APPLICATION OF AIRBORNE GAMMA RADIATION SNOW SURVEY MEASUREMENTS AND SNOW COVER MODELING IN RIVER AND FLOOD FORECASTING

By

Thomas R. Carroll* and Lee W. Larson**

INTRODUCTION

The National Weather Service (NWS) has the hydrologic forecasting responsibility for the Nation. The mission of the NWS hydrologic service program is to save lives, reduce property damage, and contribute to the maximum use of the Nation's water resources. The scope is large; current annual flood losses are estimated at approximately 200 deaths and $2 billion in property damage.

The NWS meets its hydrologic responsibilities through the efforts of the thirteen River Forecast Centers (RFC's) located throughout the United States. Each RFC provides hydrologic guidance and expertise to a state network of both National Weather Service Forecast Offices (WSFO's) and National Weather Service Offices (WSO's) located within each RFC's area of hydrologic responsibility. Products generated by the RFC's include flood forecasts, general river forecasts used for navigation and other purposes, reservoir inflow forecasts, water supply outlooks, spring flood outlooks and various types of flash flood guidance.

In addition, RFC's provide a variety of other services; they develop forecast procedures as required and requested, develop and implement new forecast techniques, and remain current in advanced hydrologic forecast techniques, computer systems, data handling techniques, and hydrologic related hardware. In addition, the RFC's provide hydrologic expertise on a wide range of hydrologic activities such as dambreak analysis for NWS and other federal, state, and local agencies. The RFC's also conduct hydrologic training courses and seminars for a wide range of topics and participants.

The NWS, with a total field hydrologic staff of 125 hydrologists, is constantly striving to improve the hydrologic products provided to the public by developing and implementing the latest hydrologic techniques and procedures. One example is the recent development and implementaton of a continuous conceptual snow accumulation and ablation model used to simulate the physical

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characteristics of the snow cover using mean areal temperature and precipitation data. A second example is the recent implementation of an operational Airborne Gamma Radiation Snow Survey Program capable of providing real-time snow water equivalent data over large areas of the upper Midwest. The snow cover model can accept as data input the observed snow water equivalent measurements generated by the Airborne Snow Survey Program. Together, these two recent technological developments repesent advanced techniques in snow cover simulation and mean areal snow water equivalent data collection.

NWS RIVER FORECASTING

Hydrologists at the River Forecast Centers analyze and process a wide range of hydrologic data and prepare river, flood, and reservoir forecasts as well as hydrologic outlooks for public distribution. The forecast procedures are based on historical data and account for current hydrologic, hydraulic, and meteorologic factors. The RFC's generate hydrologic forecasts for approximately 1600 forecast points nationwide and rely on data from a network of 1800 river gages and 4000 rainfall stations which represent a large portion of the supporting ground data collection network.

After the necessary hydrologic and meteorologic data are gathered and processed, the river and flood forecast development begins with the determination of available runoff. In the Missouri and Upper Mississippi River basins, the temperature based snow accumulation and ablation model (Anderson, 1973) determines the quantity of water from snowmelt and/or rainfall available for runoff. Outflow from the snow pack is then processed to determine runoff using either a soil moisture accounting model (Burnash, et al., 1973) or an antecedent precipiation index (API) model (Linsley, et al., 1958). Approximately 700 unit hydrographs (Sherman, 1932) are used by the Missouri Basin River Forecast Center to generate streamflow hydrographs from simulated runoff. Downstream hydrographs are developed by several routing procedures described by Goodrich (1931), Richard (1967), and Fread (1974). These routing procedures account for the change in shape and timing of a wave as it moves downstream in an ever-changing dynamic channel. U.S. Geological Survey rating curves are used to convert forecast discharge to forecast stage.

Spring Flood Outlooks, issued for the upper Midwest, are developed at the RFC's in much the same fashion as river forecasts. The outlooks, however, assume temperature and precipitation patterns for the outlook period. Once the current hydrologic and meteorologic conditions are determined from reported data, predetermined temperature and precipitation patterns are applied to the existing snow cover (Mondschein, 1971). A simulation is generated sufficiently far into the future to melt the existing snow cover and to route the resulting hydrographs downstream.

SNOW ACCUMULATION AND ABLATION MODEL

A typical continuous snow accumulation and ablation model (Figure 1) is a conceptual computer model which represents separately each significant physical process within the snow cover. The snow model simulates the snow pack accumulation, heat exchange at the air-snow interface, areal extent of snow cover, heat storage within the snow pack, liquid water retention and transmission, and heat exchange at the ground-snow interface (Anderson, 1973). Input consists of mean areal air temperature and precipitation data.

