J. Great Lakes Res., 1979
Internat. Assoc. Great Lakes Res. 5(3-4):301-311

DETERMINING OVERWATER PRECIPITATION FROM OVERLAND DATA: THE METHODOLOGICAL CONTROVERSY ANALYZED[1]

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ABSTRACT. Accurate determination of overwater precipitation from shoreline data in large lakes is critical to operational hydrology. Overlake precipitation has been recorded by standard precipitation gages located on islands and man-made structures on various occasions over the last 50 years. Those readings are then related to shoreline readings by lake/land ratios. In the absence of overwater data, the ratios are applied to shoreline data to obtain overwater precipitation estimates. Recent studies indicate that the lake-land differences observed by such techniques are smaller than probable gage catch errors and that the differences are not statistically significant.

Alternative methods for measuring or estimating overwater precipitation are recommended to determine whether or now new, operationally useful lake/land ratios can be provided. Initial costs of some of these programs, such as radar observations, would be high, but they might be discontinued after sufficient confidence in the accuracy of new ratios was gained. It is, of course, possible that any set of ratios might vary from lake to lake necessitating individual programs for each lake. It is also possible that varying regional precipitation patterns over time would necessitate recalculation of the ratios. Either of these situations might indicate that solution to the lake-land precipitation problem is not economically feasible.

INTRODUCTION

The spatial and temporal variation of precipitation over land areas is reasonably well known in many regions of the world due to the density and quality of data from precipitation gage networks. Similar characteristics of precipitation over large bodies of water, such as the Laurentian Great Lakes, are not well known since overwater gage networks, or even individual gages, are nearly non-existent. Thus, knowledge of the relationship of lake precipitation to land precipitation is critical in estimating precipitation over the lake. Small errors in extrapolating overwater precipitation from shoreline station data result in serious errors in estimating the total volume of water collected in a large lake and in calculating related water levels. Shoreline property owners, shipping interests, and hydro-electric power operators are thereby adversely affected.

The purpose of this paper is to discuss the literature on determining overlake precipitation from shoreline data with the aim of assessing the usefulness and accuracy of the reported methodologies. Measurement problems, ambiguities, and as yet unresolved questions are examined.

METHODS ANALYSIS–GAGE TECHNIQUES

For the past 50 years, the traditional method of estimating overwater precipitation on large lakes has been to measure precipitation with standard precipitation gages on islands, towers, or water intake cribs located on the lake for a limited time period. Those measurements are then related to measurements at shoreline stations for similar time periods for the purpose of computing lake/land precipitation ratios or percentages. The lake gages are removed after relatively short time periods due to the high costs of operating such remote networks. The ratios derived from the studies are subsequently used to estimate overlake precipitation from shoreline data by simply multiplying the shoreline measurements by the ratios for the time period involved. A complete listing of ratios obtained in all conventional lake-land precipitation investigations is provided by Phillips and McCulloch (1972). Although the basic methodology has not changed, questions regarding the validity of the results of such studies

[1]GLERL Contribution No. 151

have become increasingly critical. It appears that a change in the traditional method of determining the relationship of lake-to-land precipitation is necessary.

In an early study, Horton and Grunsky (1927) compared precipitation at two island sites in the northern portions of Lakes Michigan and Huron with precipitation measured at mainland nearshore sites. They found that the ratio of precipitation at the island stations to precipitation at shoreline stations was 0.94 in summer and 0.93 in winter.

In a more recent report, Verber (1955) found that the islands in western Lake Erie received less precipitation than the adjacent mainland. He noted that in summer the lake water was cooler than the air masses that passed over the lake, producing a more stable atmosphere and less summertime thunderstorn activity over the lake. Hunt (1959) used data from a precipitation storage gage located in northern Lake Michigan to determine that lake precipitation was less than that on the land.

In what is perhaps the classic study in this field, Blust and DeCooke (1960) used data from standard precipitation storage gages at six island sites in northern Lake Michigan to find that lake precipitation was less than that at perimeter stations in the summer and greater in winter. Due to the remote locations of the sites, all island gages, except one, were read and maintained only in May and October. Shoreline sites were both regular Weather Bureau stations and installations specifically established for the study (Figure 1).

Blust and DeCooke recognized that the amount of both solid and liquid precipitation caught by a standard precipitation gage is a function of its exposure. They accordingly equipped the gages with Alter wind shields and calculated an exposure index for each site to determine the effects of topographic features, trees, and buildings on gage catch. Anemometers were installed at some sites to esimate the effects of wind speed on gage catch. The results of their study, which used data corrected for exposure, are given in Table 1.

Changnon (1967, 1968) and Changnon and Jones (1972) completed an extensive analysis of Lake Michigan precipitation patterns using Blust and DeCooke's data and data from a water intake crib 4 miles east of Chicago. Records from the St. James, Beaver Island, station, a regularly reporting National Weather Service station (Figure 1), and the water intake crib were used to extrapolate the island data to spatially estimate precipitation over the entire Lake Michigan Basin on a monthly basis.

TABLE 1. Deviation of water area precipitation from perimeter precipitation (from Blust and DeCooke 1960).

