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APPLICATION OF OBJECTIVE TECHNIQUES FOR ASSESSING PRECIPITATION GAUGE REQUIREMENTS FOR STREAMFLOW FORECASTING

by

L.O. Mapanao and W.I. Pugsley

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ABSTRACT

This paper describes the application of a physically defined topographic precipitation index (TPI) and Gandin's correlation analysis method in assessing the adequacy of precipitation networks in the Saint John River basin for purposes of water supply and daily river forecasting.

These objective techniques permit identification of network data gaps corresponding to a prescribed uncertainty in estimating areal precipitation. The TPI method also demonstrates the feasibility of simulating the spatial variations of a field from known physical relationships to assess the requirement without the necessity of first establishing a dense network.

APPLICATION DE MÉTHODES OBJECTIVES À L'ÉVALUATION DES EXIGENCES EN MATIÈRE DE PLUVIOMÈTRES POUR LA PRÉVISION DE L'ÉCOULEMENT

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RÉSUMÉ

Dans cette étude, les auteurs décrivent l'application d'un indice de précipitation topographique (IPT) défini physiquement et de la méthode d'analyse de la corrélation de Gandin pour évaluer dans quelle mesure les réseaux pluviométriques du bassin de la rivière Saint-Jean correspond aux exigences en matière de prévision de la distribution de l'eau et de l'écoulement quotidien.

Ces méthodes objectives permettent de déceler les lacunnes du réseau en matière de données qui correspondent à une incertitude voulue de l'évaluation de la précipitation dans une zone donnée. La méthode IPT illustre également la possibilité de simuler les variations spatiales d'un champ à partir de relations physiques connues afin de déterminer les exigences sans qu'il soit nécessaire d'établir au préalable un réseau dense.

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(Manuscript received August 2, 1977)

1. Introduction

In support of a WMO pilot project to assess the application of World Weather Watch to operational hydrology, the Atmospheric Environment Service undertook a study to evaluate the adequacy of the Saint John River Basin precipitation network (Figure 1) to provide the necessary input and data precision required by hydrologic models. One approach to the problem of the optimum network density needed to deliver a prescribed precision for streamflow forecasting is to examine the spatial and temporal variations of the precipitation field itself. In this study, sampling of terrain-induced variations of the seasonal precipitation field was accomplished by the "Topographic Precipitation Index" method developed by Pugsley (1972), while space-time variations of precipitations on a daily basis were assessed by Gandin's (1963) optimum interpolation technique. The application and results achieved using these two independent schemes from the standpoint of water supply and river forecasting data requirements are described.

2. Techniques

2.1 Topographic Precipitation Index (TPI) Method

The conventional approach to network design may be briefly summarized as follows:

a) Establish a dense observational network;

b) Gather data over a specified period;

c) Calculate interstation correlations, or determine the spatial coefficient of variation over sub-areas of the network;

d) Establish a network density corresponding to a specified correlation criterion, or deduce the sample size statistically using spatial distributions of coefficient of variation.

With the TPI method, steps (a) and (b) are circumvented by a numerical simulation of terrain-induced precipitation on a fine mesh of grid points. The precipitation rate R produced by lifting a saturated layer of air has been given by Haltiner and Martin (1957):

$$R = \rho_o W_o (m_o - m_1)$$

where: ρ is air density
W is vertical velocity
m is precipitable water

Subscripts $_o$, $_1$ refer to the bottom and top of the layer, respectively.

In the simulation of seasonal precipitation, precipitation rate is integrated over a three month season and the layer is considered to be the boundary layer within which all vertical motion is assumed to be terrain-induced. Thus the precipitation index may be defined by:

$$TPI = m \sum_{i=1}^{4} V_i S_i + km \qquad (1)$$

where: m is boundary layer moisture parameterized by mean seasonal precipitable water as given by Hay (1971),

V_i is the mean horizontal wind speed from quadrant i, weighted by frequency of occurrence following the 850 mb wind values given by Henry (1957);

S_i is the average slope in a quadrant within the square grid area (100 km^2);

k is a coefficient dependent on the portion of the precipitation from non-topographic sources such as convection.

The convective term, km, was added to the topographic term to permit the computation of coefficient of variation of precipitation about a reasonable mean value. From previous tests by Pugsley (1972), k was given a numerical value of unity. Thirty year mean seasonal values of moisture and wind speed were specified on a 10 km grid over the entire basin. Terrain height and slope are available for all of Canada at this interval. Values were extracted from the physiographic tables given by Environment Canada (1973a) for the Saint John Basin.

The calculation of TPI values at a prescribed array of points therefore provides a substitute for the precipitation field, the spatial variations of which can be analyzed to derive network density. The coefficient of variation of the TPI field, C_v, was computed for a number of sub-areas (25 grid values per sub-area). The number of required samples, N, for each sub-area may then be found from the usual sampling equation.

$$N = t^2 C_v^2 / E^2 \tag{2}$$

where: t is the value of Student's t and
E is the specified error criterion in the mean areal precipitation.

2.2 Gandin's Optimum Interpolation Method

This scheme described by Gandin (1970) is a formal mathematical analysis technique using the statistical characteristics of a field as defined by interstation (i, j) correlation coefficients ($r_{i,j}$) and given by Kagan (1972) as:

$$r_{i,j} = \frac{\overline{\sum P_i P_j} - \overline{\sum P_i \sum P_j}}{\left[(\sum P_i^2 - \overline{P}_i^2)(\sum P_j^2 - \overline{P}_j^2)\right]^{\frac{1}{2}}} \tag{3}$$

where: P_k denotes precipitation value at data point k, and the bars indicate averaging in time.

In practice, correlation coefficients are assumed to decrease exponentially with distance (d), thus:

$$r_{i,j} = r(d) = r(o) \exp(-d/D) \tag{4}$$

where: D is taken as correlation radius, i.e., r(D) = r(o)/e.

In the application of Gandin's method, correlation functions were computed from daily non-zero precipitation amounts of station pairs from a set of thirty-four stations in the Saint John river basin. The relationship so established was assumed valid over the region, so that from a prescribed tolerable error of 20% (Es) in estimating mean areal precipitation, optimum spacings between gauges can be determined for a chosen network configuration. Kohler (1972) refers to a 15% uncertainty in areal precipitation as a suitable objective in precipitation network development for river forecasting in the United States where convective precipitation is more dominant. Kagan (1966) describes the relationship between standard error (Es), standard deviation of a time series of precipitation totals (σ), and linear interpolation and random errors (ξ) as:

$$Es = \sigma (\xi)^{\frac{1}{2}} \tag{5}$$

In particular, Gandin (1970) gives the optimum interpolation error (ξ opt) halfway between grid points of separation, d, as:

$$\xi \text{ opt} = 1 - \frac{2 \left[r(d/2)\right]^2}{2 - r(o) + r(d)} \tag{6}$$

From five years (1971-1975) of observations (excluding winter months), 74 days were selected on which precipitation was widespread over the region. Daily precipitation amounts from 34 stations within the basin were then used for analysis. Results of the study are presented in the next section.

