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Operational aerial snow surveying in the United States

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Abstract. An airborne gamma radiation detector and data acquisition system has been designed for rapid measurement of the snow cover water equivalent over large open areas. Research and field tests conducted prior to the implementation of an operational snow measurement system in the United States are reviewed. Extensive research test flights were conducted over large river basins of the north-central plains and in the high mountain valleys of the inter-mountain West. Problems encountered during development include (1) error in the gross gamma flux produced by atmospheric radon gas daughters, (2) spatial and temporal variability in soil moisture, and (3) errors in gamma radiation count rate introduced by aircraft and cosmic background radiation. Network design of operational flight line and ground observation data used in a river forecasting system are discussed.

Etude de neige aérienne effectuée aux Etats Unis

Résumé. On a préparé un détecteur de rayonnement aéroporté et un système pour l'acquisition des données dans le but de la mesure rapide de l'eau équivalente de la couche de neige sur les grandes étendues découvertes. On passe en revue les recherches et les essais sur le terrain qu'on a effectués avant l'implémentation d'un système de mesure de neige opérationnel aux Etats Unis. On a effectué des vols d'essai extensifs dans le but des recherches sur de grands bassins des fleuves des plaines au Nord-central et dans les vallées montagneuses de l'ouest d'entremont. On a rencontré les problèmes suivants au cours de la période du développement: (1) des écarts dans le flux global gamma engendrés par les produits de première géneration du gaz radon atmosphérique; (2) variabilité spatielle et temporelle dans l'humidité du sol; (3) des erreurs dans la vitesse de comptage du rayonnement gamma introduits par l'avion et le rayonnement de fond cosmique. On discute la préparation d'un réseau des opérations aériennes et les données des observations faites sur la terre qu'on a utilisées dans un système pour le calcul du comportement d'une rivière.

INTRODUCTION

The National Weather Service of the National Oceanic and Atmospheric Administration has the responsibility of providing a flood warning service in the United States. The ability to predict snowmelt flooding is dependent on an accurate and timely estimate of the snow cover water equivalent available for runoff. The difficulty in obtaining accurate and representative measurements of snowfall or snow cover water equivalent over large river basins is well known (Rodda, 1971; Peck, 1972).

In the north-central plains of the upper Missouri and Minnesota River basins, snowmelt is the primary cause of spring flooding which may affect a large segment of the population and economy of the region.

During the winter of 1968–1969 a heavy snowfall occurred over much of the upper Missouri River basin. It was evident that a major snowmelt flood was

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inevitable for this basin. Field investigations were made to determine if new techniques of measurement might be developed to improve the accuracy of estimation of the average water equivalent for a river basin. It was concluded that additional efforts to improve the usefulness of the ground measurements were not warranted. Consequently, the aerial gamma radiation survey principle developed in the USSR and described by Kogan *et al.* (1965) and Zotimov (1968) was considered as a possible technique to obtain representative and timely measurements of snow cover water equivalent over large areas.

EARLY RESEARCH

In the fall of 1969 the National Weather Service began research on an aerial gamma radiation snow survey system for potential operational river forecasting.

Research flight lines

The principal research site is located near Luverne, Minnesota, in the Rock River basin, a tributary to the Missouri River basin. This location receives an average snow cover of 3 cm of water equivalent, has a minimum spatial variability, and is representative of the agricultural lands located in the upper Missouri River basin. An initial flight line 13.6 km long (elevation 442 m) was established. Four additional flight lines were established in the immediate proximity: two running parallel and two running perpendicular to the initial line. All flight lines are parallel to all-year highways to allow positive location from the air and to facilitate the collection of ground truth data. A second research line 6.7 km long was established in a high mountain valley (elevation 2130 m) near Steamboat Springs, Colorado, where the average peak snow accumulation is near 25 cm of water equivalent.

Ground observations

The research flight lines are divided into sections separated by roads crossing the flight path at 1.6 km intervals. Most ground sampling along the flight lines consisted of taking snow depth data at 10 m intervals, water equivalent measurements at 100 m intervals, and soil moisture measurements at two or three pre-selected locations per kilometre. Water equivalent measurements were collected using an Adirondack sampling tube (6.7 cm diameter) at Luverne and a Mount Rose sampling tube (3.8 cm diameter) at Steamboat Springs. Soil moisture was determined for the upper 20 cm using the standard gravimetric method.