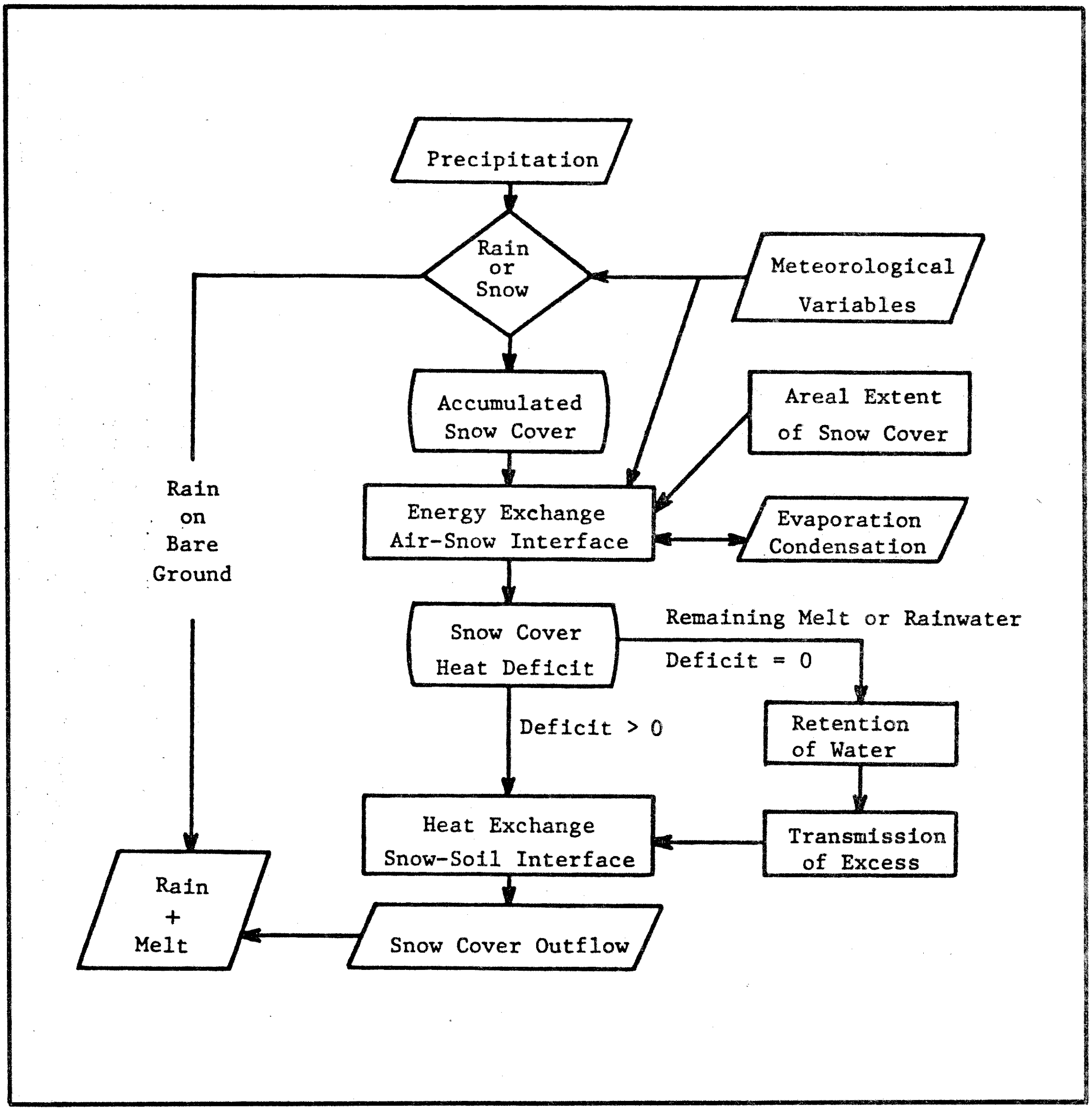

FIGURE 1.
Flowchart of typical snow accumulation and ablation model (after Anderson, 1978).

The accumulation of the snow cover is based on precipitation and air temperature data. If the air temperature is below 0°C (or any temperature selected by the user), the model accumulates snow during precipitation events. If the temperature is equal to or greater than 0°C, precipitation enters the snow pack as rain. Heat exchange at the air-snow interface is the most critical factor in snow pack ablation. The model assumes melt can occur only if the air temperature is greater than 0°C. If melt and rain occur simultaneously, the model accounts for net radiative heat transfer, latent heat transfer, sensible heat transfer, and heat transfer by rainwater. If melt occurs without rain, then melt is based on a seasonally varying melt factor.

During cold periods of non-melt, the snow cover loses heat. This negative heat flow is determined by an antecedent temperature index and a negative melt factor. The negative melt factor varies seasonally and represents a varying conduction of heat based on changing snow density. The change in heat storage in the snow pack during non-melt periods is represented as a depth of water equivalent. Also included in the model is a constant melt rate at the ground-snow interface which represents the geothermal heat flux. The areal extent of snow cover is used to determine the area over which heat exchange is taking place and the areal extent of rain which falls on bare ground. Areal depletion curves of snow cover for a given area have similarities from year to year and are used to relate snow water equivalent to areal extent of snow cover. The snow model maintains a continuous accounting of heat storage of the snow pack. When the pack is isothermal and the liquid water capacity is satisfied, excess liquid water is used as input to API or soil moisture accounting procedures which in turn generate runoff. Prior to exiting the snow pack, the excess water is lagged and attenuated through the pack before being input to a runoff model.