Season	Percent
Summer	-6.2
Winter	+4.5

Changnon offered the concept of comparing island station data to land station data from locations both upwind and downwind of the island sites. The results noted later show significant differences in lake/land ratios. Changnon's studies seemed to heighten the awareness of uses of lake-land precipitation relationships to the potential of such research.

Considerable discussion has centered on the accuracy of shielded or unshielded standard precipitation gages. Kresge, Blust, and Ropes (1963) examined the data from storage gages at the Lake Michigan stations used by Blust and DeCooke (1960) and concluded that exposure had a significant effect on gage catch, especially during winter. Nevertheless, they felt it was feasible to estimate mean monthly overwater precipitation for the Great Lakes by using data from regular National Weather Service shore stations. Kresge, Blust, and Ropes also stated, "There is growing evidence that radar surveillance of the lakes holds promise for obtaining quantitative precipitation observations over the lakes."

In a more recent study on the inaccuracies of precipitation measurements, Larson and Peck (1974) reported gage catch deficiencies (undercatch) due to poor exposure of as high as 80% for solid precipitation. Warnick (1956) also estimated that an unshielded gage could be expected to catch only 20% and a shielded gage only 35% of the actual solid precipitation at a wind speed of 32 km/h. For liquid precipitation, catch deficiencies are much less. Results for various studies differ, but a catch deficiency of 15% for a 16 km/h wind was reported by Linsley, Kohler, and Paulhus (1958). As a general rule, a 45% catch deficiency at 16 km/h can be expected for solid precipitation and a 70% deficiency can be expected at 32 km/h. A 10% deficiency at 16 km/h is likely for liquid precipitation. Shields are beneficial for reducing this error with solid precipitation, but have little effect at winds speeds above 32 km/h (Larson and Peck 1974). In a comparison of gage and radar methods, Woodley *et al.* (1975) stated, "It is unreasonable to expect to measure point rainfall to an accuracy of better than 5-10% with gages."