3. Results

3.1 Seasonal Network by TPI Method

For convenience in mapping the TPI field, a regular grid network made up by 10 by 10 km squares was selected in order to be compatible with the square grid data bank established for all of Canada (see Environment Canada, 1973b).

As a check on the degree to which the simulated values approach observed precipitation values in the basin, seasonal comparisons were plotted as shown in Figure 2 for some fourteen stations in the basin. To compare on equal terms, each set of values was normalized by the average station value and expressed as a per cent. Points falling below diagonal line indicate underestimation of observed data, and vice-versa (overestimation) with points above the line. It is noted that in the winter season, when weather systems are much more organized and widespread, a good agreement is indicated between computed TPI values and observed precipitation at the selected stations by the small scatter of points about the line.

The seasonal gauge density requirements calculated for the Saint John river basin are shown in Figure 3. In general, the patterns identify three high density regions - the basin's western boundaries, northern Maine, and the central sections with density orientations consistent with the rough terrain in these regions. By imposing a twenty per cent acceptable error in estimating areal precipitation, and using coefficient of variations derived from the TPI field, seasonal gauge requirements for the Saint John river basin are summarized in Table 1. The average network density requirement is about seven gauges per 1000 km^2, or 137 km^2 coverage per gauge. Thus, the Saint John river basin requirement corresponds to the "mountainous region" (type II) category (see World Meteorological Organization, 1974, p. 3.9) with the TPI method of analysis.

To identify data gaps in the basin, the density distributions of Figure 3 were resolved into circular areas centered on the existing climatological stations. In particular, the current network coverage for the winter situation (at 20% error) is shown in Figure 4. The unshaded areas of the basin correspond to data gaps where additional gauges should be deployed.

3.2 Identification of Data Gaps by Gandin's Method

The correlation between each station and a control gauge located at Edmunston and at Fredericton, New Brunswick are shown in Figures 5a and 5b, respectively. Based on interstation distance along, it is noted that in the southern half of the basin the correlation field decays gradually in a north-south direction and falls off quite rapidly west and east of control gauge. This would suggest that the assumptions of isotropy and homogeneity in the Gandin scheme are less valid at distances greater than 100 km. These figures indicate to some degree the gauge density required and suggests an elliptical distribution of gauges in the basin, i.e. fewer gauges are needed in a north-south direction.

The correlation function derived from the correlation field was further resolved by equation 5 into an error response surface as functions of interstation distances and standard deviation of the daily rainfall sample (see Figure 6a). The linear plot on the right-hand side of Figure 6b integrates the error response surface into a single relationship between interstation spacings, and the ratio, of any acceptable error criterion (Es) in interpolating precipitation values at gauged points to ungauged areas; to local standard deviation (σ) inherent in the development sample.

To demonstrate the utility of Figure 6b, consider Fredericton which had a mean daily rainfall of 16 mm and a standard deviation of 18 mm. From a 20% acceptable error, Es = 3.2 mm, and normalizing by 18 mm yields a ratio of about 0.18. With this entry in Figure 6b (note dashed line) a requirement is indicated for gauges beyond a 9 km radius from Fredericton's location.

In Figure 6a, one can also obtain an estimate of the most likely error when gauge values are extrapolated into ungauged areas. For instance, if the daily rainfall at Saint John with a standard deviation of 21 mm is extrapolated 11.5 km away (noted dash line), the extrapolation error would correspond to 4 mm. This value is twice the acceptable error for hydrological forecasting (see World Meteorological Organization, 1974, p. 6.10). However, with a mean daily rainfall at Saint John of about 17 mm, the 4 mm extrapolation error is only 23.5% in relative terms.

The curves of Figure 6 are the major tools used in depicting data gaps in the basin. Before one can employ these curves however, one must know the spatial distribution of Es and σ, as shown in Figures 7a and 7b respectively. By abstracting the necessary information from Figure 7, and working out interstation spacings from Figure 6a, the circular areas of Figure 8 were identified; the envelopes of which were shaded to depict the extent of representativeness of data at gauged points corresponding to the 20% error criterion specified for the particular application. The hatched circles indicate available data points that could supplement the real-time data base currently used for flood forecasting in New Brunswick (SSARR network). That part of the basin not shaded or hatched identifies the current data gaps in the Saint John River Basin for the daily flood forecasting operations.

For this purpose, the existing network is almost satisfactory in the central and northern regions. However large gaps appear in central Maine and southeastern New Brunswick, along with smaller gaps along the northeast border areas. Following the accepted practice in the design of networks, the most efficient procedure would be to first completely satisfy the requirements in the latter areas rather than distributing additional gauges uniformly across the basin. Another consideration is the smaller effect in terms of volume of a given rainfall on the main stem flow near the river's mouth compared to the same amount falling in the headwaters area. On this basis, additional gauges should be placed in central Maine before southern New Brunswick.

The advantage of the Gandin method is that it defines the spatial representativeness of each station in the existing network. From this knowledge, redundant stations may be identified from where circles overlap. However, in the data gap areas, where existing station observations are not representative, one must assume a standard deviation and mean of the rainfall field as interpolated from the observational field. A new station installed in this gap area may indicate higher or lower variability in the precipitation field. Thus the additional gauge requirement is not precisely known.

It is interesting to compare the results of the two methods, although the TPI technique clearly does not represent the spatial variability of the precipitation field over periods of less than a season. The TPI requirement does indicate the effect of terrain-induced precipitation over the entire basin area. The Gandin method, being based on statistical principles, is limited by the size of the sample set - the number of events and the number of stations - as well as the absence of stations at all points in the basin. This method does offer precise answers from the existing stations subject only to the assumption of isotropy which may be verified.

The emphasis of the two methods is shown by a comparison of Figure 4 (TPI winter gauge requirement) with Figure 8 (Gandin requirement). In the relative flat areas of southern New Brunswick, topography is less important as shown by large TPI circles, and convection and advection are more important as shown by small Gandin circles. On the other hand, in northwestern Maine, the rough terrain produces a more stringent TPI requirement and a moderate Gandin requirement. Central New Brunswick and Maine present a mixed requirement from each approach. The main benefit from these two techniques is the precise identification of network needs and their causes.