Detection system

The Aerial Radiological Measuring System (ARMS) designed and operated by EG & G. Inc., for the US Atomic Energy Commission (presently the Energy Research and Development Administration) was used for experimental research. The gamma detector system in the aircraft consists of fourteen 10.16 cm by 10.16 cm NaI (Tl) scintillation crystals. The system includes an on-board computer used to record all flight and radiation information and is described in detail by Anderson *et al.* (1969).

The radiation data collected on-board the aircraft are of two types. The total count, or gross count, is the total number of photons detected with energies greater than 50 keV. Spectral data consist of count values in each of 200 channels ranging from 15 keV to 3.0 MeV in energy. Well defined peaks in the energy spectrum reveal the presence of isotopes emitting specific energy gamma radiation.

Atmospheric radon gas distribution

Errors in snow cover measurements may be introduced due to the dynamic nature of radon, a radioactive noble gas which originates in the soil and whose daughter products ^{214}Pb and ^{214}Bi are major sources of gamma radiation seen by the detector. Other investigators have reported the seasonal and diurnal variation in atmospheric radon gas concentration (Gold *et al.*, 1964; Bissell, 1974). Radon gas concentration is generally low in the spring and high in the fall. Additionally, early morning temperature inversions tend to facilitate the accumulation of radon gas near the ground while vertical mixing in the afternoon tends to disperse any previous radon gas buildup (Peck & Bissell, 1973). The accuracy of airborne measurements is limited, in part, by variation in the general radon distribution along a survey line and between missions.

Several techniques have been developed to isolate the effect of radon gas; these include over-lake flights, dual altitude flights, dual detectors (upward and downward looking detectors), mathematical procedures to remove the radon effect from spectral peaks, and the use of air filter systems to indirectly measure radon gas daughters present in the air mass. In general the use of dual detectors has not proved useful for an operational system. In the detector configuration tested, high correlations between observed radiation from the upward and downward looking detectors were found. Consequently, it is difficult to isolate only that gamma radiation originating from the ground.

Additional tests were made on the dual detector approach at a snowmelt research experimental site near Danville, Vermont. Heavy lead shielding was used in an attempt to measure separately the ground and atmospheric radiation. Again the effort did not prove successful because of the high correlation found in the two measurements. The test did demonstrate the use of the detector for measuring soil moisture and/or water equivalent except during and immediately after periods of precipitation (Bissell & Peck, 1973). The dual gauge approach has been used successfully for geological surveying to account for variations in radon gas contributions.

An air filter system can satisfactorily measure atmospheric gamma radiation but the increased weight of the equipment and need for an in-flight operator limits the usefulness of the technique for an operational survey system (Fritzsche & Feimster, 1975).

Two techniques which have been useful in isolating radon gas contribution are (1) over-lake surveys (virtually no radioactivity emanates from lakes) and (2) mathematical procedures (stripping equations) used to account for the extraneous gamma rays and to remove their contribution from the sum of gammas counted in selected pulse height windows (^{40}K and ^{208}Tl) (Grasty *et al.*, 1973; Kogan *et al.*, 1971). The application of both approaches can minimize the error introduced by the radon gas component.

WATER EQUIVALENT CALCULATION TECHNIQUES

The two primary measuring techniques that have been tested are the total count and the photopeak area method. The total count approach integrates the counts under the energy spectrum from 50 keV to 3 MeV. The total count approach is attractive because the large number of counts (up to one million per 13 km flight line) produce a standard deviation due to natural gamma count fluctuations of less than 1 per cent (Peck *et al.*, 1971). The spectral photopeak area method uses the number of uncollided gamma count rates indicated by the area under the peaks near 1.46 MeV for ^{40}K and near 2.62 MeV for ^{208}Tl. Several methods have been used to determine the number of uncollided gamma counts for ^{40}K and ^{208}Tl (Bissell, 1974). The latest method uses count rates from specific energy windows as shown in Fig. 1.

Early studies clearly indicate that corrections for soil moisture are required for both the total count and photopeak area approaches. Techniques for introducing soil moisture corrections and adjusting the measured counts have been described (Peck *et al.*, 1971; Jones *et al.*, 1973). The daughter products of radon gas in the atmosphere (^{214}Bi) introduce a significant number of counts which affect the total count and the ^{40}K photopeak count, but does not affect the ^{208}Tl photopeak. The total effect varies considerably within a day and from day to day.