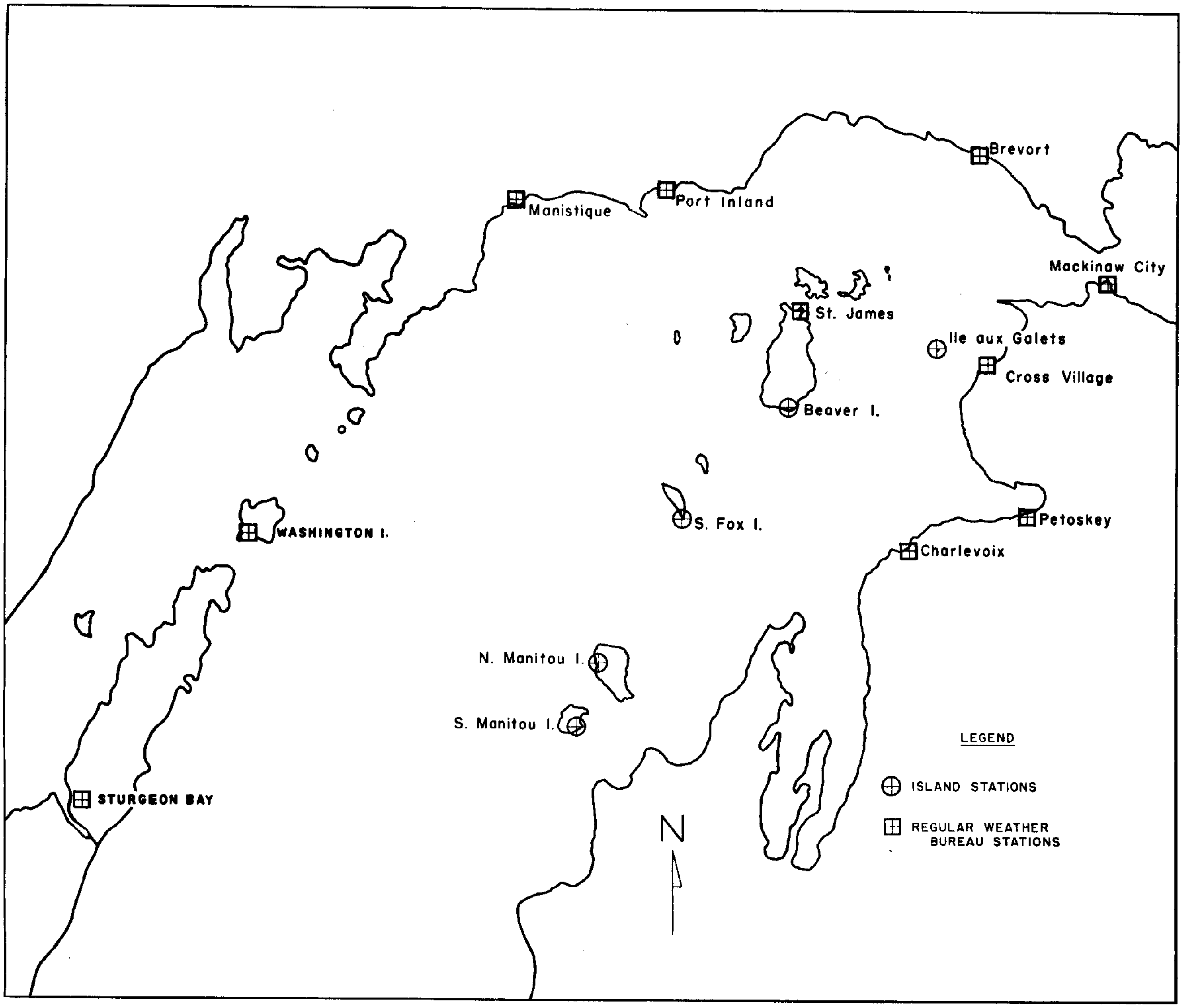

FIG. 1. Northern Lake Michigan network showing most of the stations used by Blust and DeCooke (1960) and all of the stations used by Bolsenga (1977).

Peck, Larson, and Wilson (1974) discussed measurement errors for a snowfall measurement network in the Lake Ontario Basin. Thirteen standard shielded precipitation gages were placed at well protected locations in a coniferous forest. The readings at these gages were compared with nearby climate gages (Table 2). The percent difference values indicate that gage exposure is a dominant factor. The catch of properly exposed gages averaged 16% more than the climate gages.

A classic case of gage undercatch is illustrated by data from a 5-year study of island versus shoreline precipitation conducted during the International Field Year for the Great Lakes (Bolsenga and Norton 1975). The island gages, located at the eastern end of Lake Ontario, were placed in relatively unprotected sites. Figure 2 shows a comparison of the island precipitation data to shoreline data. Shoreline data are from Canadian and United States climate gages located on the north, east, and south shores of Lake Ontario. When all of the land stations are compared with the island data, only 1 month shows island precipitation higher than land precipitation. When upwind land stations (located on the northern shore) and downwind land stations (located on the eastern and southern shores) are compared to island data, only 3 months with higher island than

TABLE 2. Comparison of specially sited snow precipitation gages (numerical designation) with climate gages (Mallory, Bennets, Bridge, etc.) in the nearby area (after Peck, Larson, and Wilson 1974). Differences and % differences are expressed using the special (numerically designated) gages as standards. Precipitation amounts in centimeters.

Month	November		December		January		February		March		Total	
					MALLORY VERSUS #9							
Gage	9	MAL	9	MAL	9	MAL	9	MAL	9	MAL	9	MAL
Catch*	2.06	1.63	27.74	23.88	13.23	11.10	14.91	13.94	5.36	5.11	63.30	55.60
Diff.		-0.43		-3.86		-2.13		-0.97		-0.25		-7.70
% Diff.		-28		-16		-19		-7		-5		-14
					BENNETTS BRIDGE VERSUS MEAN OF (#3, #4, #7)							
Gage	3, 4, 7	BB	3, 4, 7	BB	3, 4, 7	BB	3, 4, 7	BB	3, 4, 7	BB	3, 4, 7	BB
Catch*	11.02	8.33	41.86	30.78	20.27	16.84	21.29	16.97	11.94	11.73	106.38	84.63
Diff.		-2.69		-11.08		-3.43		-4.32		-0.21		-21.75
% Diff.		-33		-36		-20		-25		-2		-26
					CAMDEN VERSUS #12							
Gage	12	CAM	12	CAM	12	CAM	12	CAM	12	CAM	12	CAM
Catch*	6.78	6.83	29.87	30.91	12.98	12.52	16.84	17.88	5.54	5.82	72.01	73.94
Diff.		0.05		1.04		-0.46		1.04		0.28		1.93
% Diff.		1		3		-4		6		4		3
					SELKIRK SHORES VERSUS #1							
Gage			1	SS	1	SS	1	SS	1	SS	1	SS
Catch*			31.09	29.06	22.50	12.93	19.69	16.79	20.65	17.42	93.93	76.20
Diff.				-2.03		-9.57		-2.90		-3.23		-17.73
% Diff.				-7		-74		-17		-18		-23

*(cm)

TABLE 3. Ratios of lake precipitation to upwind, downwind, and combined (all stations) land precipitation data (from Bolsenga 1977).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Upwind	0.97	0.99	1.03	1.02	0.79	0.86	0.75	0.75	1.11	0.70	1.09	0.96
Downwind	1.02	1.03	1.12	1.10	1.07	1.16	0.91	0.72	1.15	0.70	0.89	0.83
Combined	1.00	1.01	1.06	1.05	0.89	0.98	0.82	0.74	1.13	0.70	0.99	0.89

land precipitation are indicated. The precipitation patterns shown could be real, but they are interpreted here as strong evidence of gage undercatch.

In a recent study, Bolsenga (1977) analyzed data from gages that recorded total precipitation on an hourly basis located on the islands shown in Figure 1. He compared those data with total monthly precipitation from National Weather Service stations located around the perimeter of the lake. The data set represents the most extensive and complete island precipitation sequence for the Great Lakes collected from other than storage gages. A summary of Bolsenga's monthly ratios is given in Table 3. Apparent new information is indicated, which provides lake/land ratios on a monthly basis. A resulting analysis seems to reveal significant variations in the monthly lake/land precipitation ratios previously masked due to storage gage data. Surficially it appears that a critical gap in determining the water balance of a large lake has been filled. However, serious questions must be raised as to the significance of the data.