4. Conclusion

This study demonstrates the application of standard techniques to rational network evaluation as long as error criterion for specific applications can be stated. In the absence of observational data, it is still possible to develop from physical principles, using substitute variables that are readily available, associated functions or indices that could be employed to simulate the real world, thereby providing insight to practical solutions which can be pursued further. Efforts are now directed to refine the correlation functions by increasing and stratifying the development sample. The generality of this approach permits a rational evaluation of existing networks in Canada in order to meet specific data requirements or applications.

5. Acknowledgements

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Table 1

Summary of Seasonal Gauges Required for the Saint John River Basin (area - 53, 560 km^2) Derived from TPI Method

	Winter	Spring	Summer	Autumn
Required Gauges	392	430	369	378
Gauge Density (per 1000 km^2)	7	8	7	7
Coverage (km^2) per gauge	137	125	145	142

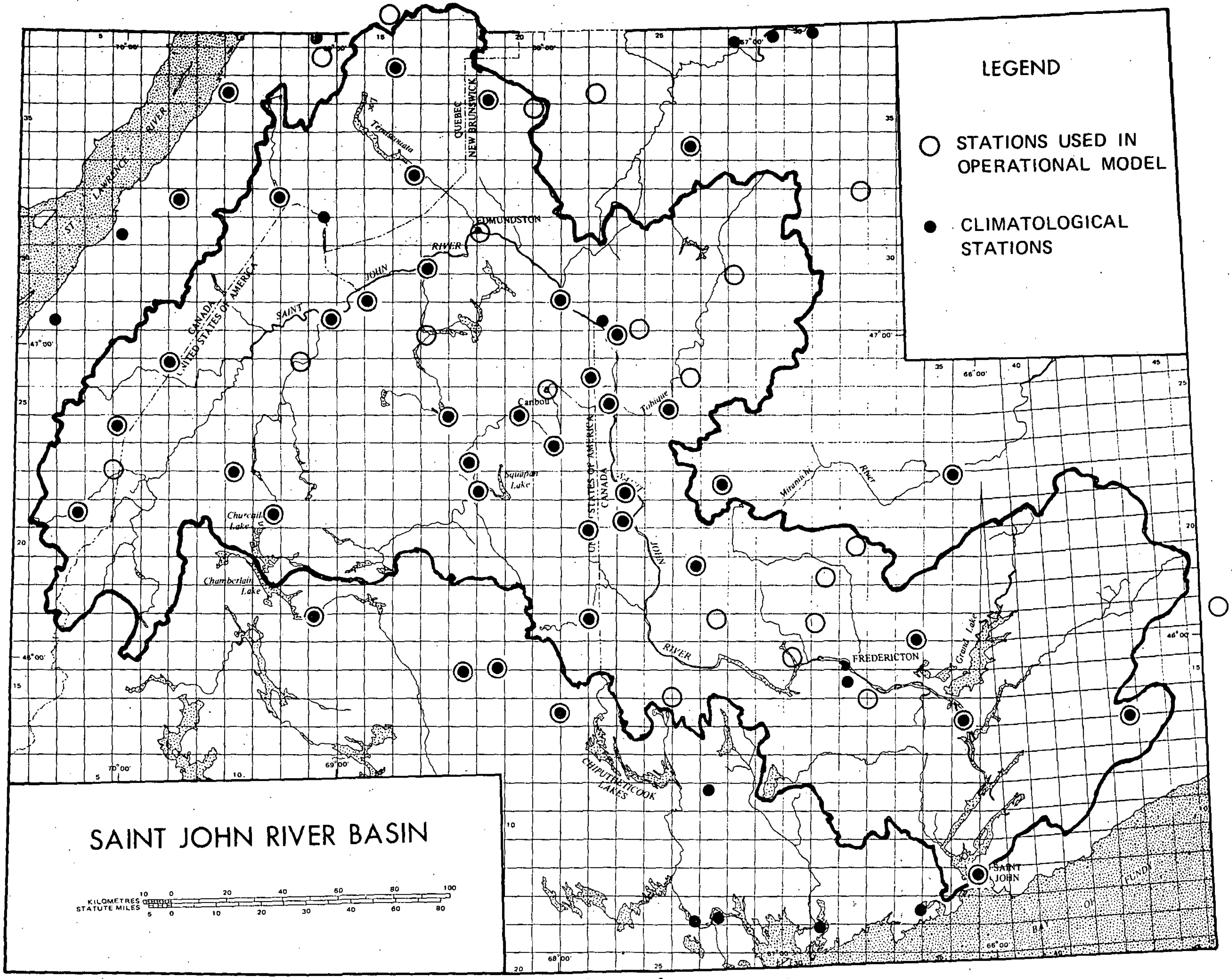

Figure 1

Data network used by SSARR Model (62 stations, 51 inside basin)

