COST-BENEFIT ANALYSIS OF AIRBORNE GAMMA RADIATION SNOW WATER EQUIVALENT DATA USED IN SNOWMELT FLOOD FORECASTING

by

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INTRODUCTION

From February 10 to 14, 1985, a significant snowfall contributed to a total accumulation of 6.5 to 9.0 cm of snow water equivalent over large portions of Indiana, Michigan, and Ohio. Soil moisture near the surface over the region was at (or above) field holding capacity. On February 15, 16, and 17, the National Weather Service made airborne snow water equivalent measurements over 92 flight lines covering 52,000 square km in northern Indiana, southern Michigan, and northwestern Ohio. On February 19, the Indianapolis WSFO issued a statement warning of the potential for severe flooding in northern Indiana. On February 25 at 1:15 PM, the Weather Service issued a crest forecast of 2.90 meters above flood stage for the Maumee River at Anthony Boulevard in Fort Wayne. Thirty-four hours and forty-eight minutes later (34 hrs : 48 min) on February 27 at 12:03 AM, the Maumee River at Anthony Boulevard in Fort Wayne crested at 2.91 meters above flood stage.

The paper briefly discusses (1) the technique used to make airborne snow water equivalent measurements using natural terrestrial gamma radiation, (2) the errors associated with airborne measurements made over agricultural areas, and (3) an estimate of the marginal and total costs to conduct the February 1985 airborne snow survey over Indiana, Michigan, and Ohio.

Additionally, an estimate of the 1982 flood costs and the subsequent flood protection plans implemented later are discussed. An estimate of the 1985 flood costs is given with and without the implementation of the 1982 flood protection plan and the 1985 airborne snow survey. The various costs associated with the airborne snow survey conducted over the three state region are summarized and contrasted with the benefits obtained as a result of the flood forecast for the city of Fort Wayne.

AIRBORNE GAMMA RADIATION SNOW MEASUREMENT TECHNIQUE

The Office of Hydrology of the National Weather Service has developed and maintains an operational Airborne Gamma Radiation Snow Survey Program serving the northern portion of the country from Maine to Montana (Peck, et al., 1980). The airborne snow water equivalent data are used by the National Weather Service River Forecast Centers and Weather Service Forecast Offices when issuing spring flood outlooks, water supply forecasts, and river and flood forecasts for the region. The technique uses the attenuation of natural terrestrial gamma radiation by the mass of the snow cover to make airborne snow water equivalent measurements with a Root Mean Square error of 0.8 cm snow water equivalent over agricultural environments and with an error of 2.0 cm over forested areas (Carroll, et al., 1985). There are currently over 1,000 flight lines in the operational network covering 16 states and 5 Canadian provinces. Each flight line is typically 16 km long and 300 m wide covering an area of approximately 5 sq km. Consequently, each airborne snow water equivalent measurement is a mean areal measure integrated over the 5 sq km area of the flight line.

Presented at the Western Snow Conference, Phoenix, Arizona

Office of Hydrology, National Weather Service, 6301 - 34th Avenue South, Minneapolis, Minnesota 55450

"Reprinted Western Snow Conference 1986"

The physics and calibration of the airborne gamma radiation spectrometer were developed under contract by EG&G, Inc. in Las Vegas and have been described by Fritzsche (1982). A procedure to make airborne soil moisture measurements for the upper 20 cm was developed by Carroll (1981). Results of recent airborne snow water equivalent and soil moisture measurements made in agricultural environments have been reported by Jones and Carroll (1983) and Carroll et al. (1983). Details of the system hardware and radiation spectral data collection and analysis procedures have been described by Fritzsche (1982) and others and will not be discussed here.

