifts, ice layers, etc., all of which are difficult to ground sample properly. It would be reasonable to expect ground estimates to be low if ice layers are present. Third, some of the airborne W.E. line estimates are being compared to a single point sample on the ground. The value of such a comparison would depend entirely on the representativeness of the point location and should therefore be viewed with caution. Finally, even with dense ground sampling along the flight paths, the ground sample averages may not be representative of the total area surveyed by the airborne sensor. A comparison of airborne W.E. estimates with ground W.E. estimates is not meant to imply that the ground estimates are "true" values.

Line ND61 was located so that it crossed many of the coulees located just west of the Des Lac River near Minot. The observations from this line were interesting because the use of aerial gamma techniques in mountainous or hilly areas has not been previously tested. The airborne W.E. estimate on this line in February was 1.1 inch, while in March it was 0.26 inch, indicating a loss of 0.84 inch of water during the month. Ground observations substantiated this loss. While most of the line was snow covered in February, in March, considerable portions of the line had spotty snow cover and all south-facing slopes were completely snow free. In addition, the NWS River District Office at Bismarck indicated that they had had reports of snowmelt runoff from the coulees during a warm spell in late February.

CONCLUSIONS

The airborne gamma survey flights in the Souris Basin demonstrated the operational capability of the total system. The accuracy of the system in determining snow cover W.E.'s under the conditions encountered compared favorably to that obtainable by extensive ground sampling. Larger differences than were observed between airborne and ground W.E. estimates could have been expected because of the problems involved in obtaining a representative ground average of snow cover W.E.

Table 1.--Souris River discharge records

Gaging station	Drainage area (sq. mi.)	Mean discharge (cfs)	Maximum discharge (cfs)	Years of record
Sherwood, ND	8,940[1]	106	12,400	45
Minot, ND	10,600[2]	142	12,000	72
Westhope, ND	16,900[3]	191	6,400	45

[1] 5,900 sq. mi. non-contributing
[2] 6,700 sq. mi. non-contributing
[3] 10,300 sq. mi. non-contributing

Table 2.--Souris River snow survey line locations

Name	Length (mi.)	Nearest town	End point locations of lines: Long., W. ° '	Lat., N. ° '	Long., W. ° '	Lat., N. ° '
ND50	10.2	Voltaire, ND	100 55.8	48 3.2	100 43.4	48 00.0
51*	5.0	Minot	101 17.9	48 25.4	101 17.9	48 27.6
52*	7.2	Berthold	101 35.7	48 15.8	101 44.5	48 18.8
53	10.8	Tolley	101 47.1	48 43.5	102 1.2	48 43.5
54	10.8	Bowbells	102 14.4	48 50.0	102 15.5	48 59.3
55	11.2	Columbus	102 32.6	48 53.7	102 45.9	48 53.7
56	11.0	Sherwood	101 32.1	48 47.4	101 36.8	48 56.1
57	12.0	Bottineau	100 52.8	48 49.2	100 37.3	48 49.2
48	10.0	"	100 21.5	48 48.4	100 8.4	48 48.4
59	9.8	Russell	101 3.0	48 40.0	100 50.6	48 40.7
60	13.2	Karlsruhe	100 37.2	48 5.3	100 22.2	48 00.0
61	17.4	Foxholm	101 34.4	48 22.1	101 53.3	48 30.5
CA1	10.2	Hirsch, Sask.	102 1.6	49 0.9	102 1.6	49 9.8
2	13.2	Glen Ewen	102 26.1	49 10.5	102 43.5	49 10.5
3	15.5	Hitchcock	103 1.4	49 9.3	103 15.8	49 18.8
4	10.0	Torquay	103 29.9	49 1.7	103 29.9	49 10.5
5	10.0	Colgate	103 53.3	49 24.5	103 53.3	49 33.2
6*	8.3	Halbrite	103 33.2	49 29.5	103 41.1	49 34.5
7*	6.0	Staughton	103 1.4	49 47.1	103 1.4	49 41.8
8	12.0	Carlisle	103 16.4	49 27.8	102 15.0	49 38.1
9	11.2	Radville	104 18.9	49 28.0	104 33.8	49 28.0
10	11.2	Yellow Grass	103 47.6	49 42.6	104 9.5	49 48.4
11	14.8	Corning	102 58.8	50 1.1	103 18.2	50 1.1

*Ground true lines.