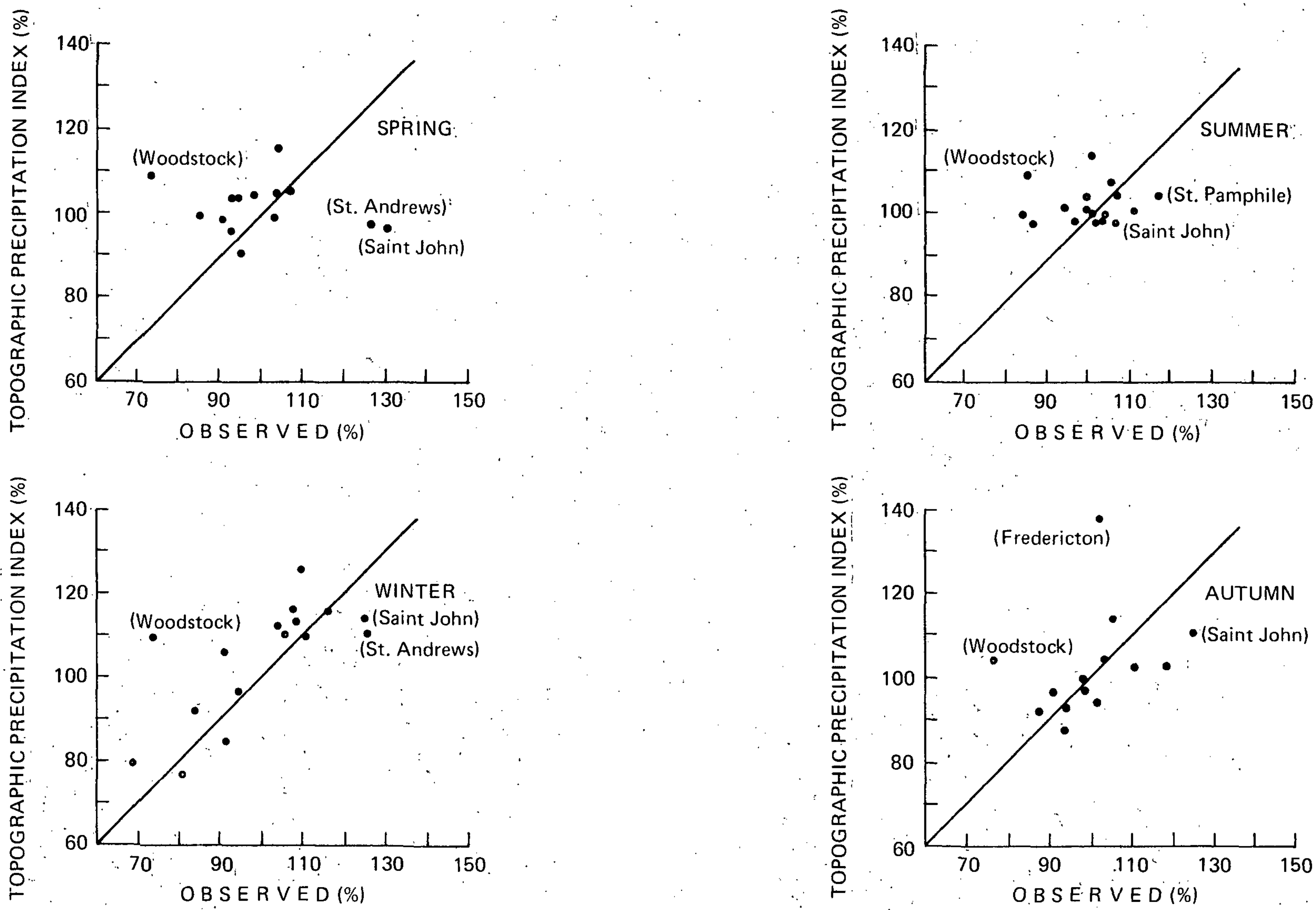

Figure 2

Seasonal comparisons of computed TPI against observed precipitation at fourteen stations in the basin (normalized by average station values)

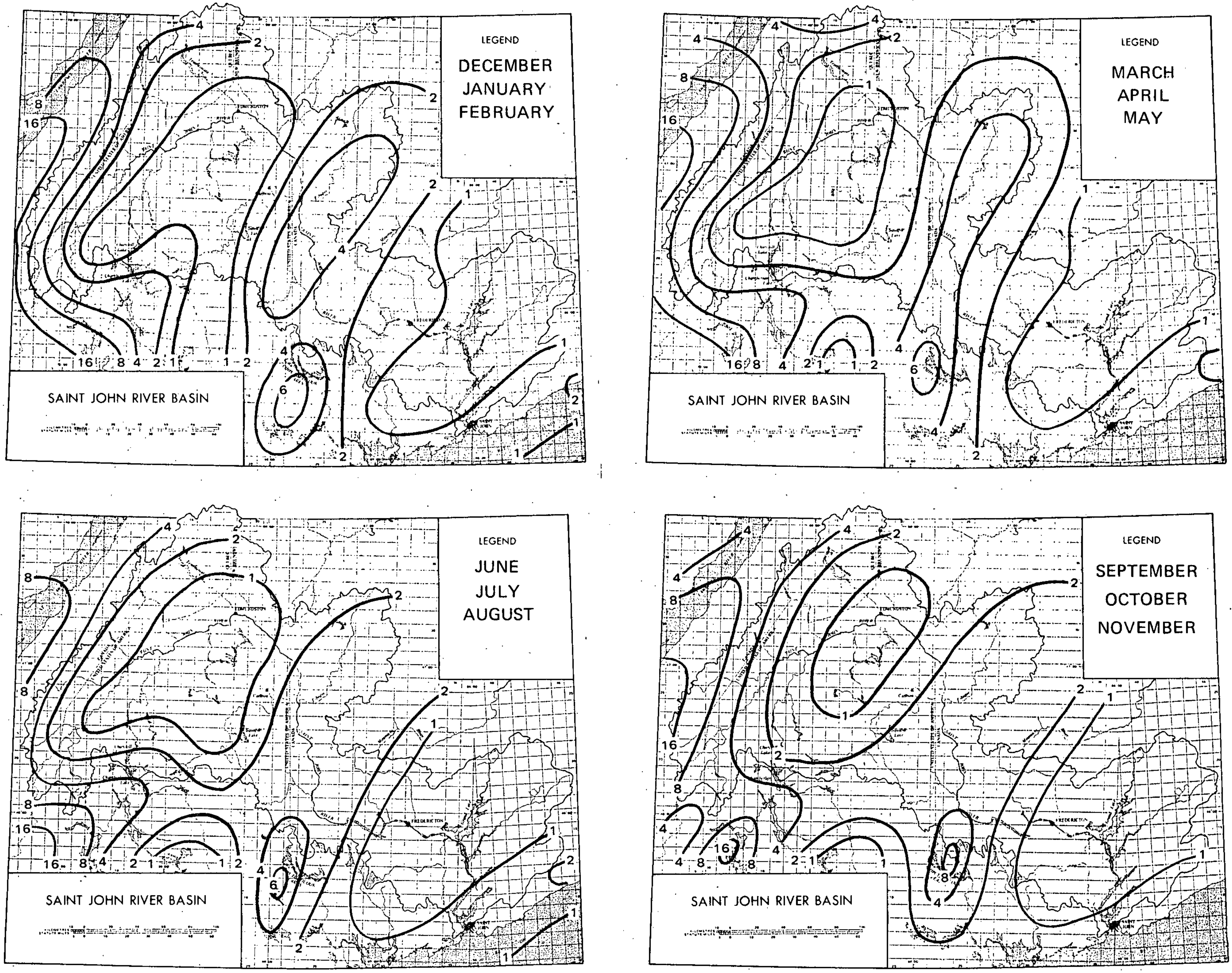

Figure 3

Seasonal distribution of gauge density (gauges/1000 km^2)