Airborne snow water equivalent measurements are made using the relationship given in equation (1).

$$SWE = \frac{1}{A}\left[\ln\frac{Co}{C} - \ln\left(\frac{100 + 1.11\ M}{100 + 1.11\ Mo}\right)\right]\ g\ cm^{-2} \qquad (1)$$

where:

C and Co = Uncollided terrestrial gamma count rates over snow and bare ground,

M and Mo = Percent soil moisture over snow and bare ground,

A = Radiation attenuation coefficient in water, cm2/g

Extraneous radiation is contributed to the spectra by the Compton tails associated with the peaks of higher energy, the cosmic radiation component, the airborne and fuel, the pilots, and the detection system itself. The raw radiation count rates for various photopeaks must be "stripped" of the extraneous sources to give the pure, uncollided radiation count rates (Fritzsche, 1982). Airmass between the airborne sensors and the terrestrial radiation source also attenuates the radiation signal. Consequently, air temperature, air pressure, and radar altitude are recorded continuously to calculate and compensate for the intervening airmass. After the appropriate photopeaks have been stripped of extraneous radiation, they are normalized to a standard airmass of 17 g/cm2.

Airborne Measurement Error and Simulation

The principal sources of error in airborne snow water equivalent calculation using the relationship given in equation (1) are: (1) errors in the normalized count rates (C,Co), (2) errors in the estimate of mean areal soil moisture over the flight line (M,Mo), and (3) errors in the radiation attenuation coefficient (A) derived from calibration data.

Vogel, et al. (1985) simulated the principle sources of error for airborne measurements made over forested watersheds with as much as 60 cm of snow water equivalent. The results indicate that airborne snow water equivalent measurements can be made in forest environments with 60 cm of water equivalent with an error of approximately 12 percent. The simulated results agree closely with the empirical errors derived from ground snow survey data collected in a forest environment with 48 cm of snow water equivalent (Carroll and Vose, 1984). In addition, the simulation technique can be used to assess the effect of the principle sources of error on airborne measurements made over agricultural environments with 2.0 to 15.0 cm of snow water equivalent. The results indicate that the error of the airborne snow measurement is, in part, a function of snow water equivalent and ranges from 4 to 10 percent. Again, the errors derived from the simulation agree closely with the errors derived using airborne and ground-based snow survey data collected over an agricultural environment (Carroll, et el., 1983). The simulation procedure and assumptions are described in detail by Vogel.

AIRBORNE SURVEY COSTS

Table 1 gives the assumptions and the relevant cost data required to calculate the cost of the 1985 Fort Wayne airborne snow survey. The costs are calculated on a per flight line and per flight line km basis. The marginal costs are those direct costs required to conduct the survey while the total costs include the marginal costs and the indirect costs.

Table 1

AIRBORNE SNOW SURVEY COSTS FOR
FEBRUARY 1985 FORT WAYNE SURVEY

ASSUMPTIONS:		
Average line length		13.9 km/fl
Average aircraft survey speed		185 km/hr
Percent of time on flight line		43%
Flight time per year		550 hrs/yr
Flight time per day		6.4 hrs/day
Flight days per year		86 days
Number of pilots		2
Survey efficiency		5.7 lines/hr
AIRCRAFT OPERATION COSTS:		
Aircraft operating costs		$132.00 per hr
Pilot travel costs		$130.00 per day
		$20.31 per hr
	Total	$152.31 per hr
		$26.55 per line
		$1.91 per km
AIRCRAFT FERRY COSTS: (for Fort Wayne survey)		
Ferry hrs (non-survey; one way)		3.2 hrs
Total flight lines in survey area		92 lines
Total flight line kms in area		1248.5 km
(Days to complete survey, hrs) 15.69		2.5 days
(Days required to ferry and survey)		3.5 days
	Total	$62.13 per hr
		$10.83 per line
		$0.78 per km
SPECTROMETER ANNUALIZED COST:		
Initial cost (1985)		$100,000
Life expectancy		20 years
Interest rate		10%
	Total	$11,746 per year
		$21.36 per hr
		$3.72 per line
		$0.27 per km
AIRCRAFT ANNUALIZED COST:		
Initial cost (1985)		$250,000
Life expectancy		20 years
Interest rate		10%
	Total	$29,365 per year
		$53.39 per hr
		$9.31 per line
		$0.67 per km
ADMINISTRATIVE OVERHEAD AND PERSONNEL COSTS:	Total	$112,000 per year
		$203.64 per hr
		$35.50 per line
		$2.56 per km