When the individual months and combined upwind and downwind values are considered, Bolsenga found, among other results, that from May through August land precipitation exceeds that on the lake (Table 3). Lake precipitation was

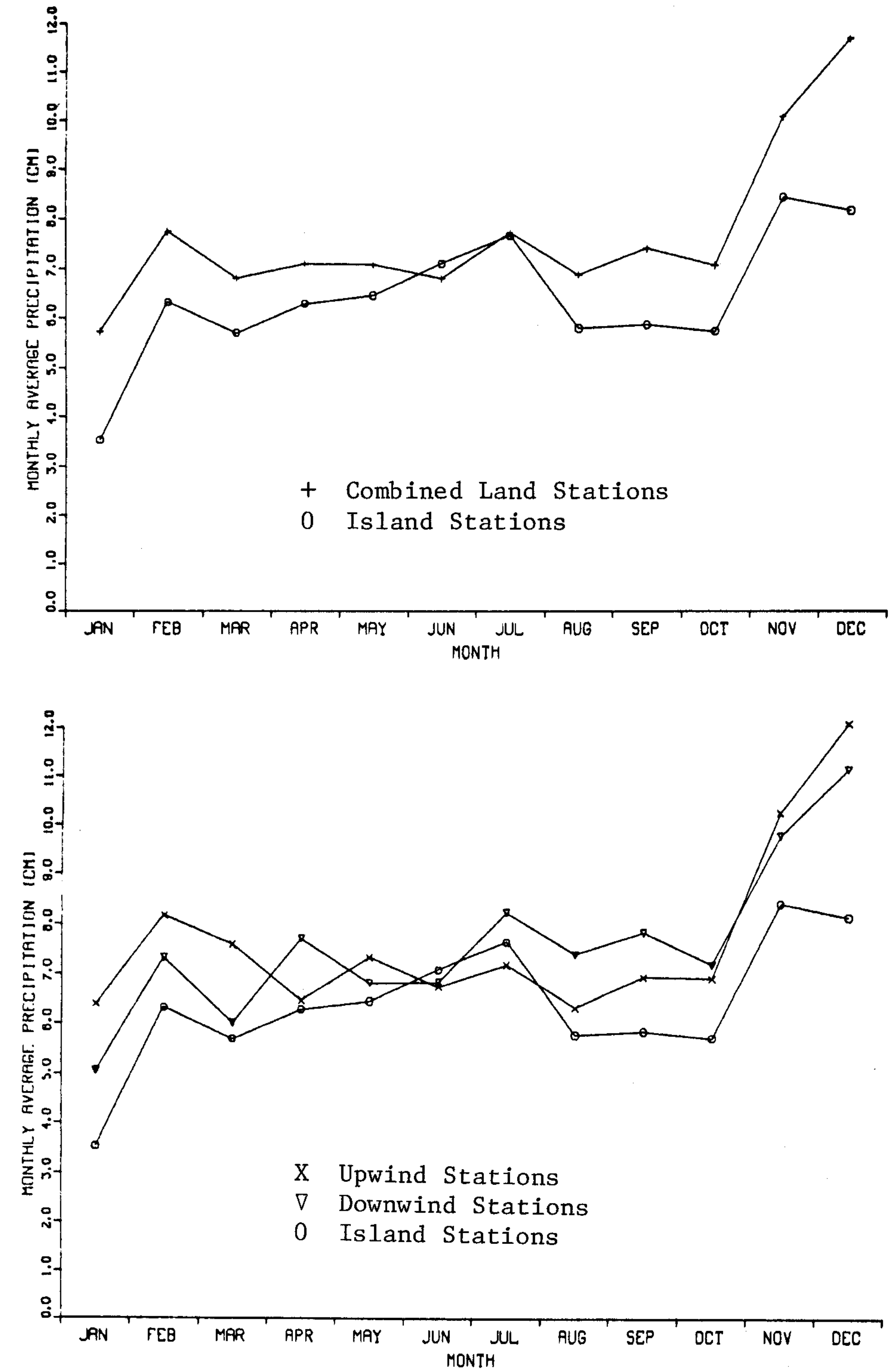

FIG. 2. A comparison of average monthly precipitation (1969-74) at island sites with average monthly precipitation at upwind, downwind, and combined upwind-downwind shoreline sites in eastern Lake Ontario.

significantly higher and lower than that on the land in September and October, respectively. For the individual months of November through April, lake and land precipitation were nearly equal. On a yearly basis, land precipitation exceeds lake precipitation by 2 inches. The dramatic increase in upwind, downwind, and combined ratios (Table 3) in September is noteworthy. Precipitation amounts for the upwind and downwind land stations as well as the lake stations were highly variable during the month of September for the period of data collection (1964-68). High precipitation amounts were noted for most downwind stations in 1964 and 1965. High precipitation was noted for most upwind land stations in 1965 and 1968 and to lesser extent in 1964. The lake stations showed high precipitation primarily in 1965 and to a lesser extent in 1964 and 1968. With the 1965 lake and land data removed, for example, ratio computations show lake/upwind land = 0.98; lake/downwind land = 1.16; lake/combined land = 1.07. A complete explanation would involve a complex analysis of specific synoptic events and/or gage catch errors and was not investigated here. However, Changnon (1967) reported that fall transects across Lake Michigan showed "a steady increase in precipitation from west to east, with a greater increase near the eastern shore." Fall thunderstorm frequency and precipitation patterns support his results which are also in agreement with the results of the computations above and of Bolsenga's (1977) study.