Multiple altitude flights

The data from the early investigations demonstrates the value of as low an altitude as possible for operational surveying. Figure 2 shows the relationship between net count data (corrected to a common atmosphere and corrected to a base soil moisture) with the ground observed snow cover water equivalent values for five different flight levels. The data in the figure represents the average of many flight lines for the different water equivalents and at the different altitudes. It is evident that the most accurate measurement is observed at the lowest flight elevation of 61 m, but a sufficiently strong relationship is observed for the 152 m altitude for operational purposes.

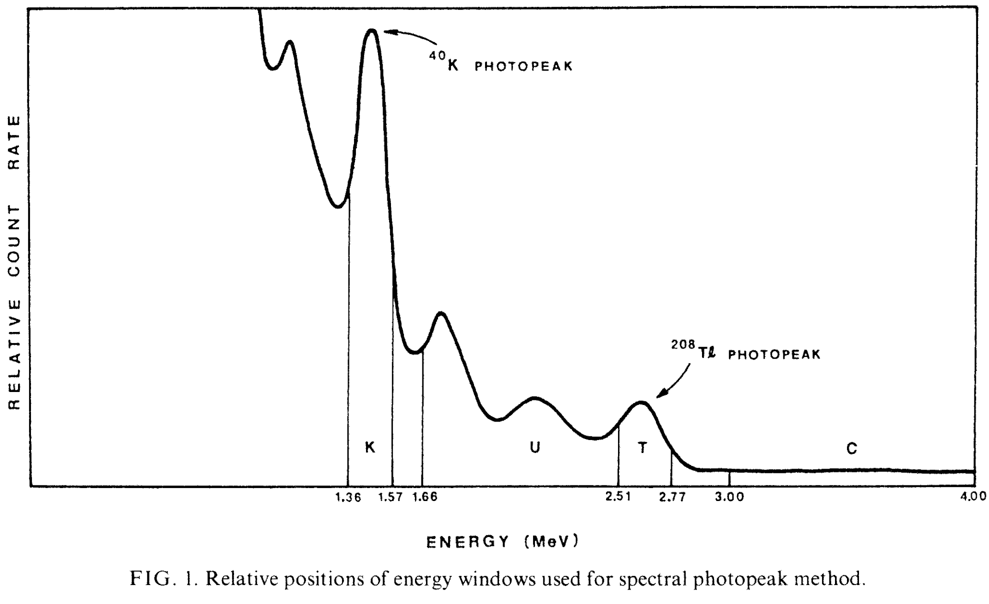

FIG. 1. Relative positions of energy windows used for spectral photopeak method.

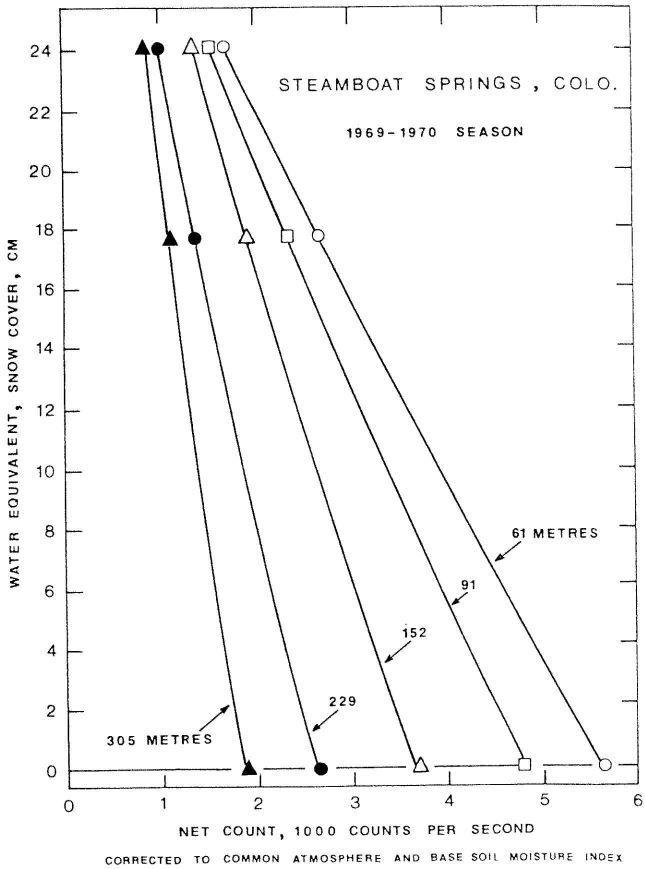

FIG. 2. Relation between net count and snow water equivalent, Steamboat Springs, Colorado, 1969–1970 research period.