API models are a simplified but effective index approach to determining runoff. Soil moisture accounting procedures, however, have been developed (Burnash, et al., 1973) to simulate processes of moisture movement within the soil which contribute to stream flow generation. Rain and snow melt generated by the snow model are input to the soil moisture accounting model and distributed to various conceptual compartments using rational percolation characteristics. In the upper Midwest, the permeability of the upper layer of soil can have an important influence on spring snow melt flooding. The most important snow-soil interaction to stream flow simulation is the effect of frozen ground on snow cover runoff. These effects can be quite large where extensive areas of concrete frost have developed over a basin during the winter (Anderson, 1978).

SNOW WATER EQUIVALENT MEASUREMENTS AND MODEL CALIBRATION

Mean areal temperature and precipitation estimates are used by the snow model to simulate continuously snow pack accumulation and ablation. Errors associated with the simulated snow water equivalent values are, to a large degree, generated by the paucity of point temperature and precipitation data used to estimate mean areal values. A more dense network of input data would tend to reduce simulation errors. Snow cover observations, however, can be compared to the simulated snow water equivalent generated for the time of the snow cover observation. The observed snow water equivalent values can be used as a check on the simulated values which can be subsequently modified to reflect more accurately the true snow cover conditions.

Ground snow cover data are used by NWS hydrologists in the RFC's to assess the impact of winter snow cover on spring flood potential in the upper Midwest. Ground snow cover observations have also been objectively incorporated into the snow model for watersheds in the West to update the simulated snow water equivalents to reflect more accurately ground snow cover conditions (Carroll, 1978). Ground snow cover data, however, are difficult, time-consuming, and, in some cases, hazardous to collect. Additionally, ground snow data may be significantly in error. Ice lenses within the pack and at the ground-snow interface can contribute substantial error to the measurement. Redistribution of the snow cover into drifts and blown-clean areas makes the selection of a representative sampling site virtually impossible. Various problems associated with sampling techniques, sample site locations, and snow sampling hardware all tend to generate errors in point snow cover data collected on the ground. The sporadic and infrequent nature of available ground snow cover measurements coupled with associated errors makes it particularly difficult to calculate reliable, real-time mean areal snow water equivalents for river systems subject to snow melt flooding.

In an effort to provide more useful snow water equivalent data, the NWS Office of Hydrology began research and development in 1969 on a technique using natural terrestrial gamma radiation to measure mean areal snow water equivalent from a low-flying aircraft (Peck and Bissell, 1973; Peck et al., 1971; Larson, 1975). The early research ultimately led to the implementation of an operational Airborne Gamma Radiation Snow Survey Program located in Minneapolis which presently serves North Dakota, South Dakota, and Minnesota (Peck, Carroll, and VanDemark; 1979). The operational snow survey program is designed to provide mean areal snow water equivalent data from large areas of the upper Midwest to Weather Service offices prior to spring snow melt. These airborne data, along with ground snow cover information, are currently being used by the North Central and Missouri Basin RFC's to help assess the spring flood threat on major river systems in the region. Spring Flood Outlooks are issued to the public by these River Forecast Centers in early spring each year. Prior to each outlook, an airborne snow survey is conducted over the upper Midwest and the resulting snow water equivalent data along with other information are used by the RFC's in preparing the Spring Flood Outlook.

AIRBORNE SNOW WATER EQUIVALENT AND SOIL MOISTURE MEASUREMENT TECHNIQUE

The technique used to measure natural terrestrial gamma radiation attenuation and subsequently infer snow water equivalent and soil moisture values has been described recently by Carroll and Vadnais (1979, 1980) and Carroll (1981); consequently, only a brief overview will be given here.

The gamma radiation flux near the ground originates primarily from the natural ^{40}K, ^{238}U, and ^{208}Tl radioisotopes in the soil. In a typical soil, 96 percent of the gamma radiation is emitted from the top 20 cm (Zotimov, 1968). After measures of the background (no snow cover) radiation and soil moisture are made, the attenuation of the radiation signal due to the snow pack over-burden is used to calculate the amount of water in the snow cover. Each flight line is approximately 20 km long and 300 m wide; consequently, each snow water equivalent measurement is a mean areal value for approximately 6 km^2 of snow cover.

Three operational and independent snow water equivalents are calculated by measuring the attenuation of the gamma radiation flux in specific windows of the radiation spectrum. The three mean areal snow water equivalents are calculated using data from the K window (1.36-1.56 MeV), the Tl window (2.41-2.81 MeV), and the gross count (GC) energy spectrum (0.41-3.0 MeV). The potassium photopeak is consistently the strongest in the energy spectrum and has been used successfully to measure snow water equivalent in Canada (Grasty, 1979) and in the US (Peck, Carroll, and VanDemark, 1979). The gross count window accumulates an order of magnitude more counts than the K and Tl photopeak windows. Consequently, gross counts are useful when measuring the variability of snow cover along a line or a mean areal snow cover with 15 to 25 cm of snow water equivalent.

The gamma radiation attenuation technique can also be used to measure soil moisture in the upper 20 cm. The gamma radiation emitted from the radioisotopes in the soil is attenuated by the presence of soil moisture near the surface. Consequently airborne radiation data collected over bare gound conditions reflect both the radioisotope and soil moisture concentration near the surface. Recent tests show a high correlation between airborne and ground soil moisture measurements (Carroll, 1981).