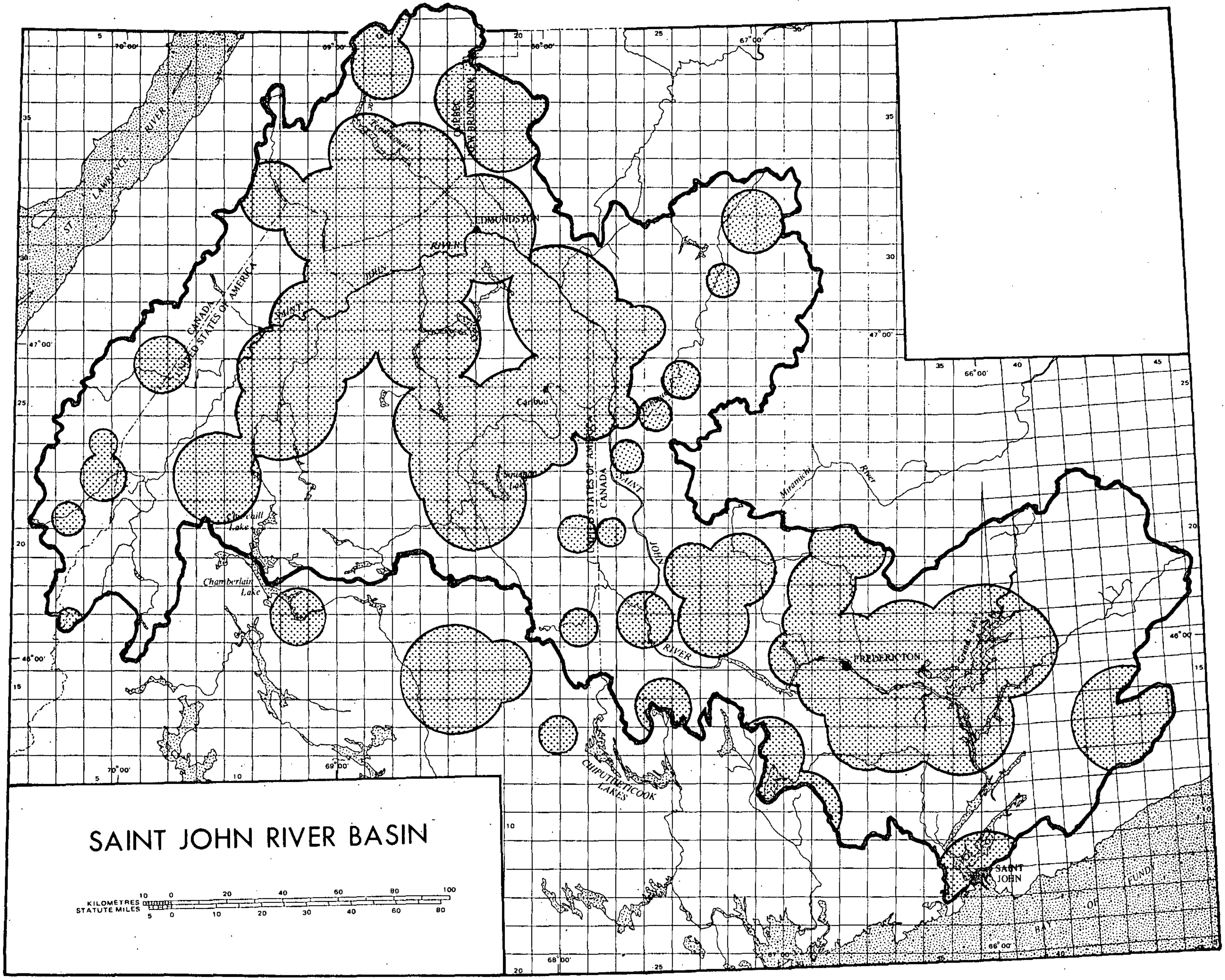

Figure 4

Network data gaps (unshaded) for seasonal precipitation with a 20% prescribed areal error using TPI method.

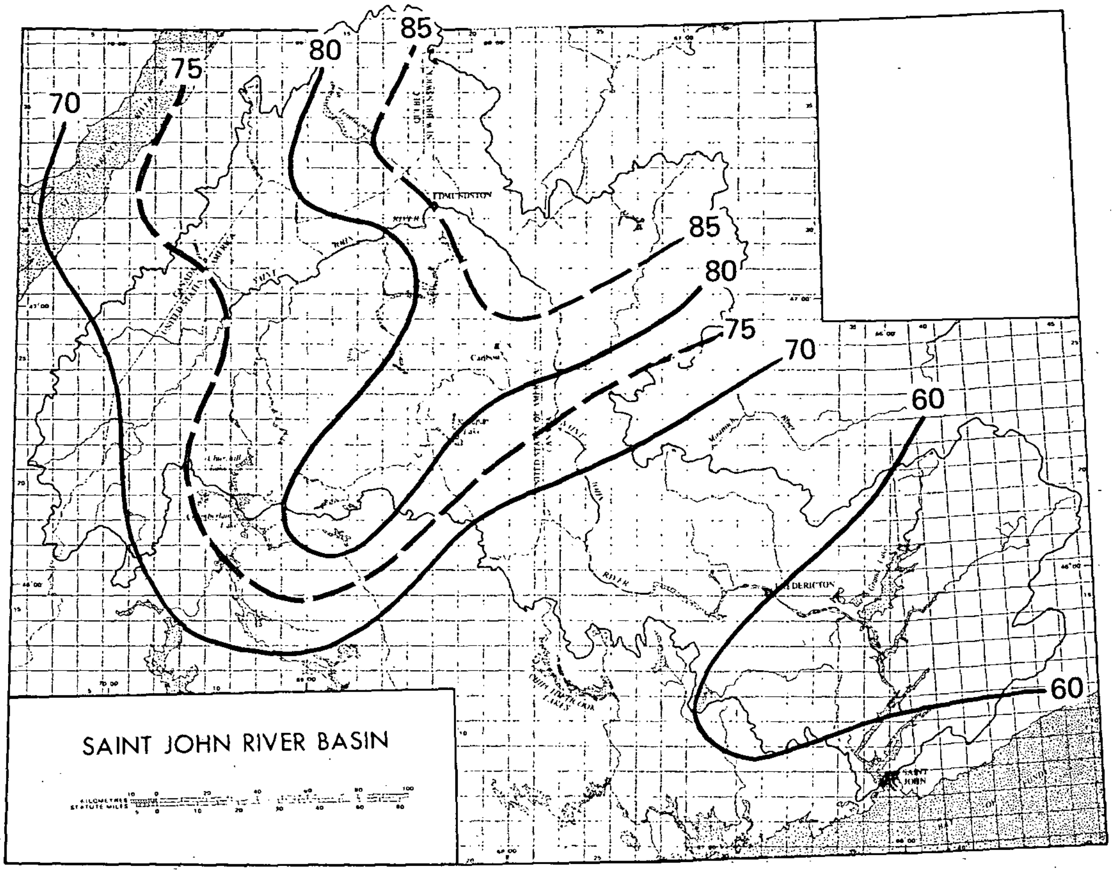

Figure 5a

Correlation field between Edmunston's Precipitation (daily) and 34 other stations in the basin.