When the monthly data are reduced to seasonal data and compared with the previous works of Blust and DeCooke and Changnon, agreement is not impressive, but yet, within the range of accuracy for standard rain gages. For example, Table 4 shows a comparison of the upwind and downwind lake/land ratios of Changnon (1967) with those of Bolsenga (1977). Although a complete reversal between the two authors of both the warm and cold season upwind case is apparent, the differences are within expected gage catch errors noted in the previously cited studies. Thus, agreement and seemingly valid explanation can be found among the various lake-land precipitation studies, but both the physical and statistical significance of the studies can be even more readily questioned due to the expected gage catch errors and small lake-land differences involved.

Bolsenga analyzed his monthly data for statistical significance using a paired Student's t test and the t statistic for two means. The paired t statistic showed only 4 months with significance at the 5% level. No months showed significance at the 5% level using the t statistic for two means. The lack of significance is further demonstrated by observing the range of ratios of all lake station data

TABLE 4. A comparison of lake/land ratios found by Changnon (1967) with those found by Bolsenga (1977) for upwind and downwind land stations during warm and cold seasons as defined by Changnon.

	Warm Season Ratio June through Oct.		Cold Season Ratio Nov. through May	
	Changnon	Bolsenga	Changnon	Bolsenga
Upwind	0.93	1.04	1.06	0.97
Downwind	0.95	0.93	1.02	1.00

(combined to one value) to the individual land stations (Table 3). Additional evidence that lake/land ratios using standard gages lack significance is provided by Larson and Peck's (1974) conclusions on gage catch error. Although wind measurements were not taken during Bolsenga's study, it is probably safe to say that wind speeds occurring during most precipitation events were of sufficient velocity to cause a significant error in gage catch. Bolsenga's conclusions state:

> "Thus, while the results of this study indicate that differences occur between lake and land precipitation, the differences are small enough to be statistically insignificant, in most cases, and where large differences occur, possible gage catch errors throw serious doubts on their significance. It is thus concluded that precipitation measurements using standard gages on most natural islands in the Great Lakes or on towers in the lake are susceptible to errors significant enough to render those readings only marginally useful for determining differences in lake-to-land precipitation."

Since the traditional methods of conducting lake-to-land precipitation studies appear to introduce serious errors in the results, new methods of resolving this problem are necessary. Development of gages of new design to accurately record precipitation in unsheltered areas and new field programs conducted in the traditional manner using such instrumentation would obviously solve the problems. Since new instrumentation of adequate design does not appear to be forthcoming, two options involving new methodologies are available.

Conventional recording gages and anemometers might be reinstalled at the island sites for a long-term period after sufficiently adequate empirical relationships are developed between wind speed and gage catch. The costs of such a program would be high. It should also be noted that numerous studies have already been conducted to obtain the wind speed-gage catch relationship without resolution of the problem to the accuracy required for such a study.

At the present time, it appears that the only practical alternative is improvement in remotely sensed precipitation techniques to be used to establish relationships between easily available standard shoreline gages and the remotely sensed overwater precipitation. The required accuracy might thus be obtained with economy of operation (after the initial high cost of calibration of the empirical techniques is achieved). Currently, radar offers the most viable remote sensing technique available.

METHODS ANALYSIS–RADAR TECHNIQUES

The most recent and most comprehensive program evaluating lake-land precipitation in the Great Lakes by radar was undertaken as part of the International Field Year for the Great Lakes (Wilson 1975, 1977). Precipitation estimates over Lake Ontario and its drainage basin were made for a 1-year period, based on data from three weather radars and 167 precipitation stations. Every point on the lake was within 130 km of a radar, producing excellent coverage. Final estimates of precipitation were based on combined radar and gage data according to the following four steps: (1) gage measured precipitation field obtained, (2) radar adjustment (calibration) field obtained from analysis of ratio of individual gage and radar estimates, (3) adjusted radar field obtained by multiplying the radar field and adjustment field, and (4) preparation of combined gage and adjusted radar field. A 100% weight was assigned to the gage field when a grid point corresponded to a gage location, with a linear decrease in this weight as the distance from the point decreased.

The radar "measurements" are thus dependent on standard precipitation gages for calibration. During periods of malfunction, beam blocking, and in areas of extensive ground clutter, the precipitation field was entirely determined from gage measurements. It is apparent that the problems of inaccurate gage readings due to difficulties such as gage undercatch and improper location must be carefully considered in this type of radar study, especially for the calibration field.