COST SUMMARY: (per flight line km)

Aircraft oper. and pilot travel (marginal)	$1.91	30.9%
Aircraft ferry to survey area (marginal)	$0.78	12.6%
Spectrometer anualization	$0.27	4.3%
Aircraft annualization	$0.67	10.8%
Administrative and Personnel	$2.56	
MARGINAL COSTS	$3,364	per survey
	$37.28	per line
	$ 2.70	per km
TOTAL COSTS	$7,732	per survey
	$85.91	per line
	$ 6.20	per km

FEBRUARY 1985 FORT WAYNE FLOOD SUMMARY

NWS Airborne Snow Survey

January 1985 was the fifth snowiest January on record in the Fort Wayne area. From February 10 to 14, 1985, a significant snow fall contributed to a total accumulation of 6.5 to 9.0 cm of snow water equivalent over large portions of Indiana, Michigan, and Ohio. It is interesting to note that a total snow water equivalent accumulation of 7.6 cm at Fort Wayne during the March 1 to 15 period has a reoccurrence interval of approximately 3300 years (U.S.DOC/WB, 1964). Soil moisture near the surface over the region was at (or above) field holding capacity. On February 15, 16, and 17 (Friday, Saturday, and Sunday), the National Weather Service made airborne snow water equivalent measurements over 92 flight lines covering 52,000 square km in northern Indiana, southern Michigan, and northwestern Ohio. Table 2 summarizes the snow survey activity for the Fort Wayne survey.

Table 2

AIRBORNE SNOW SURVEY SUMMARY

DATE	BASIN	No. FLS
850215	Maumee	19
850215	St. Joseph (FW)	6
850215	St. Marys	9
850215	Wabash	1
850216	Elkhart	4
850216	Maumee	2
850216	Raisin	15
850216	St. Joseph (Elk)	14
850216	St. Joseph (FW)	6
850217	Kankakee	12
850217	St. Joseph (FW)	4
	Total	92

The airborne data were sent digitally to the office in Minneapolis, checked for accuracy, entered into SHEF format, and sent over AFOS approximately one hour after the aircraft landed each noon and evening during the three day survey. In this way, the appropriate NWS offices in the Eastern and Central Regions had access to the airborne data within one hour after the aircraft landed from each survey mission. Figure 1 is a contour map giving the snow water equivalent data collected over the 92 flight lines in the region during the three day survey.