The principal sources of error in calculating snow water equivalent or soil moisture values using any of the three windows are incorporated in: (1) the stripping equation derived during the calibration procedure, (2) the measurement of airmass (i.e., temperature, pressure, and radar altitude), (3) the measurement of mean areal soil moisture for a flight line, (4) the measurement of the radon gas contribution to the gamma flux spectrum, and (5) counting statistics. Nonetheless, the technique is capable of measuring snow water equivalent with an accuracy of 1 cm (Carroll and Vadnais; 1979, 1980) and soil moisture with an error of approximately 3.2 percent soil moisture (Carroll, 1981).

SNOW AND SOIL MOISTURE MODEL UPDATING

The continuous snow and soil moisture models used by the RFC's are physically based models and as such simulate real-world states in the hydrologic process. Consequently, simulated states or variables can be updated based on observed measurements and thus reflect more accurately the true conditions at any given time. A data base of airborne snow water equivalent values is currently being accumulated for a network of over 300 flight lines in the upper Midwest. After a sufficient data base is developed, the snow model can be calibrated using the airborne snow measurements in addition to the mean areal temperature and precipitation data. Consequently, the data base being collected today will be indispensable in future calibrations of the snow model for the region.

The capability of making airborne soil moisture measurements also has an important hydrologic application in the upper Midwest. The need to adequately understand the permeability of the upper soil surface at the time of snow melt has been described by Anderson (1978). The soil moisture conditions in the spring are largely related to the fall soil moisture conditions immediately prior to winter freeze-up and snow accumulation. Currently, fall soil moisture conditions can only be generally inferred from precipitation data. The operational collection of fall soil moisture data could provide a means to incorporate important soil moisture information into soil moisture accounting procedures used by hydrologists at the RFC's and WSFO's in the upper Midwest. In a fashion similar to that used in the snow model, it would be possible to update appropriate soil moisture states based on observed measurements at critical times in the hydrologic cycle.

1980 AIRBORNE AND GROUND SNOW SURVEYS

During February, March, and April of 1980 both airborne and ground snow cover data were collected in the upper Midwest and used by NWS field hydrologists to assess the magnitude of spring snow melt flooding. On both the North Dakota and Minnesota side of the Red River of the North, a network of cooperative observers took traditional ground-based snow samples. During the week prior to the March 14 release of the Spring Flood Outlook, cooperative observers took 22 depth and density snow samples and seven depth samples along the main stem of the Red River covering an area in excess of 50,000 km^2. These data were subject to substantial error caused by sampling technique and the nonrepresentative character of the sample site location. Consequently, it was difficult to calculate a reliable mean areal snow water equivalent value for a runoff zone or watershed based on available ground snow cover observations.

In addition to the ground observations, an airborne snow survey was made over the same region and the data were used in the Spring Flood Outlook issued by the River Forecast Center in Minneapolis. Data were collected on 62 flight lines located along the main stem of the Red River. Each flight line is approximately 20 km long and 300 m wide; consequently, each airborne measurement represents a mean areal value for approximately 6 km^2. The snow water equivalent measurement represents an average depth of water equivalent over the flight line. In this way, small scale variability in the snow cover is measured and averaged to give a useful mean areal value which represents the snow water equivalent of the general area.

During the late winter of 1980 most of the snow in the upper Midwest was located in the Souris River basin in north central North Dakota. On March 10, approximately 10 cm of snow water equivalent was centered over the Turtle Mountains just north of the U.S. border in Canada covering an area 20 km in diameter. A narrow band of snow with 6 cm of water equivalent and 20 km wide extended south 150 km from the center in Canada covering much of the lower Souris River basin. A network of 48 flight lines has been established over both the Canadian and United States portions of the Souris River basin. Ground data collected by cooperative observers at 13 sites and airborne data collected over flight lines in the region were used to map prevailing snow cover conditions (Figure 2).

With the ability to make reliable mean areal snow water equivalent measurements over a comparatively dense network of flight lines, it will be possible to define more precisely the natural variability of snow water equiva-