Wilson and Pollock (1977) listed the following factors known to contribute to errors in radar precipitation measurement:

- –Anomalous propagation
- –Beam blocking
- –Errors in radar calibration
- –Time changes in radar sensitivity
- –Reflectivity losses due to precipitation attenuation
- –Attenuation during periods of heavy rain on the radome
- –Received power averaging errors in regions of very strong precipitation gradients
- –Nonuniform filling of the radar beam by precipitation
- –Beam interception of the freezing level
- –Presence of hail
- –Variation in the drop-size distribution
- –Variation in snow-crystal type
- –Strong localized air divergence
- –Strong vertical air motions affecting drop or flake fall speed
- –Evaporation or growth of precipitation below the radar beam
- –Wind drift of precipitation below the beam
- –Frequency of radar collections

Corrections may be assumed for some of these factors, but Wilson (1977) and Wilson and Pollock (1977) felt that adjustment by gage networks was preferable. Collier, Harrold, and Nicholass's (1975) study resulted in a similar conclusion. Thus, radar determines spatial precipitation distribution and the gages determine precipitation magnitude.

Wilson (1977) states that the land (total basin) receives 5.1% more precipitation than the lake during the warm season (May-September) and 4.8% less during the cold season (November-March). Blust and DeCooke (1960) found that the land (nearshore only) received 6.2% more precipitation during the warm season (May-October) and 4.5% less during the cold season (October-May). Using the same time periods as Blust and DeCooke, Bolsenga (1977) found that the land (nearshore only) received 0.6% more precipitation during the warm season and 6.4% more during the cold season. The considerable difference in cold season values is probably due to gage undercatch in Bolsenga's measurements. Wilson and Pollock (1977) provide an explanation for situations where radar and gage estimates are in close agreement:

> "The gage-adjusted radar estimates are superior to those derived from either radar or gage data alone. However, the improvement is very dependent on the length of the measurement period, the size of the area, and precipitation variability. The improvement is greatest for showery precipitation over small areas for short time periods. For average daily totals over an area the size of the Lake Ontario Basin, the radar data provides little improvement over estimates from gages alone, simply because

the gage density (average 350 to 700 km^2/gage) is sufficient to adequately sample the rainfall for such a large area. The sampling error is, in fact, similar to the error inherent in individual gage measurements."

Woodley *et al.* (1975) agree: "The better agreement between gage and radar for the day than for individual showers was expected."

Wilson did not compute monthly lake/land ratios, but it is possible to do so (personal communications) from his data (Wilson 1975). The computations, along with Bolsenga's (1977) monthly lake/land ratios, are presented in Table 5. It should be noted that Wilson's ratios were computed by using total lake and total land basin precipitation whereas Bolsenga's ratios were computed by using only nearshore land stations. The similarity is close considering that Wilson used data for only 1 year and for a different lake. Larger diffierences in the values occurred in June, August, September, and October. A detailed examination of the data, which was not conducted for this study, would likely explain these differences. Hurricane Agnes accounts for the lack of agreement in June. Some of the differences for the other months can probably be explained by differences in lake-effect patterns between Lake Michigan and Lake Ontario. Nevertheless, it is in fact difficult to determine why any reasonable agreement occurs between the two sets of values. A conclusion might be reached that the agreement is quite normal based on Wilson and Pollock's (1977) statement quoted above that the gage calibrated radar data provide little improvement over gages alone for time periods over 1 day. However, it would seem, then, that the carefully sited and maintained radar gage calibration network has produced gage catch errors similar to those encountered in the northern Lake Michigan network. If the gage catch errors found by the previous authors were applicable to most standard gages, results such as those obtained by Bolsenga (1977) are surely suspect and also the radar calibrated data are equally suspect. On the other hand, it is probably equally valid to argue that a well planned and monitored radar calibration network (such as Wilson's) would greatly reduce gage undercatch errors. For lake/land studies the gage undercatch problem would be eliminated (with the added accuracy of gage calibrated radar) while enabling overlake precipitation measurements in the absence of islands, towers or cribs. The meaning of the partial agreement between Bolsenga's ratios and the ratios computed from Wilson's data cannot be solved without additional information. Logically, however, it seems that radar is a much more practical and accurate tool for overlake precipitation studies than standard gages.

Wilson (1977) briefly addressed the problem of predicting overlake precipitation from shoreline data concluding that the shoreline (nearshore only) averaged 5.6% more precipitation than the lake during the warm season and 2.1% less during the cold season. He noted that the exposure for a shoreline gage is particularly critical due to the probability of high winds at such locations.

Bolsenga and Hagman (1975) selected a group of land stations in order to estimate precipitation over Lake Ontario with a Thiessen polygon weighting procedure (no lake-land ratios applied) for part of the same period as Wilson's (1977) and Wilson and Pollock's (1977) studies. When gages removed from the immediate vicinity of the shoreline were included in the network (Figure 3), overlake estimates increased during the warm season and decreased during the cold season. The warm season decrease in shoreline precipitation with only nearshore gages included in the network can be explained as a real phenomenon or as gage undercatch due to high winds. Wilson and Pollock (1977) concluded that this decrease was real for the Bolsenga-Hagman study since exposures at the shoreline and inland stations were probably similar (all climate gages) and since the radar showed average rainfall to increase away from the shoreline. Their conclusion emphasizes the importance of proper location for shoreline gages used to estimate overlake precipitation.