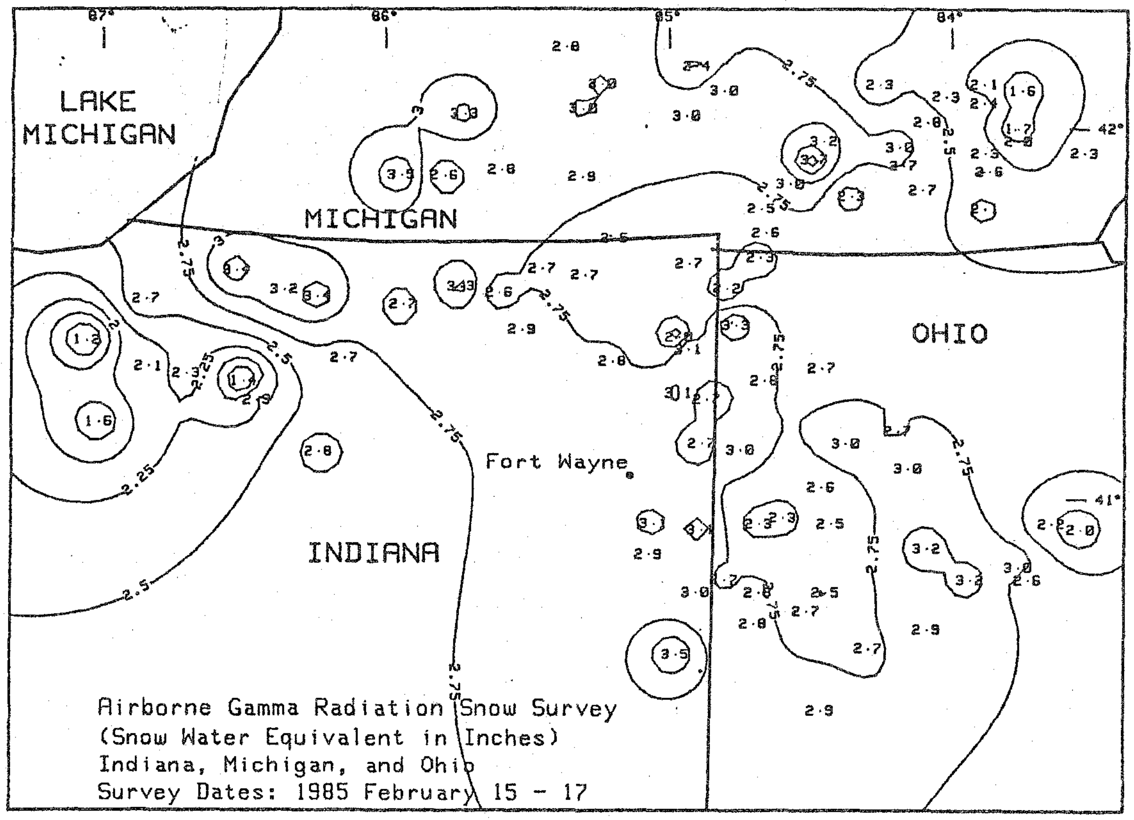

Figure 1: Contour map of airborne snow water equivalent data collected over northern Indiana, southern Michigan, and northwestern Ohio on February 15, 16, and 17.

NWS WSFO and WSO Warnings and Statements

Monday, February 18, was a government holiday. Based on the airborne data collected on February 15 - 17, WSO Fort Wayne notified on February 18 Allen, Adams, and DeKalb County governmental units that snowmelt flooding was possible for the region. On Tuesday, February 19, the Indianapolis WSFO issued a severe flood potential statement for northern Indiana. Additionally, the Indiana Governor and various state agencies were warned of the threat of severe snowmelt flooding for the northern portion of the state during the coming weekend. The Thursday, February 21, weather forecasts called for above freezing temperatures and precipitation. Consequently, WSO Fort Wayne called a meeting on February 21 with the Red Cross, Civil Defense, Lutheran Social Services, Salvation Army, Church of the Brethern, and the city of Fort Wayne to warn of the flooding threat over the coming weekend. On February 25 at 1:15 PM, the Weather Service issued a crest forecast of 2.90 meters above flood stage for the Maumee River at Anthony Boulevard in Fort Wayne. Thirty-four hours and forty-eight minutes later (34 hrs : 48 min) on February 27 at 12:03 AM, the Maumee River at Anthony Boulevard in Fort Wayne crested at 2.91 meters above flood stage.

Shipe, et al. (1985) give details of the precipitation, temperatures, and hydrographs at five forecast points associated with the Fort Wayne flooding in late February. In addition, the flood ALERT system used to monitor in real-time the precipitation, temperature, and river stage data during the February flood is discussed in detail.

Flood Summary for 1978, 1982, and 1985

Fort Wayne has experienced substantial snowmelt flooding during the century. Major floods occurred in 1913, 1943, 1950, 1959, 1978, 1982, and 1985. Table 3 summarizes the four greatest floods on the Maumee River at Anthony Boulevard in Fort Wayne where flood stage is 4.57 meters. It is interesting to note that although the 1978 flood crested 0.21 meter below the 1985 flood crest, the damage caused by the 1978 flood was over $50 million greater than the damage estimated for the 1985 flood by Fort Wayne officials.

Table 3

FOUR GREATEST FORT WAYNE FLOODS

Year	Stage (meters)	Event (years)	Actual Damage (Feb. 1985 $)
1913	7.96	110	$52.0 million
1978	7.25	25	$56.8 million
1982	7.89	77	$56.1 million
1985	7.47	50	$ 4.0 million

1982 Flood Costs

Both the U.S. Army Corps of Engineers (Detroit District) and Fort Wayne officials have estimated the 1982 flood damage cost at approximately $57 million (in February 1985 dollars). The Corps has summarized the total 1982 flood costs for each of nine major categories given in Table 4.