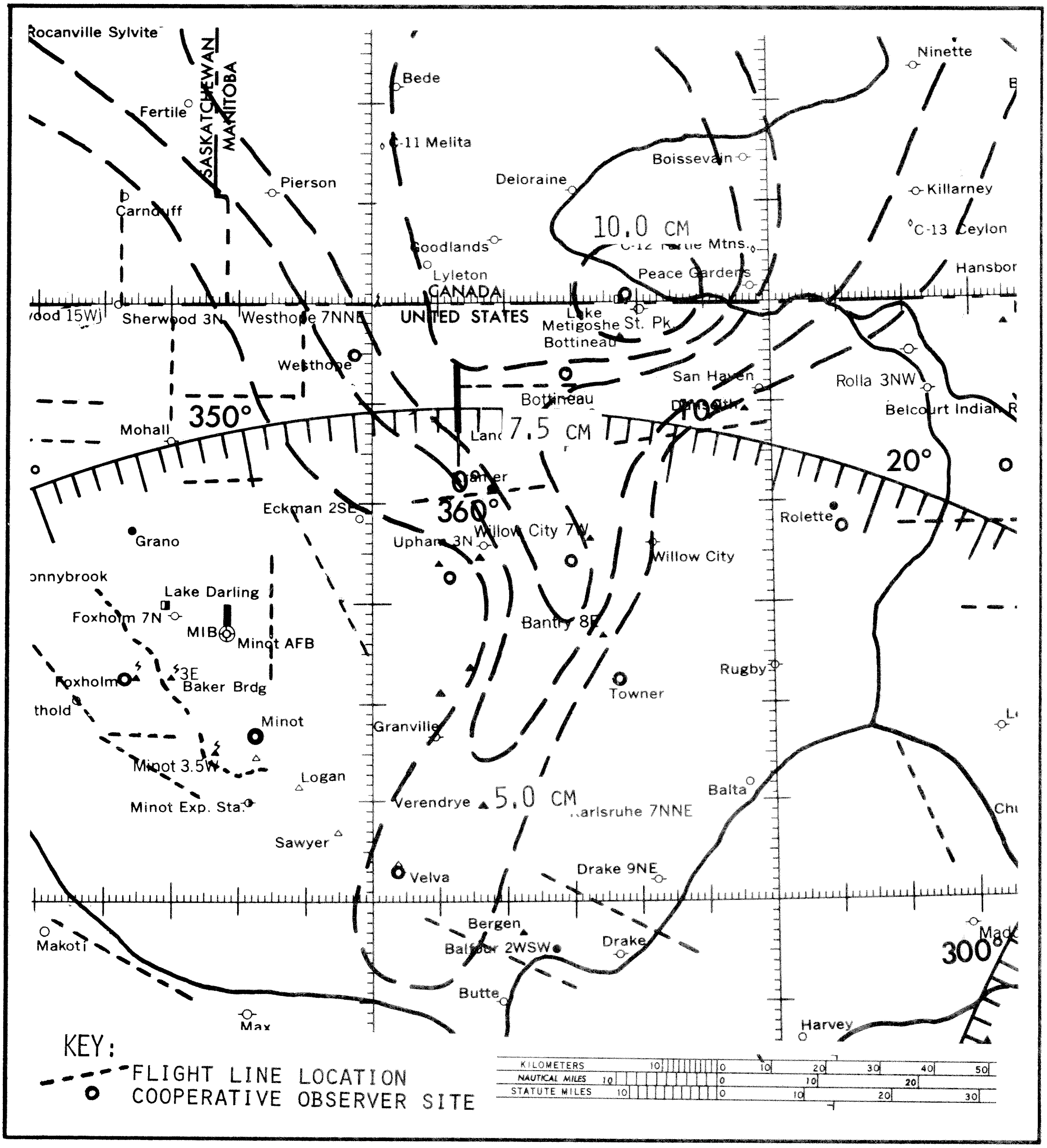

FIGURE 2.
Snow cover distribution in the lower Souris River basin in North Dakota on 1980 March 10 using airborne and ground snow water equivalent data.

lent over large areas. Airborne data collected in 1980 suggest that the natural variability of snow water equivalent may be higher than previously suspected, assumed, or measured using traditional ground sampling techniques.

The last scheduled Spring Flood Outlook is generally released to the public during mid-March. Significant spring snow storms, however, can occur during late March and April. Consequently, the snow survey aircraft remains in Minneapolis until mid-April in anticipation of a heavy late spring snow storm. In 1980, for example, in excess of 45 cm of snow and 8 cm of water equivalent fell in the Souris River basin during a 36 hour period on April 6 and 7. A special airborne snow survey was immediately conducted in the area, the data were reported to the RFC in Minneapolis, and the river forecasts were quickly modified to reflect the new snow cover conditions. The ability to make not only reliable but also rapid snow water equivalent measurements over large areas is essential for accurate, real-time river and flood forecasting in regions with a significant snow melt flooding threat.

CONCLUSIONS

Recent technological developments in snow cover data collection and simulation modeling have contributed substantially to river and flood forecasting in areas where the spring snow melt flood is an annual threat to life and property. The snow accumulation and ablation model is used in conjunction with reliable, real-time airborne snow water equivalent data collected over large areas of the upper Midwest for use by the River Forecast Centers in Kansas City and Minneapolis. Airborne snow cover and soil moisture data can be used by field hydrologists to (1) update specific states and variables in both the snow model and runoff model, (2) assess the mesoscale variability of snow cover deposition, and (3) measure the fall soil moisture immediately prior to freeze-up which can contribute substantially to impermeable conditions and subsequent rapid snow melt flooding in the spring. The incorporation of airborne snow cover measurements into the continuous conceptual snow model provides the mechanism for continued improvements in the hydrologic forecasting services provided by the National Weather Service to the public in the upper Midwest.