A comparison of Wilson's (1975) daily radar-determined overwater precipitation values with overwater values obtained from Bolsenga and Hagman's (1975) polygon network and shoreline data (for a period of intensive study during IFYGL) are given in Table 6. The similarity is good and indicates that further radar studies

TABLE 5. Comparison of lake/land ratios computed from Wilson's (1975) data with those from Bolsenga (1977).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Wilson	1.07	1.03	1.12	1.07	0.82	0.69	0.85	1.00	0.89	0.98	1.03	0.88
Bolsenga	1.00	1.01	1.06	1.05	0.89	0.98	0.82	0.74	1.13	0.70	0.99	0.89

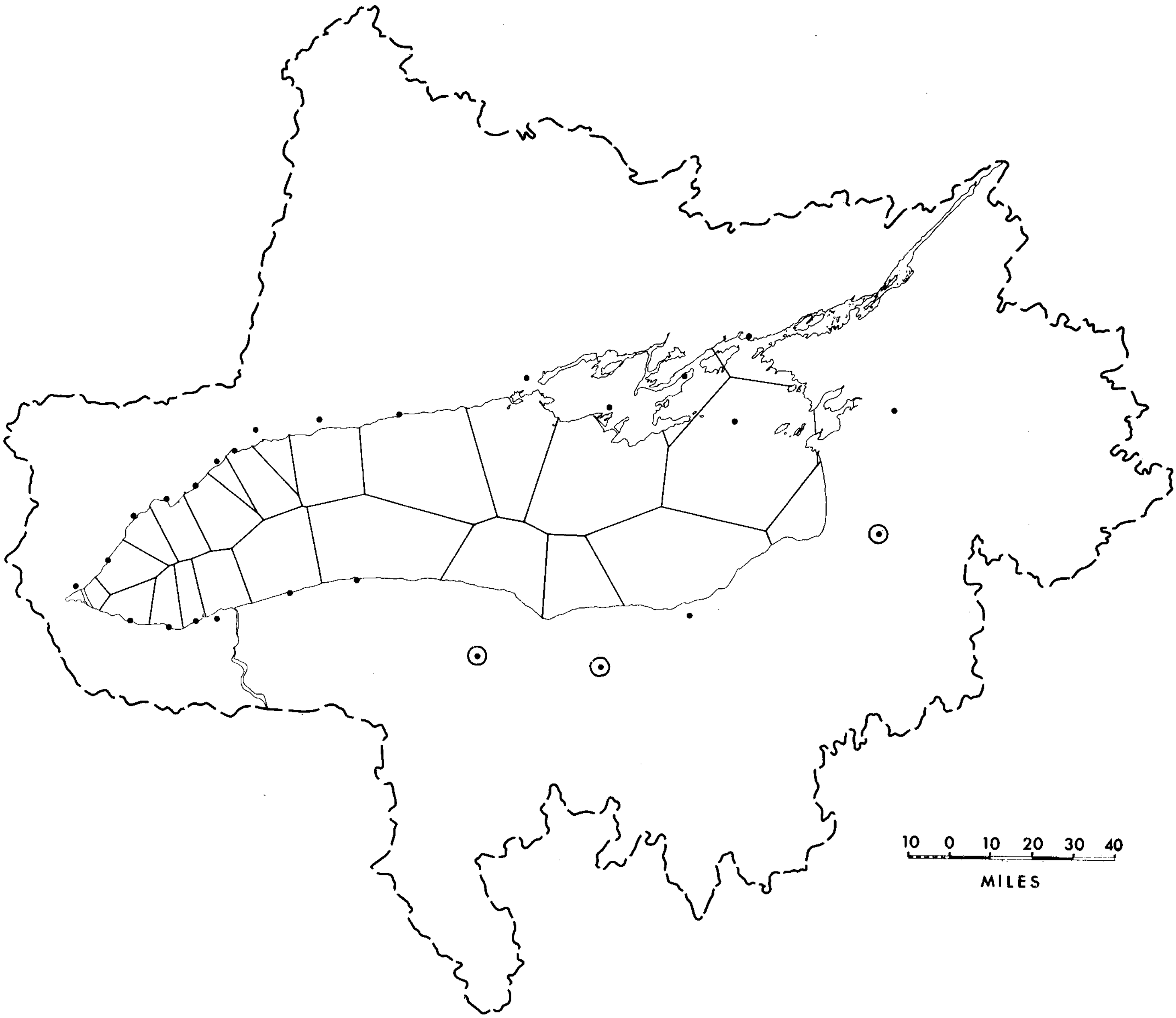

FIG. 3. Polygon network used in Bolsenga and Hagman's study (from Bolsenga and Hagman 1975). Circled stations were later removed from the network and the polygons redrawn.

combined with carefully selected shoreline networks might provide the basis for sufficiently accurate overwater precipitation estimates for many types of hydrologic studies. The use of one island gage, at the eastern end of the lake (Main Duck Island, 43° 56′N 76° 39′W), also probably contributes much to the close agreement.