Table 4

ACTUAL 1982 FLOOD COSTS
(Estimated by the U.S. Army Corps of Engineers,
Reconnaissance Report - June 1984)
(in February 1985 dollars)

FLOOD COSTS (Feb. 1985 $)	1982 ACTUAL
Structure and Content Damage	$11,138,000
Public (city and county) Costs	$10,079,000
Agency Costs	$2,332,000
Evacuation-Residential	$1,964,000
Evacuation-Commercial	$2,910,000
Lost Wages	$6,370,000
Lost Business Revenue	$19,943,000
Vehicle Operational Costs	$743,000
Opportunity Costs for Vehicle Occupants	$611,000
TOTAL	$56,090,000

In response to the 1982 flood the City of Fort Wayne produced a "Fort Wayne - Allen County Flood Protection Plan: April 1982" which outlines an "18 Month Work Program" designed to minimize the impact of future flooding. The $11 million dollar program describes measures to:

1. Install river gages, prepare emergency action plans, implement an early warning system (ALERT) in cooperation with the National Weather Service, and develop a flood proofing program,

2. Build new dikes and repair and increase the height of old dikes,

3. Install backwater gages to prevent floodwater backup through the city water and sewage system,

4. Improve existing channels,

5. Acquire floodplain property,

6. Install emergency pumping stations, and

7. Prepare damage survey reports.

In addition, the National Weather Service expanded the Airborne Snow Survey Program operational flight line network to cover much of the area in Indiana, Michigan, and Ohio which experienced significant snowmelt flooding in 1982.

1985 Flood Costs

The U.S. Army Corps of Engineers Reconnaissance Report (1984) provides a procedure to estimate flood costs based on flood stage both with and without the implementation of the Fort Wayne "18 Month Work Program." Consequently, it is possible to take the 1985 flood stage and estimate what the flood damage would have been without the implementation of the Work Program, the flood ALERT system, or the Airborne Snow Survey Program. Table 5 summarizes the estimate of the 1985 flood costs without the aforementioned improvements.

Table 5

ESTIMATED 1985 FLOOD COSTS WITHOUT IMPLEMENTATION OF THE FORT WAYNE 18 MONTH WORK PROGRAM, THE FLOOD ALERT SYSTEM, OR THE AIRBORNE GAMMA RADIATION SNOW SURVEY PROGRAM (in February 1985 dollars)

FLOOD COSTS (Feb. 1985 $)	1985 ESTIMATE
Structure and Content Damage	$8,954,000
Public (city and county) Costs	$7,239,000
Agency Costs	$1,681,000
Evacuation-Residential	$903,000
Evacuation-Commercial	$1,064,000
Lost Wages	$1,739,000
Lost Business Revenue	$5,445,000
Vehicle Operational Costs	$541,000
Opportunity Costs for Vehicle Occupants	$433,000
TOTAL	$27,999,000

DISCUSSION

The February 25 Quantitative Precipitation Forecast (QPF) for the next 36 hours was for 6.4 cm of rain over the St. Joseph and St. Marys basins. Both flow into the Maumee at Fort Wayne. The Maumee River at Anthony Boulevard was at 1.22 meters. The rainfall-runoff relationship for Anthony Boulevard is given in Figure 2. The rainfall-runoff relationship indicates that the QPF forecast of 6.4 cm of rain alone would exceed the flood stage by 0.46 meters. In addition, however, both basins had a significant snowpack. The mean areal airborne snow measurements over both the St. Joseph and St. Marys was 7.3 cm of snow water equivalent. Consequently, the total QPF plus snow water equivalent of 13.7 cm would raise the river stage to 7.46 meters, 2.89 meters above flood stage.