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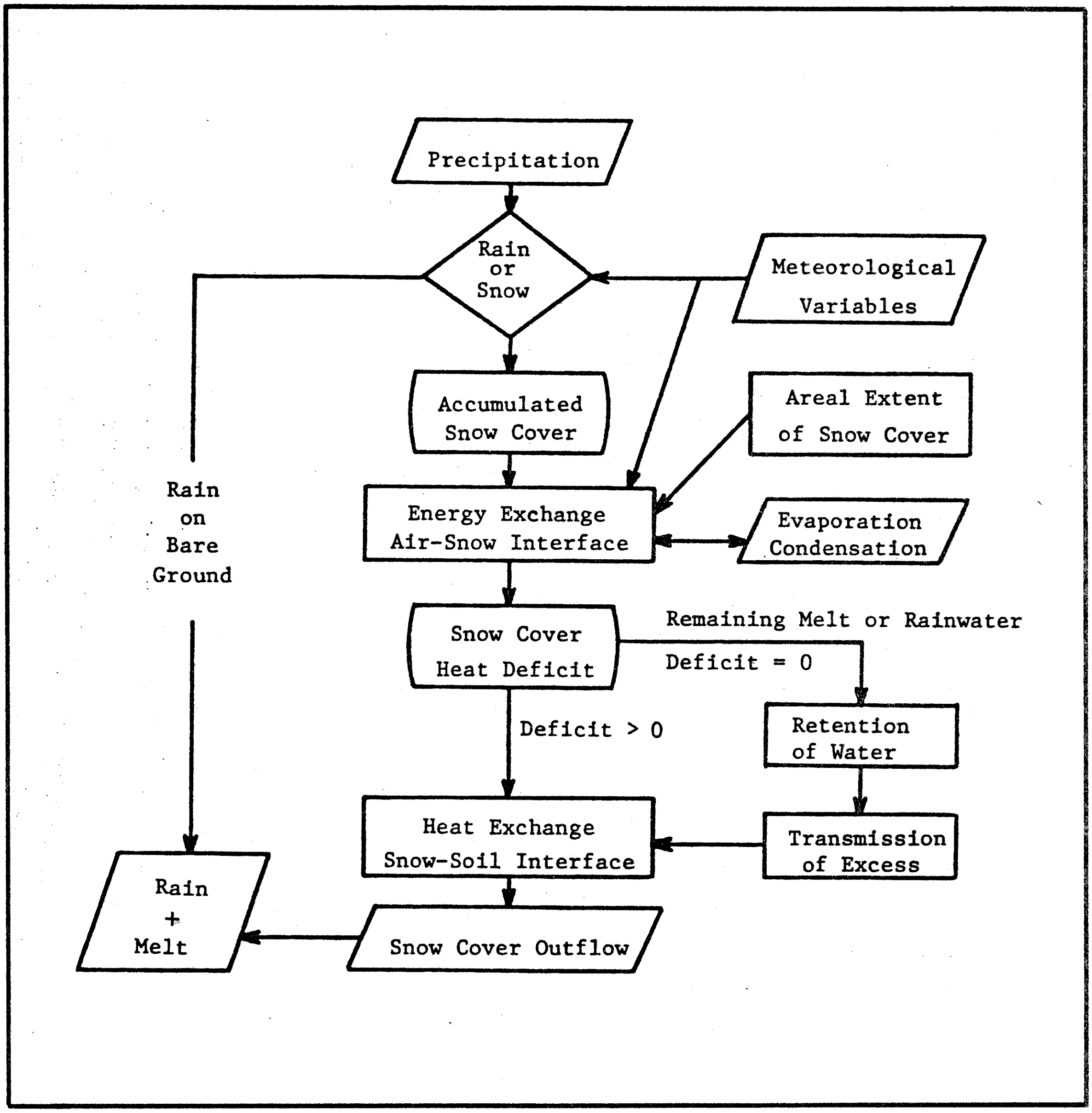

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AIRBORNE SNOW WATER EQUIVALENT AND SOIL MOISTURE MEASUREMENT TECHNIQUE

The technique used to measure natural terrestrial gamma radiation attenuation and subsequently infer snow water equivalent and soil moisture values has been described recently by Carroll and Vadnais (1979, 1980) and Carroll (1981); consequently, only a brief overview will be given here.

The gamma radiation flux near the ground originates primarily from the natural ^{40}K, ^{238}U, and ^{208}Tl radioisotopes in the soil. In a typical soil, 96 percent of the gamma radiation is emitted from the top 20 cm (Zotimov, 1968). After measures of the background (no snow cover) radiation and soil moisture are made, the attenuation of the radiation signal due to the snow pack over-burden is used to calculate the amount of water in the snow cover. Each flight line is approximately 20 km long and 300 m wide; consequently, each snow water equivalent measurement is a mean areal value for approximately 6 km^2 of snow cover.

Three operational and independent snow water equivalents are calculated by measuring the attenuation of the gamma radiation flux in specific windows of the radiation spectrum. The three mean areal snow water equivalents are calculated using data from the K window (1.36-1.56 MeV), the Tl window (2.41-2.81 MeV), and the gross count (GC) energy spectrum (0.41-3.0 MeV). The potassium photopeak is consistently the strongest in the energy spectrum and has been used successfully to measure snow water equivalent in Canada (Grasty, 1979) and in the US (Peck, Carroll, and VanDemark, 1979). The gross count window accumulates an order of magnitude more counts than the K and Tl photopeak windows. Consequently, gross counts are useful when measuring the variability of snow cover along a line or a mean areal snow cover with 15 to 25 cm of snow water equivalent.