Table 3.--North Dakota snow cover water equivalents

Line	Feb 3-9, 1975 Airborne (in.)	Feb 3-9, 1975 Ground (in.)	Feb 3-9, 1975 No. of W.E. locations	Mar 5-6, 1975 Airborne (in.)	Mar 5-6, 1975 Ground (in.)	Mar 5-6, 1975 No. of W.E. locations
ND50	1.5	1.30	1	0.96	0.50	1
51*	.9	.99	22	.82	.19	16
52*	.7	.70	21	.51	.20	10
53	1.5	--	--	.85	--	1
54	1.9	2.40	1	1.42	.95	1
55	1.9	1.70	1	1.45	.70	1
56	1.5	--	--	.65	--	--
57	1.9	.70	2	1.78	.69	2
58	1.4	.80	2	.54	.33	1
59	1.6	.80	1	1.87	.66	2
60	2.0	1.90	1	1.35	--	--
61	1.1	1.30	12	.26	.51	1
$\bar{X}$	1.49	1.26		1.04	.53	
$\bar{X}$*	.80	.85		.67	.20	

*Ground true lines.

Table 4.--Canada snow cover water equivalents

Line	Feb 3-9, 1975 Airborne (in.)	Feb 3-9, 1975 Ground (in.)	Feb 3-9, 1975 No. of W.E. locations	Mar 5-6, 1975 Airborne (in.)	Mar 5-6, 1975 Ground (in.)	Mar 5-6, 1975 No. of W.E. locations
CA1	1.1	--	--	0.89	--	--
2	1.4	--	--	1.11	0.89	4
3	1.5	--	--	1.15	1.04	18
4	1.1	0.94	3	.57	.09	12
5	1.1	.31	?	1.24	.73	11
6*	1.5	1.4	55	1.76	1.42	58
7*	1.4	1.7	50	1.24	1.69	52
8	1.9	--	--	1.59	2.43	4
9	.8	--	--	.75	--	--
10	.9	1.1	?	1.95	1.17	18
11	1.6	--	--	1.87	--	--
$\bar{X}$	1.30	1.09		1.28	1.18	
$\bar{X}$*	1.45	1.55		1.50	1.56	

*Ground true lines.

Table 5.--North Dakota--percent soil moisture summaries for all lines

Line	Oct[a] 1-2	Jan[b] 20-31	Feb[a] 3-5	Feb[b] 26	Mar[a] 5	Soil moisture change Oct-Mar
ND50	5.1	17.0	--	12.0	17.1	+12.0
51*	13.8	17.5	16.4	16.6	23.9	+10.1
52*	15.6	17.7	16.1	19.5	18.7	+3.1
53	17.3	17.5	--	20.0	25.1	+7.8
54	10.8	12.5	14.2	17.4	--	--
55	15.3	17.5	11.8	12.5	13.4	-1.9
56	21.9	16.1	20.9	25.4	31.6	+9.7
57	27.5	27.7	--	22.5	32.6	+5.1
58	17.7	23.5	--	35.9	23.8	+6.1
59	18.4	22.3	--	22.8	18.5	+.1
60	9.3	24.4	--	16.5	--	--
61	9.6	15.0	--	24.1	36.3	+26.7
$\bar{X}$	15.2	19.1		20.4	24.1	+7.8
$\bar{X}$*	14.7	17.6		18.1	21.3	+6.6

Note: All values are percent soil moisture.
[a]During flight.
[b]Pre-flight.
*Ground true lines.

Table 6.--Canada--percent soil moisture summaries for all lines

Line	Oct[a] 1-2	Jan[b] 20-31	Feb[a] 3-5	Feb[b] 26	Mar[a] 5	Soil moisture change Oct-Mar
CA1	9.5	--	--	--	--	--
2	16.4	--	--	--	18.0	+1.6
3	11.3	--	12.6	--	24.0	+12.7
4	13.4	--	16.3	--	21.6	+8.2
5	13.3	--	25.2	--	27.0	+13.7
6*	12.6	15.0	14.0	--	15.2	+2.6
7*	14.4	16.8	20.5	14.	14.2	-.2
8	12.8	--	--	--	13.8	+1.0
9	13.8	--	--	--		--
10	20.6	27.0	15.9	--	31.0	+10.4
11	--	--	--	--	--	--
$\bar{X}$	13.8		17.4		20.6	+6.2
$\bar{X}$*	13.5		17.2		14.7	+1.2

Note: All values are percent soil moisture.
[a]During flight.
[b]Pre-flight
*Ground true lines.