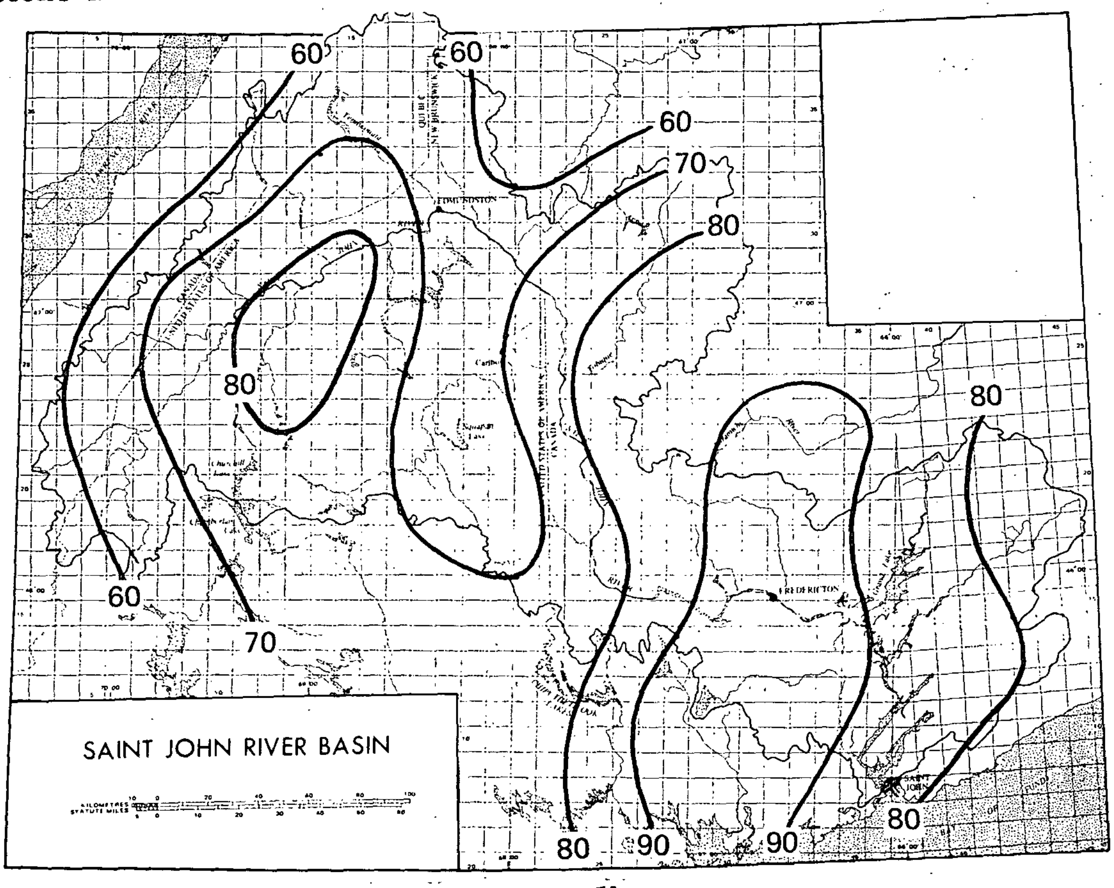

Figure 5b

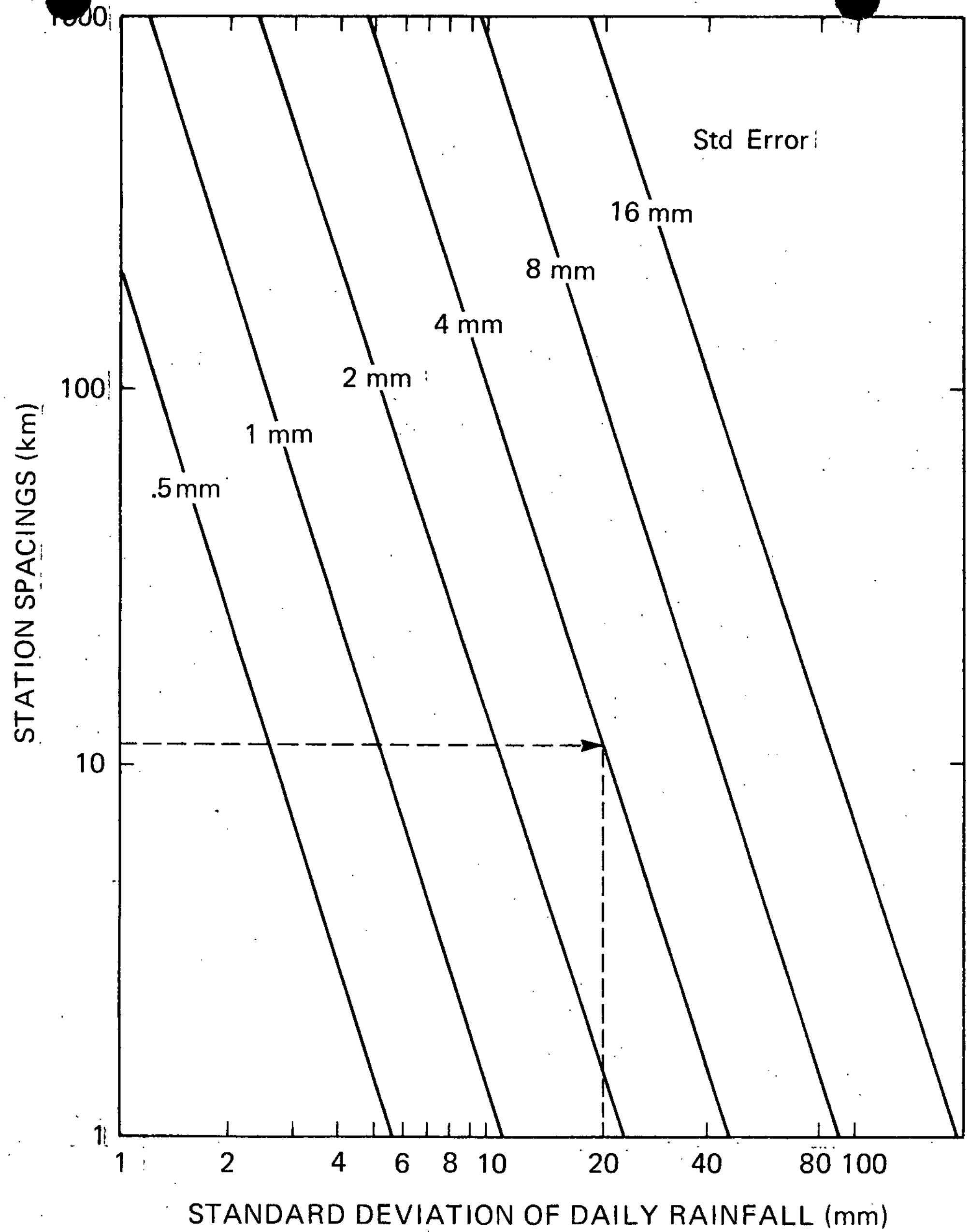

Figure 6a Error response surface as function of standard deviation of daily precipitation and station spacings.