The gamma radiation attenuation technique can also be used to measure soil moisture in the upper 20 cm. The gamma radiation emitted from the radioisotopes in the soil is attenuated by the presence of soil moisture near the surface. Consequently airborne radiation data collected over bare gound conditions reflect both the radioisotope and soil moisture concentration near the surface. Recent tests show a high correlation between airborne and ground soil moisture measurements (Carroll, 1981).

The principal sources of error in calculating snow water equivalent or soil moisture values using any of the three windows are incorporated in: (1) the stripping equation derived during the calibration procedure, (2) the measurement of airmass (i.e., temperature, pressure, and radar altitude), (3) the measurement of mean areal soil moisture for a flight line, (4) the measurement of the radon gas contribution to the gamma flux spectrum, and (5) counting statistics. Nonetheless, the technique is capable of measuring snow water equivalent with an accuracy of 1 cm (Carroll and Vadnais; 1979, 1980) and soil moisture with an error of approximately 3.2 percent soil moisture (Carroll, 1981).

SNOW AND SOIL MOISTURE MODEL UPDATING

The continuous snow and soil moisture models used by the RFC's are physically based models and as such simulate real-world states in the hydrologic process. Consequently, simulated states or variables can be updated based on observed measurements and thus reflect more accurately the true conditions at any given time. A data base of airborne snow water equivalent values is currently being accumulated for a network of over 300 flight lines in the upper Midwest. After a sufficient data base is developed, the snow model can be calibrated using the airborne snow measurements in addition to the mean areal temperature and precipitation data. Consequently, the data base being collected today will be indispensable in future calibrations of the snow model for the region.

The capability of making airborne soil moisture measurements also has an important hydrologic application in the upper Midwest. The need to adequately understand the permeability of the upper soil surface at the time of snow melt has been described by Anderson (1978). The soil moisture conditions in the spring are largely related to the fall soil moisture conditions immediately prior to winter freeze-up and snow accumulation. Currently, fall soil moisture conditions can only be generally inferred from precipitation data. The operational collection of fall soil moisture data could provide a means to incorporate important soil moisture information into soil moisture accounting procedures used by hydrologists at the RFC's and WSFO's in the upper Midwest. In a fashion similar to that used in the snow model, it would be possible to update appropriate soil moisture states based on observed measurements at critical times in the hydrologic cycle.

1980 AIRBORNE AND GROUND SNOW SURVEYS

During February, March, and April of 1980 both airborne and ground snow cover data were collected in the upper Midwest and used by NWS field hydrologists to assess the magnitude of spring snow melt flooding. On both the North Dakota and Minnesota side of the Red River of the North, a network of cooperative observers took traditional ground-based snow samples. During the week prior to the March 14 release of the Spring Flood Outlook, cooperative observers took 22 depth and density snow samples and seven depth samples along the main stem of the Red River covering an area in excess of 50,000 km^2. These data were subject to substantial error caused by sampling technique and the nonrepresentative character of the sample site location. Consequently, it was difficult to calculate a reliable mean areal snow water equivalent value for a runoff zone or watershed based on available ground snow cover observations.

In addition to the ground observations, an airborne snow survey was made over the same region and the data were used in the Spring Flood Outlook issued by the River Forecast Center in Minneapolis. Data were collected on 62 flight lines located along the main stem of the Red River. Each flight line is approximately 20 km long and 300 m wide; consequently, each airborne measurement represents a mean areal value for approximately 6 km^2. The snow water equivalent measurement represents an average depth of water equivalent over the flight line. In this way, small scale variability in the snow cover is measured and averaged to give a useful mean areal value which represents the snow water equivalent of the general area.

During the late winter of 1980 most of the snow in the upper Midwest was located in the Souris River basin in north central North Dakota. On March 10, approximately 10 cm of snow water equivalent was centered over the Turtle Mountains just north of the U.S. border in Canada covering an area 20 km in diameter. A narrow band of snow with 6 cm of water equivalent and 20 km wide extended south 150 km from the center in Canada covering much of the lower Souris River basin. A network of 48 flight lines has been established over both the Canadian and United States portions of the Souris River basin. Ground data collected by cooperative observers at 13 sites and airborne data collected over flight lines in the region were used to map prevailing snow cover conditions (Figure 2).

With the ability to make reliable mean areal snow water equivalent measurements over a comparatively dense network of flight lines, it will be possible to define more precisely the natural variability of snow water equiva-