Recent research indicates that airborne snow water equivalent measurements tend to overestimate ground-based snow water equivalent measurements by 0.8 to 1.3 cm (Carroll, et al. 1983; Carroll and Vose, 1984). The systematic overestimate should be expected since problems related to accurate sampling of ground surface ice layers and depth hoar are inherent in the traditional ground-based snow sampling techniques. The systematic underestimate of true snowcover conditions using ground-based sampling techniques is further aggravated by untrained observers.

Only airborne snow water equivalent measurements were available immediately before the snowmelt flood in Fort Wayne in February, 1985. If, however, several hundred ground-based snow water equivalent measurements were made over the same 52,000 square km area during the same time the airborne measurements were made, it is reasonable to expect the ground-based snow water equivalents measurements to average approximately 6.0 cm in contrast to the 7.3 cm average of the airborne measurements.

The QPF of 6.4 plus a ground-based snow water equivalent measurement of 6.0 would give a crest forecast of 7.18 meters -- or 0.29 meters below the observed crest. In the case of the February 1985 Fort Wayne snowmelt flood, the difference between airborne snow water equivalent data and ground-based snow data (if available) used in forecasting the flood crest would have been equal to approximately 0.29 meters of stage. The alternative flood stages are given in Figure 2 and Table 6.

Table 6

RAINFALL-SNOWMELT-RUNOFF RELATIONSHIP
Fort Wayne, Indiana
1985 February 27

	RAIN plus MELT (cm)	STAGE (meters)
Initial stage	0.0	1.41
Flood stage	5.5	4.57
QPF stage	6.5	5.03
QPF plus Ground SWE	12.4	7.18
QPF plus Airborne SWE	13.7	7.46
Flood crest		7.47

It is interesting to note that an over forecast of the crest by 0.15 meters would have cost the city of Fort Wayne in excess of $800,000 in unnecessary diking and sandbagging costs alone. Consequently, an error or positive bias of approximately 1 cm in the mean areal snow water equivalent used when issuing a crest forecast could require an expenditure of $1,500,000 in municipal funds for unnecessary preventative measures. Likewise, an underestimate of true snow water equivalent by 1 cm would have contributed to an under forecasted crest and consequently contributed to major flooding of unknown proportions.

SUMMARY

Most of the recommendations suggested in the "18 Month Work Plan" were implemented before the 1985 flood. The flood ALERT system was installed and the operational airborne flight line network was established in the region before the 1985 flood. These three major improvements limited actual damage in the 1985 Fort Wayne flood to $4 million (Table 3). Consequently, it is reasonable to suggest that the improvements prevented approximately $24 million in 1985 flood damage.

The Work Plan improvements which were implemented were, no doubt, responsible for preventing a major portion of the $24 million damage which would have likely occurred without the three improvements. Additionally, the flood ALERT system contributed to damage prevention by providing essential hydrometeorological data required for accurate and timely flood forecasts. The airborne snow survey conducted one day after a major regional snow storm and ten days before the flood crest provided information necessary to issue an early severe flood warning for the region. The early warning facilitated timely flood fight planning and consequently contributed to the prevention of subsequent flood damage.