SUMMARY OF PRELIMINARY FINDINGS

Research by the National Weather Service during the last 10 years has revealed several problem areas that must be satisfactorily resolved in an operational survey programme. These are:

(1) Corrections for soil moisture must be made, especially prior to spring melt. Large changes in soil moisture occur under the influence of sustained temperature gradients in the soil where groundwater is located near the surface (Peck, 1974). Increases in the soil moisture in the upper 20 cm are commonly observed to be 10–20 per cent (of dry weight) above normal field capacity. This may occur in frozen or unfrozen ground.

(2) The large natural variability in the atmospheric radon gas decay products greatly limits the usefulness of the total count method and to a lesser extent the usefulness of the spectral photopeak ^{40}K method. These radon contributions must be isolated to calculate satisfactorily the snow water equivalent.

(3) It is necessary to collect background radiation and over-snow radiation for

exactly the same flight line. Large spatial variability in background radiation may introduce significant error with only a small deviation from the flight path.

(4) The air mass between the ground and detectors also attenuates the radiation signal. Consequently, it is necessary to correct for the mass of the air between the detector and the ground. It is then possible to correct explicitly for the change in air mass by computing the density of the air mass by the use of a radar altimeter and air pressure measurements made from the aircraft.

OPERATIONAL TESTS

Following the early experimental work, operational tests have been conducted over several sections of the northern states during periods of heavy snow cover. The ARMS detector system was used for many years in the operational tests. Later another experimental system, the Remote Aerial Measurements of Snow (RAMS) system, was developed and used for the operational tests. Most of the area of the northern plains states are conveniently covered by networks of roads layed out on a 1.6 km network. These roads provide excellent visual means for conducting operational tests.

IFYGL tests

During the International Field Year of the Great Lakes (IFYGL), aerial gamma radiation surveys were conducted on the US drainage basin of Lake Ontario (Fritzsche & Feimster, 1975; Bursen & Fritzsche, 1973). In the spring of 1973, following background surveys in 1972, a selected network of flight lines, as shown in Fig. 3, were surveyed in the Lake Ontario basin. The network for the Lake Ontario basin was divided into two sections and for each section a ground truth calibration line was established. Table 1 shows the estimated water equivalent for the calibration lines using the three techniques, gross count and spectral peak data for ^{40}K and ^{208}Tl with the measured line average data from ground surveys.

Souris River basin

A second major operational test was conducted in co-operation with Environment Canada over the Souris River basin in North Dakota and Canada (Larson, 1975). Aerial snow surveys were flown over pre-selected network lines similar to those established for the IFYGL surveys as shown in Fig. 4. The average snow cover of the Souris River basin is near the minimum for which the accuracy of the system would provide significant information. In addition, the area is subject to high winds and consequently there is significant variation in the deposition of snow over the basin. Two calibration lines were established in the United States and two in Canada. Surveys were made in 1975 prior to the onset of melt using the ARMS detector system. A comparison of the observed airborne and ground survey data is shown in Table 2. The airborne snow equivalent measurements are within the 1 cm error credited for the airborne system.

Additional surveys were made in March 1976, after snowmelt had commenced. For these surveys the RAMS system was used. Since the background data had been measured with the ARMS system it was necessary to convert these data to comparable data for the RAMS system using simultaneous data collected over a standard

FIG. 3. Gamma flight lines for Lake Ontario basin in the United States.

TABLE 1. Water equivalent (cm) of snow cover on IFYGL calibration lines

	Aerial measurements*				Snow tube†
Line	Gross count	^{40}K	^{208}Tl	Average	Line average
ROCH-180	2.9 ± 1.3	3.4 ± 1.0	3.6 ± 1.4	3.3 ± 1.0	3.3 ± 0.3
SYRC-050	9.8 ± 2.6	9.1 ± 1.0	9.3 ± 1.9	9.4 ± 1.0	9.3 ± 1.1

* Errors shown are one standard deviation.
† True average lies within these limits for 90 per cent confidence.