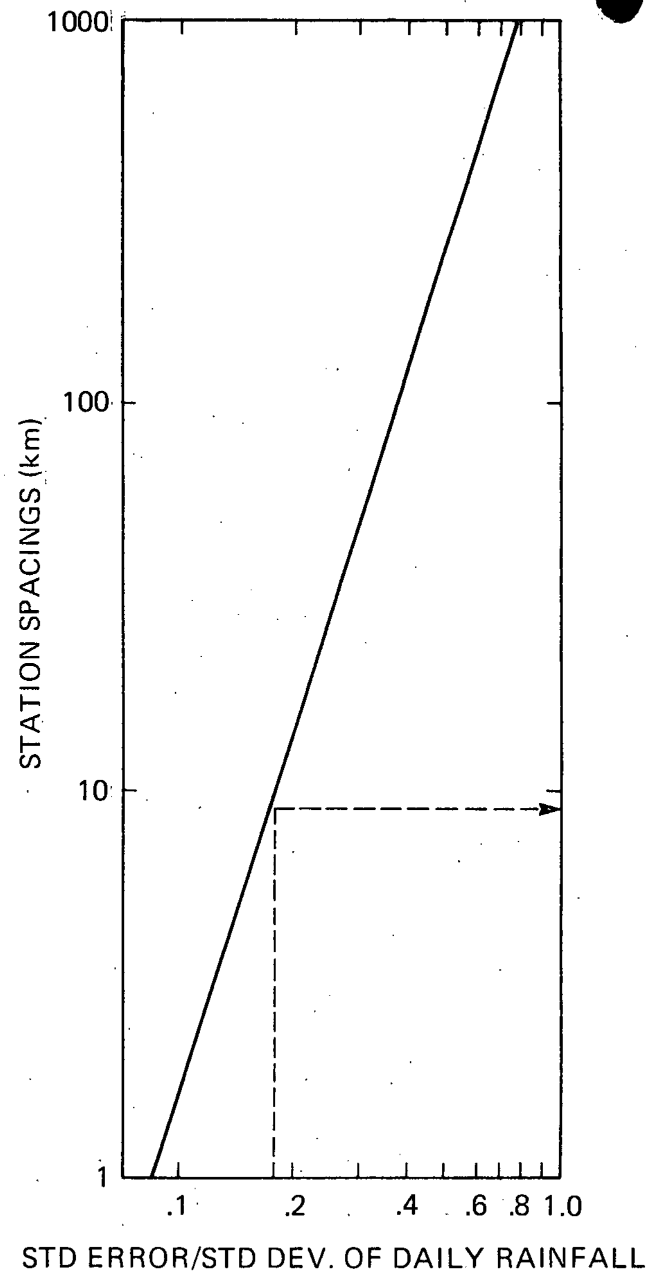

Figure 6b. Station spacings vs. the ratio of standard deviation of daily precipitation (using 74 precipitation events, r = -.60).