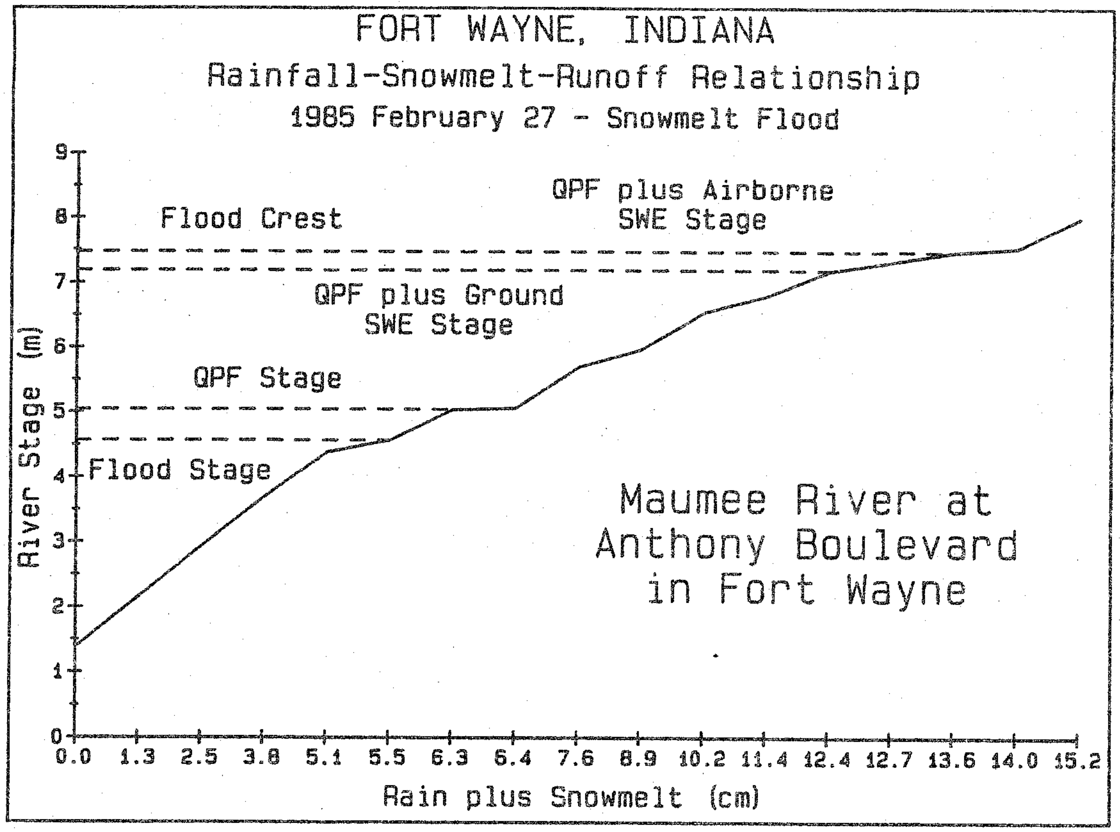

Figure 2: Rainfall-snowmelt-runoff relationship at Anthony Boulevard in Fort Wayne, Indiana for the 1985 February 25 snowmelt flood.

It is, of course, impossible to accurately partition the relative merits of each of the three major improvements implemented before the 1985 flood. It is possible, however, to arbitrarily assign various relative importances to each of the three major improvements to estimate, in a crude fashion, the contribution each improvement made to the total savings of $24 million in damage prevention. Table 7 gives three arbitrary estimates of the percent of the total $24 million savings associated with each of the three major improvements. In the first case, if the Work Plan contributed 80 percent to the total flood damage prevention, then the savings directly attributable to the Work Plan improvement would be approximately $19 million. In a similar fashion, the flood damage prevented as a direct result of the early warnings and river forecasts facilitated by the airborne snow survey data can be variously estimated from $700,000 to $2,400,000 depending on the relative importance placed on the airborne data.

Table 7

FLOOD DAMAGE SAVINGS BASED ON IMPROVEMENT TYPE

Improvement type	Case 1	Case 2	Case 3
18 Month Work Plan	80% $19.2	85% $20.4	90% $21.6
Flood ALERT system	10% $2.4	10% $2.4	7% $1.7
Airborne Snow Survey	10% $2.4	5% $1.2	3% $0.7

Note: $ in millions

The $7,700 cost of the February 1985 Fort Wayne airborne snow survey was substantially less than the projected flood damage prevented as a result of the early warnings and flood forecasts based on the airborne snow water equivalent data. Additionally, the cost savings attributed to the airborne snow water equivalent data are in keeping with the costs associated with an over or under estimate crest forecast generated using inaccurate or biased snow water equivalent data.

ACKNOWLEDGEMENTS

Thanks go to the City of Fort Wayne Engineering and Planning Departments; the U.S. Geological Survey, Indianapolis; and the U.S. Army Corps of Engineers (Detroit District) for providing much of the data on which this study was based. Thanks go also to John E. Glynn, Geological Survey of Canada, who reviewed an earlier draft of this manuscript and made valuable suggestions.

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