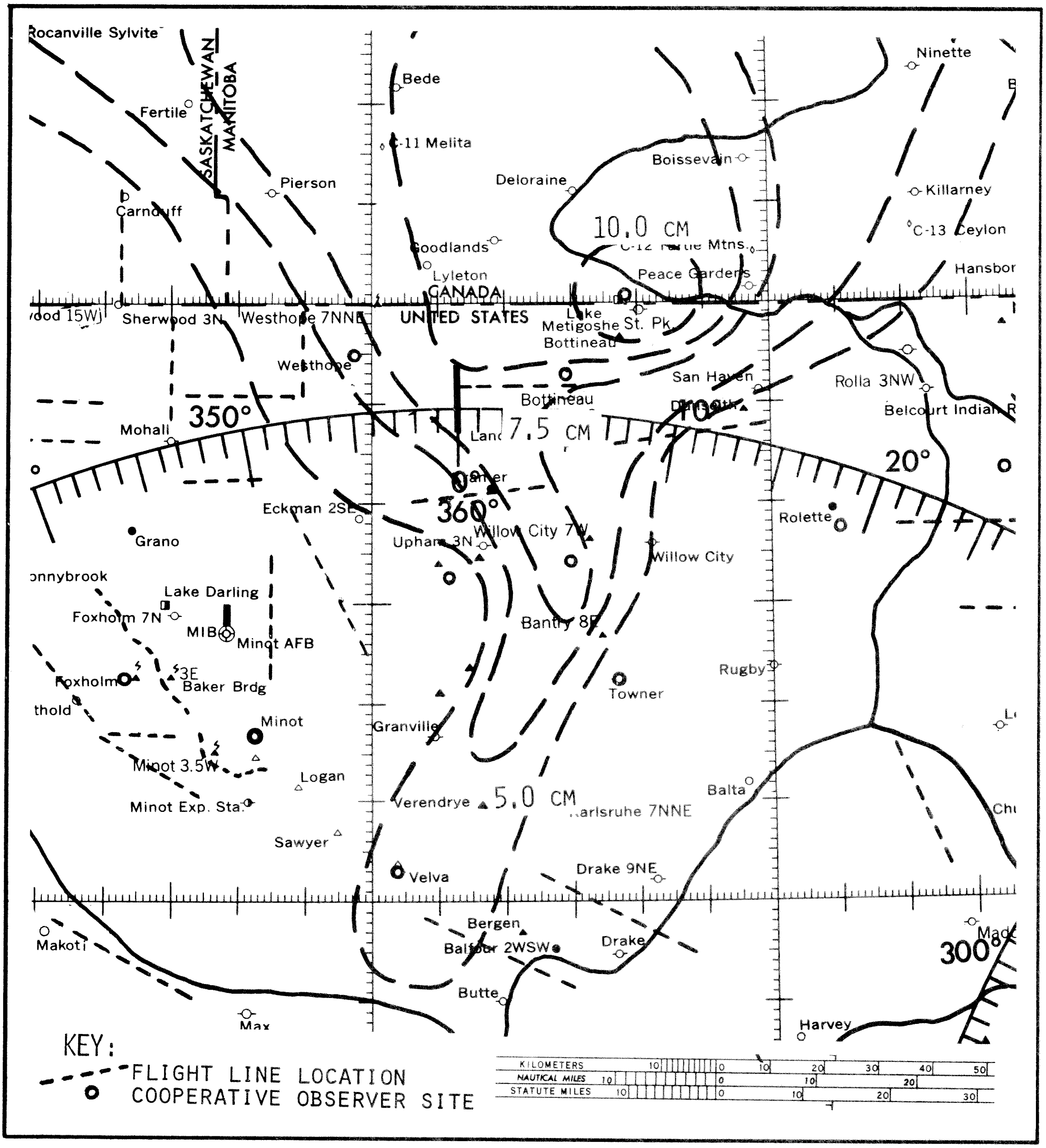

FIGURE 2.
Snow cover distribution in the lower Souris River basin in North Dakota on 1980 March 10 using airborne and ground snow water equivalent data.

lent over large areas. Airborne data collected in 1980 suggest that the natural variability of snow water equivalent may be higher than previously suspected, assumed, or measured using traditional ground sampling techniques.

The last scheduled Spring Flood Outlook is generally released to the public during mid-March. Significant spring snow storms, however, can occur during late March and April. Consequently, the snow survey aircraft remains in Minneapolis until mid-April in anticipation of a heavy late spring snow storm. In 1980, for example, in excess of 45 cm of snow and 8 cm of water equivalent fell in the Souris River basin during a 36 hour period on April 6 and 7. A special airborne snow survey was immediately conducted in the area, the data were reported to the RFC in Minneapolis, and the river forecasts were quickly modified to reflect the new snow cover conditions. The ability to make not only reliable but also rapid snow water equivalent measurements over large areas is essential for accurate, real-time river and flood forecasting in regions with a significant snow melt flooding threat.

CONCLUSIONS

Recent technological developments in snow cover data collection and simulation modeling have contributed substantially to river and flood forecasting in areas where the spring snow melt flood is an annual threat to life and property. The snow accumulation and ablation model is used in conjunction with reliable, real-time airborne snow water equivalent data collected over large areas of the upper Midwest for use by the River Forecast Centers in Kansas City and Minneapolis. Airborne snow cover and soil moisture data can be used by field hydrologists to (1) update specific states and variables in both the snow model and runoff model, (2) assess the mesoscale variability of snow cover deposition, and (3) measure the fall soil moisture immediately prior to freeze-up which can contribute substantially to impermeable conditions and subsequent rapid snow melt flooding in the spring. The incorporation of airborne snow cover measurements into the continuous conceptual snow model provides the mechanism for continued improvements in the hydrologic forecasting services provided by the National Weather Service to the public in the upper Midwest.

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