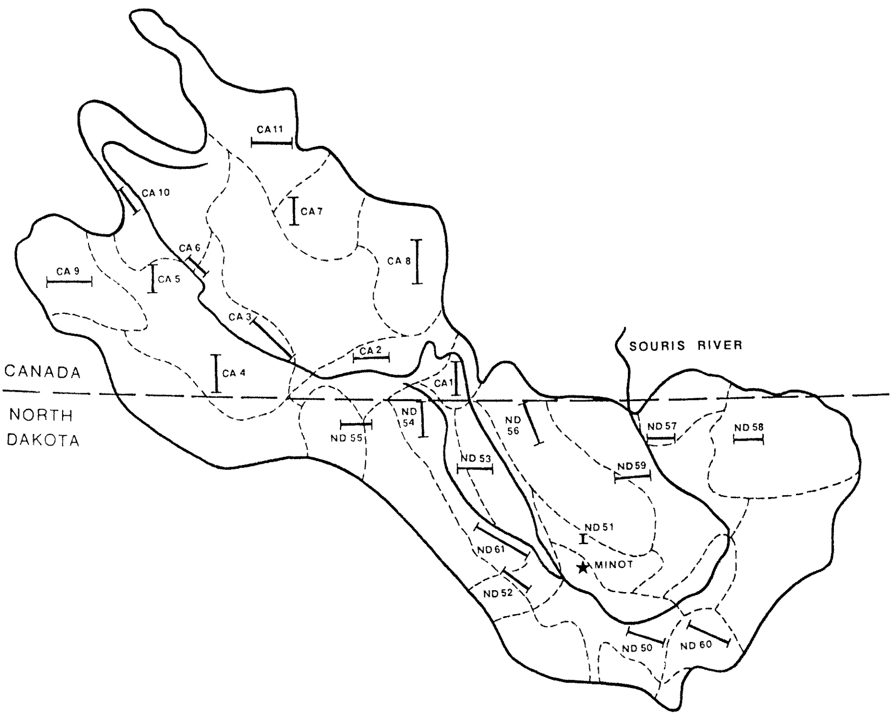

FIG. 4. Souris River basin gamma flight lines.

calibration survey line. Thus, for this particular measurement period, errors may be introduced by the change in the measurement system. Moreover, melting snow with standing water makes it extremely difficult to measure the true water equivalent of the snow. Consequently, the accuracy of ground snow measurements is limited. Comparison of aerial and ground measurements for the calibration lines for the 1976 surveys are shown in Table 2.

Other field tests

Over the past 4 years during periods of heavy snow, the RAMS system has been used to collect data for near operational use. During the winter of 1978, data were

TABLE 2. Airborne and snow tube water equivalent (cm) measurements in the Souris River basin

	February 1975		March 1975		March 1976*	
Line No.	Airborne	Snow tube	Airborne	Snow tube	Airborne	Snow tube
ND-51	2.1	2.5	1.8	0.5	2.0	1.3
ND-52	0.9	1.8	1.4	0.5	0.0	0.0
CA-6	4.1	3.6	4.4	3.6	4.6	9.4
CA-7	3.3	4.3	4.1	4.3	9.4	13.7

* The new RAMS system was used in March 1976.

collected for the Red River of the North and several small tributaries of the Missouri River basin in North Dakota. The airborne measurements gave average water equivalents for the Red River basin slightly lower than those indicated by the standard ground measurements. The previously issued forecasts for near record flooding were lowered slightly and verified by the subsequent runoff.

In 1977, an exceptionally heavy snowfall occurred in the Lake Ontario basin especially near Buffalo, New York (Fritzsche, 1977). The IFYGL lines were flown from 26 February to 1 March 1977. Additional surveys were flown southeast of Buffalo. The aerial survey made immediately south of Lake Ontario measured less snow water equivalent than the ground survey. The resulting runoff was in line with the lower water equivalent values. The airborne system measured exceptionally high water equivalents for the Black River basin east of the lake which were supported by ground reports. Record breaking floods subsequently occurred in that basin.