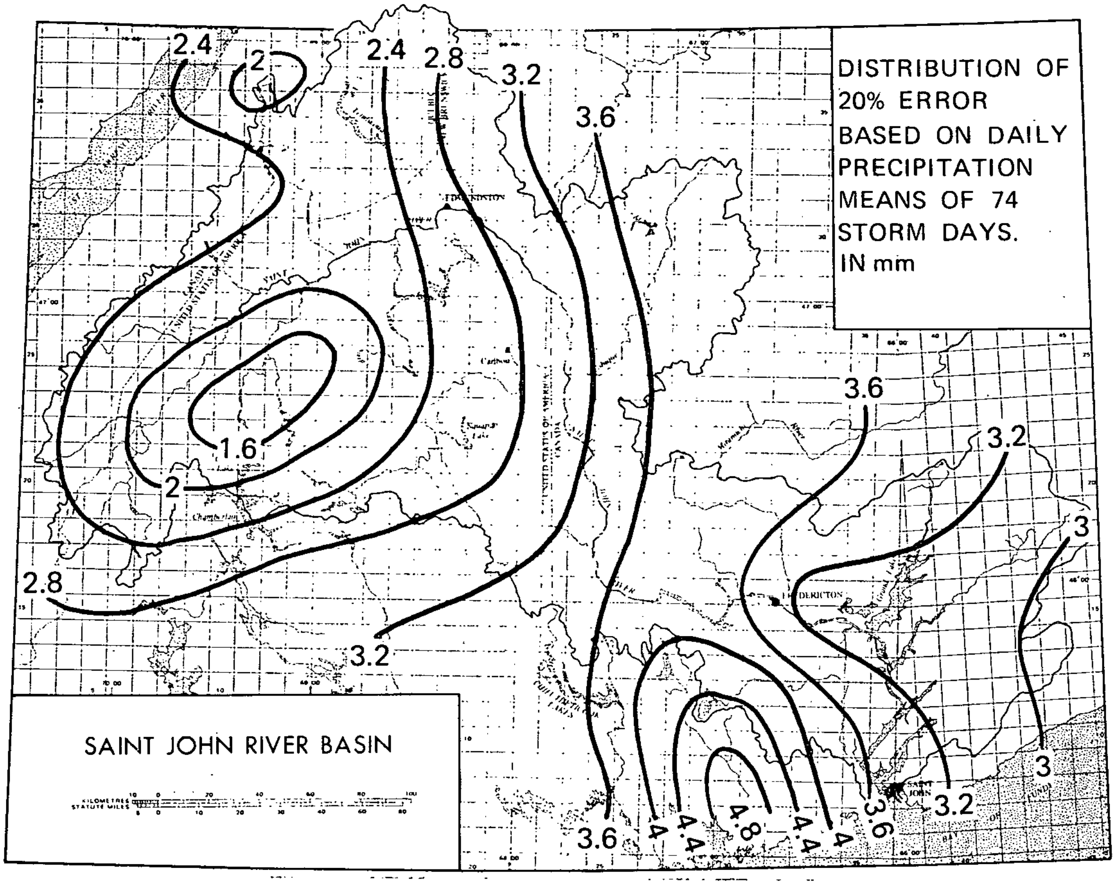

Figure 7a

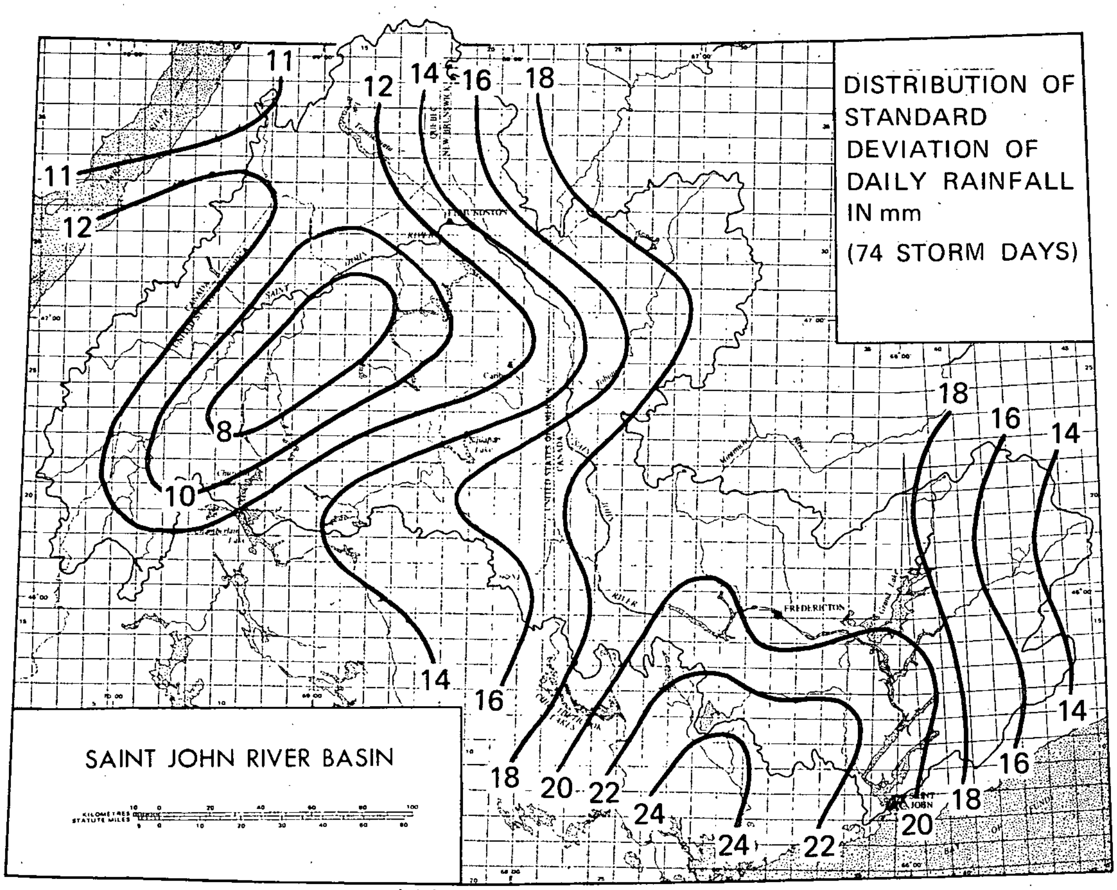

Figure 7b

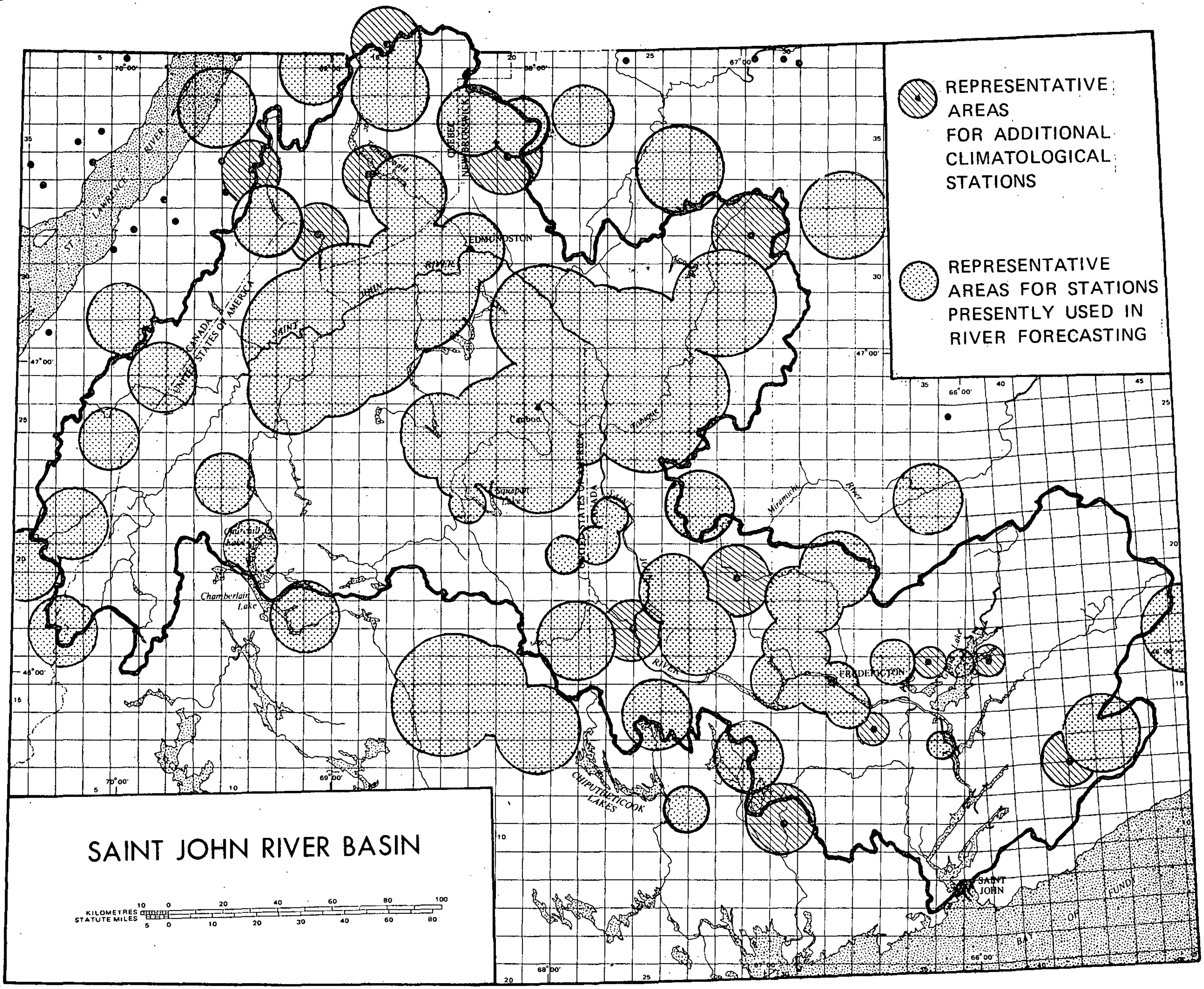

Figure 8

Network data gaps (unshaded) for daily precipitation with a 20% prescribed areal error using the GANDIN method.

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