SUMMARY AND CONCLUSIONS

It is physically impossible to synoptically measure precipitation over most large lakes of the world, including the Great Lakes, due to a lack of appropriately located islands and the cost of man-made structures. Overwater precipitation estimates are critical to operational hydrologists and modelers for computing the water volume of a lake and the related lake level.

The technique used in early studies to determine overwater precipitation locates precipitation storage gages on available islands. Often the best exposure on the islands is very poor since some are small, flat, and lacking vegetation. The island gage data are then compared to shoreline gage data by lake/land ratios. Due to the remote nature of the sites and the use of storage gages, readings were only obtained twice yearly.

Development of automatically recording precipitation gages enabled monthly lake/land ratios to be computed in one recent study satisfying objections pertaining to the use of storage gages.

TABLE 6. Daily whole lake precipitation by Thiessen polygons and by radar (cm).

1972		23 Station Network	Radar
Oct.	30	0.00	0.00
	31	0.00	0.00
Nov.	1	0.71	0.66
	2	0.71	0.69
	3	0.00	0.03
	4	0.38	0.38
	5	0.00	0.00
	6	0.00	0.00
	7	2.13	2.46
	8	2.08	1.98
	9	0.03	0.00
	10	0.10	0.13
	11	0.15	0.18
	12	0.00	0.00
	13	0.28	0.74
	14	0.51	0.86
	15	0.00	0.00
	16	0.00	0.00

However, the lake-land differences obtained were found to be smaller than expected gage undercatch. In addition, the monthly differences were statistically insignificant in most cases. Additional studies using this traditional methodology are clearly not warranted unless either new information on gage catch errors or new instrumentation becomes available.

Radar measurement of overwater precipitation appears to offer a solution to the gage catch dilemma. Results of Wilson and Pollock's recent overlake radar precipitation studies demonstrated the feasibility of collecting operational and synoptic data. Although much additional work is required to clearly outline a technique to overcome the lake/land precipitation problem, many studies indicate that radar would be a suitable tool. Greene (1975), for example, feels that "radar presents an ideal tool for hydrological purposes due to its capability to provide estimates of precipitation which has fallen over a watershed." He adds that "uncertainties are compensated for by the instantaneous remote sensing capability of radar which allows it to give complete areal coverage and to detect accurately the spatial discontinuities and temporal fluctuations associated with rainfall patterns." On the other hand, Hudlow, Pytlowany, and Marks (1976) cautioned that radar measurements during GATE possibly underestimated the true precipitation. The integrated accuracy of radar estimates can be assessed by evaluation of studies designed to compute basin yield by the radar approach. Curry, Clark, and Runnels (1970) used radar to forecast streamflow. Rainfall was computed by radar using grids and routing. The computer routed radar rainfall compared favorably to observed hydrographs. Using one test case, Grayman and Eagleson (1970) showed that a radar calibrated with a single centrally located raingage could be used to effectively simulate an actual hydrograph.

Lake/land ratios obtained from data in Wilson's radar study compare favorably in some cases with monthly ratios rejected as inaccurate in Bolsenga's traditional island precipitation study. Thus, the conclusion of the island study (that the ratios are unrepresentative due to gage catch errors) might be in error, or calibration of the radar with gages has caused similar errors to be represented in the radar study as in the island study. Other reasons for the similarity of the ratios are possible since the radar lake/land ratios are based on land data for the entire basin, whereas the traditional study used only nearshore data. Additional studies are in order, possibly involving comparisons of gage calibrated radar and radar calibrated by correction for factors known to cause measurement errors. It should be noted, however, that many investigators feel that gage calibrated radar systems are superior to and more practical than using radar alone (Wilson 1970, Woodley *et al.* 1975, Brandes 1974).

When solutions to some of the above problems are found, studies to recalibrate the existing lake/land ratios might be designed by using some viable method of measuring overlake precipitation. Designing the new program might best be conducted by a working group composed of individuals who have previously completed similar studies. Certainly no clear-cut optimum methodology presents itself at this time. The use of a working group would enable a consensus opinion concerning the optimum methodology to be derived. New ratios thus developed might solve the overlake precipitation estimating problem and provide operationally oriented programs with much needed information.

It is important to note that temporal and spatial variability might pose such formidable problems that calculation of new ratios would be deemed impractical. It is perhaps quite pertinent to ask the question: Will revised ratios determined by means more sophisticated than standard gages be valid from year to year and season to season? A family of ratios might be "keyed" to operational shoreline measurements which would signal changing conditions and the necessity for implementing a different set of ratios. It is recognized that the cost of such a program would be extremely high. Changing conditions (of any nature which would alter ratio values) not covered during the data collection phase would obviously render the newly derived family of ratios obsolete. The proposed working group would thus be compelled to seriously consider recommending no new studies balanced against the associated errors of scientific output where current lake/land ratios are used as a matter of convenience.

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