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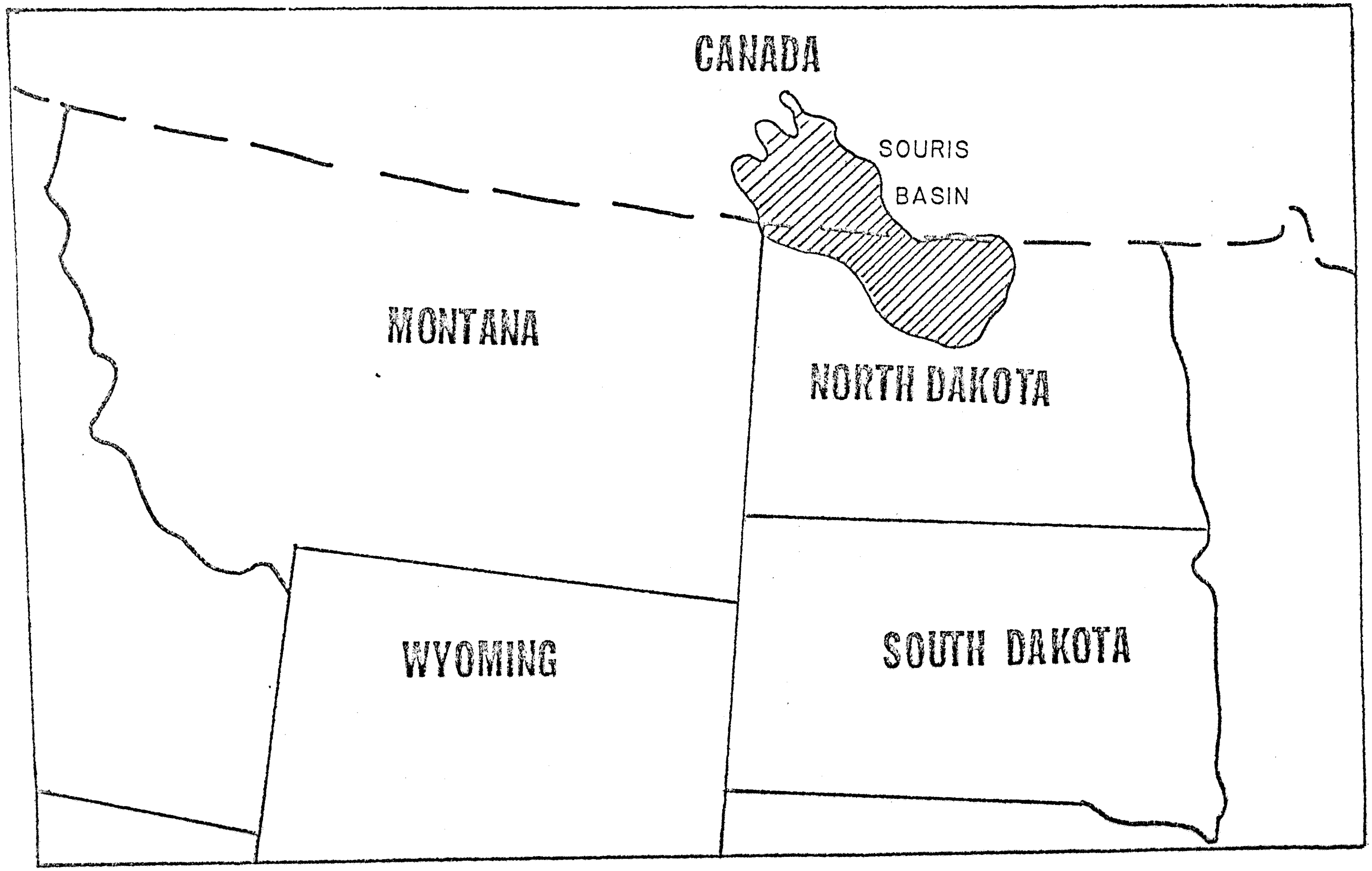
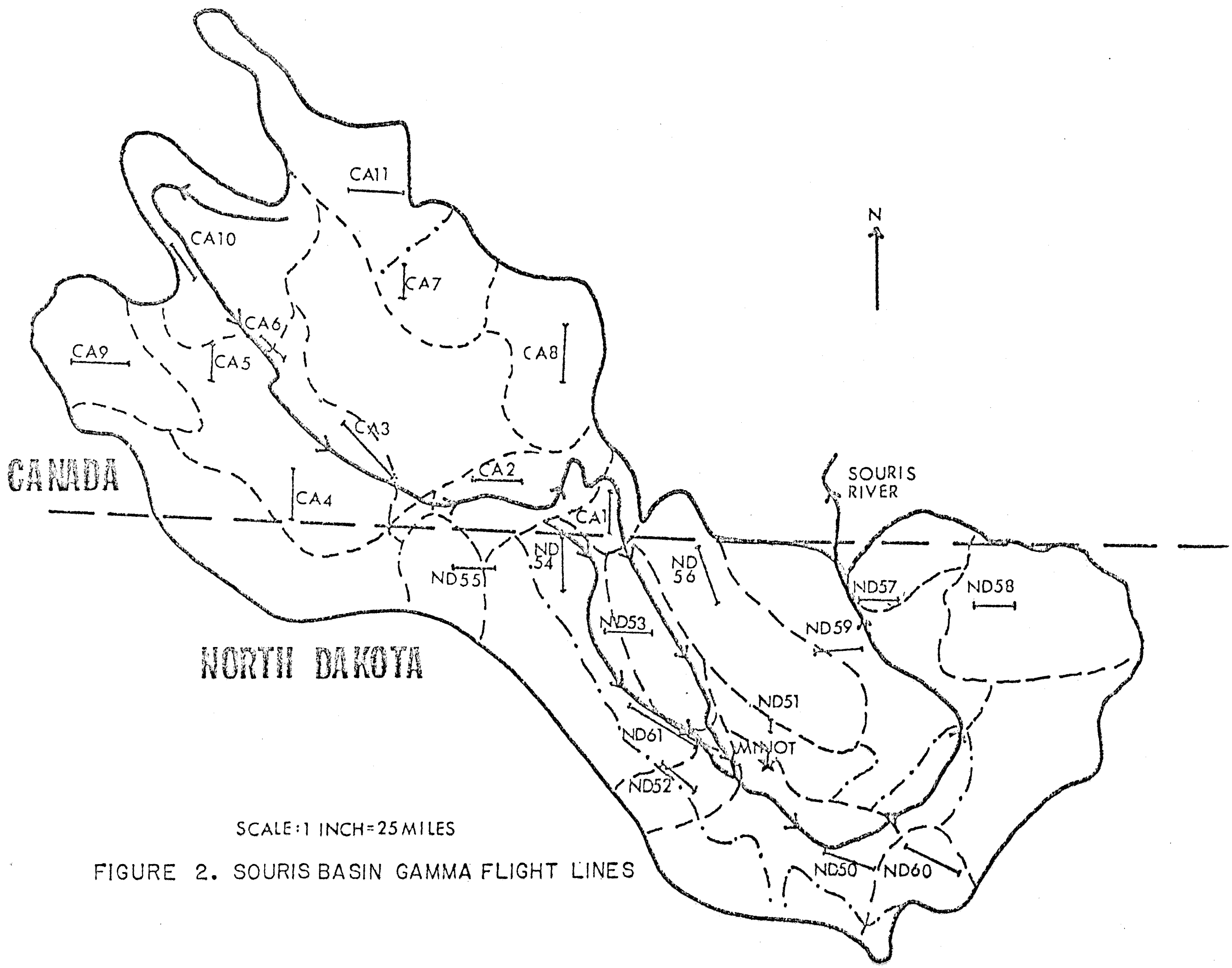


FIGURE I. GENERAL AREA SOURIS RIVER BASIN



SCALE: 1 INCH=25 MILES

FIGURE 2. SOURIS BASIN GAMMA FLIGHT LINES