OPERATIONAL PROGRAMME

Research and field testing programmes indicate the utility of the aerial gamma measurement techniques for operational purposes. The National Weather Service is initiating an operational programme for the upper Mississippi and Missouri River basins with a new survey system reported by Fritzsche (1979). A network of flight lines is being established for all areas where snowmelt flooding is possible and for which river forecasts would be required. Studies are being conducted to determine the best method for establishing the survey lines for use with the airborne system. A network of soil moisture measurement stations is being established over the area to support the airborne surveys. Many geographical and geomorphological features of the area make the operational use of the gamma radiation survey more feasible than for many areas of the world. For example, a highly developed network of roads provides an excellent basis for accurate visual navigation. In addition, there are many airports and navigational aids to facilitate aircraft maintenance and safety. Most of the area is agricultural with few swamps and wetlands; therefore, surveys are not subject to the problems associated with wet areas where the use of the gamma survey techniques is greatly limited.

The National Weather Service has established requirements for an operational airborne gamma radiation measuring system; it should be:

(1) Adaptable for use in light planes and portable for use in leased planes.

(2) Operable by two persons: a pilot and system operator, who also serves as a navigator.

(3) Modular with readily available components.

(4) Supplied with a detector system with a sensitivity to provide an accuracy of less than 1 cm water equivalent over a 16 km line.

(5) Capable of storing sufficient information for later calibration checks and computation of mile-by-mile average water equivalents.

(6) Capable of storing background radiation and soil moisture data used for on-board calculations.

(7) Capable of computing line averages of water equivalent while data processing is continuing.

Another system which will be utilized for the operational programme has been developed (Fritzsche, 1979).

LIMITATIONS

Snow cover over much of the north-central plains area is relatively uniform. However, for basins such as the Souris River where the snow cover is highly variable and subject to major changes by redeposition, the airborne estimates of average water equivalent can be underestimated. For such areas, corrections as discussed by Cork & Loijens (1979) are required.

It is clear that unusual variations in gamma radiation from radon gas daughter products and/or other sources can introduce serious errors in the measured values of the water equivalent of the snow cover. In addition, large variations in the average soil moisture from estimated values can also introduce serious error. Research is still required to improve the overall accuracy and usefulness of the measurements to the operational river forecasting programme of the National Weather Service.

USE OF MEASUREMENTS

The river forecast models now being implemented by the National Weather Service (1972) use only temperature and precipitation as input. Techniques have been developed for improving the forecast accuracy of such models by objectively including measurements of the water equivalent of the snow cover (Carroll, 1978). Thus, improved measurements of the average water equivalent of the snow cover should provide increased accuracy over the use of the present conceptual models.

Calibration of operational river forecasting models requires several years of data for adequate determination of parameter values. Since airborne measurement of the water equivalent of the snow are now being collected on a routine basis for the first time, the maximum value of these data cannot be realized for at least five years. However, the data will have an immediate value since better areal distribution information will be available. Ground measurements are not observed at present in many basins of 1000–2000 km^2 for which airborne measurements will be obtained.

ADDITIONAL RESEARCH REQUIREMENTS

Although the present system is considered adequate for operational purposes, considerable additional research is needed. Improved methods for correcting for the radon gas and better statistical methods for combining the various measuring techniques are still needed (Bissell, 1974).

At the present time the airborne measurement corrected for soil moisture provides a measurement of the water equivalent of the snow which is used as input to hydrological models for forecasting the snowmelt floods. The aircraft measurements, in fact, provide direct estimates of the total change in the water equivalent in the snow cover as well as the upper few centimetres of the soil. Since it has been estimated by Zotimov (1968) that 91 per cent of the gamma radiation originating from the ground comes from the upper 10 cm, the airborne measurements actually provide information on the change of water content in the upper 10 cm of soil as well as the snow cover. Relatively small changes in the structure of the conceptual hydrological model could provide for the direct input of the airborne measurement representing the total change in water equivalent rather than only the water equivalent of snow. The use of the direct measurement would tend to eliminate the error due to changes in the soil moisture.

Other procedures such as the Kalman filtering technique could take advantage of the direct measurement rather than only the corrected value representing the water equivalent of the snow cover.

CONCLUSION

Based on the research of the past 10 years, the National Weather Service is now implementing the use of the aerial gamma radiation surveys for operational purposes. The present status of the technique is considered to be of value for improvement in the river forecasting services. The major value of the aerial survey data cannot be realized until sufficient data are available for calibration of hydrological models for river forecasting. In addition, the maximum use of the data will come when the measurements of gamma radiation can be entered directly into the hydrological models without the need for correction of soil moisture conditions. Although there is room for considerable improvement in the measurement technique of the gamma radiation programme, the primary value will not be in a more advanced data collection procedure but rather in the development of new techniques for more efficient use of the data.

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