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ANALYSIS OF LARGE-AREA STORMS IN SWA/NAMIBIA

W. V. Pitman

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Hydrological Research Unit
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Director: D C Midgley

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PREFACE

Among the approved fields of study in the Unit's contract with the Water Research Commission under the heading Floods Studies is the extension of the scope of the HRU Design Flood Manual to cover arid areas. With this in mind we acquired the necessary data for SWA/Namibia. I am grateful to the Weather Office, Windhoek, and to the Consultants, Messrs. Chunnett, Myburgh and Partners, for transferring the data to computer cards and despatching these to Johannesburg.

In 1979 the Unit issued report No. 3/79, *Analysis of SWA-Namibia rainfall data*, which provides, among other things, the input data for establishing flood responses of small catchments. Report 2/80 provides design storm data for estimating floods for somewhat larger catchments. Once the available streamflow data have been abstracted from the records of the Directorate of Water Affairs, Windhoek, it should be possible to complete the task of preparing a Design Floods Manual for arid areas.

I am grateful to the Water Research Commission for permission to publish this report.

D.C. Midgley

Director: Hydrological Research Unit

April 1980.

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SYNOPSIS

A computer program was written to facilitate selection of significant large-area storms from the SWA-Namibia daily rainfall data file. Package program SURFACE II was used to plot isohyetal maps of the selected storms. Depth-area-duration-frequency analyses were performed and the results presented in the form of co-axial diagrams.

The depth-duration-frequency co-axial diagram developed for point rainfalls of durations up to 24 hours in SWA-Namibia in HRU report 3/79 was extended by an additional quadrant to show point rainfalls of durations up to 5 days and a diagram was developed to show the area reduction factor so as to permit point rainfall data to be used for large area storms.

Guidance in storm transposition and application of the diagrams is given.

Appendix A contains documentation of the programs developed and Appendix B contains the isohyetal maps of selected major storms for different regions of SWA-Namibia.

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1. INTRODUCTION

This report is a companion to report no. 3/79 *by B.F.C. Richardson and D.C. Midgley "Analysis of SWA-Namibia rainfall data"*, which contained a mean annual isohyetal map and a depth-duration-frequency diagram for point rainfalls up to six-hour duration.

In this report the emphasis shifts to large-area long-duration storms. Scrutiny of the results of depth-area-duration analyses of 36 well-distributed major large-area storms suggested that the territory could be sub-divided into three meteorologically homogeneous regions, viz. North, South and Coastal. For the North and the South regions co-axial diagrams have been produced to define the inter-relationships of depth, area, duration and return period but for the coastal region, which is very sparsely endowed with raingauges, resort must be had to a curve from which the areal reduction factor (ARF) can be estimated. The adjusted depth of rainfall can then be entered in the depth-duration-frequency diagram (taken from Report 3/79 and extended to storm durations up to 5 days).

2. THE DATA

Records from 572 daily-read rain gauges in 175 sections* of SWA/Namibia were transferred to computer cards in the Weather Office, Windhoek, by a local firm of consulting engineers under directions from the Hydrological Research Unit (HRU). Fig. 1 shows the distribution of the rainfall stations.

Earliest records date from about 1890 and the closing date of the data assembled is 1976. In general, the records prior to about 1913 were merely monthly totals. Most of the daily

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* Sections are quarter-degree squares numbered according to the system adopted by the Weather Bureau, Pretoria; rainfall station numbers comprise the section number and a suffix number based on position among the 900 possible square minutes of arc within each section.

rainfall data were recorded in tenths of a millimetre but, particularly during the period 1940 to 1950, the unit one-hundredth of an inch was employed. In some of the records there was frequent switching of the units so that confusion was inevitable. Of the 572 stations 314 had records that at times employed both of these units.

An editing program was developed to convert the records all to the one-tenth millimetre unit and to identify errors, such as incorrect number of days in the month or lack or agreement between monthly totals listed and sum of the daily falls recorded for the month, and various inconsistencies in the records.

Printouts of errors or inconsistencies were returned to Windhoek for clarification. Data sheets had to be sent backwards and forwards many times before the material was ready to be committed to magnetic tape. Copies of the final tape were made available to the Weather Bureau, Pretoria, and to the authorities in Windhoek.

3. SELECTION OF STORMS FOR ANALYSIS

The first step was to select a representative station in each of the 175 sections for which rainfall data were available. Fig. 2, showing the distribution, also illustrates the paucity of data in the coastal, northern and north-eastern parts of the country.

The next step was to search the records of each representative station to identify dates on which a significant fall of rain occurred. A threshold value of 25 mm was selected and a computer program, SWSTOR, was written to scan the tape for daily falls exceeding this threshold. Output from this program, written to disc for further reference, takes the form of a large matrix with each column constituting a list of dates of heavy rainfall (i.e. > 25 mm) at a particular representative station.

Before scanning the matrix for matching dates it was necessary to decide upon a suitable epoch for analysis. Although some records go back to the turn of the century it was not until the 1920s that the spread of gauges was adequate for satisfactory mapping of large-area storms. Furthermore, during World War II (1939 - 1945) many stations became inoperative. It was therefore decided to adopt for analysis the 30-year period 1947 to 1976.

A further computer program, RANK, was devised to search the output file from SWSTOR and write out, in chronological order, each date of high rainfall and the number of stations (representing sections) at which heavy rainfall was recorded. All dates prior to 1947 were ignored, as were dates on which less than five sections experienced rainfall exceeding 25 mm. The latter constraint eliminated events covering relatively small areas.

The print-out from program RANK was thus a list of possible dates of significant large-area storms. It was still necessary to establish whether these were cohesive storms or merely scattered events. At the same time the duration and areal extent of each selected storm had to be identified. Program SEARCH was written to scan the file created by SWSTOR and pick out the sections (i.e. representative stations) that yielded more than 25 mm on a particular day. The dates chosen for this analysis were, of course, derived from inspection of the print-out from program RANK. Since storms of up to five days' duration were to be considered for analysis, SEARCH was modified to pick out sections experiencing high daily falls during periods of up to five consecutive days, viz. from two days before to two days after the selected storm date. A typical output from program SEARCH is displayed in Table 1. Information from these outputs was plotted on section maps of SWA/Namibia like the example in Fig. 3. Sections of high rainfall are marked on the map with a code for each day of the duration. From maps such as these it was possible to determine both the extent and the duration of each selected storm. Fig. 4 illustrates an example of a storm that was rejected because of the dispersed pattern of the sections experiencing high rainfall.

In all, 36 storms were selected for further analysis. Of these, three were estimated to be three-day storms and twenty-three five-day (or longer) storms. To reduce the computational effort, two-day storms were grouped with the three-day storms and four-day storms with the five-day storms. Later it will be shown how design data for two- and four-day storms were interpolated among the one-, three- and five-day storm results.

Table 1 Example of output from program SEARCH

Sections with rainfall > 25 mm				
72/3/14	72/3/15	72/3/16	72/3/17	72/3/18
655	526	490	491	615
739	566	491	530	789
741	568	527	531	1209
827	610	529	565	
961	611	566	567	
1009	651	568	613	
1104	652	609	654	
1159	655	610	700	
1206	698	611		
1207	699	612		
	740	614		
	742	653		
	782	654		
	829	656		
	873	696		
		698		
		701		
		742		
		784		
		1209		

4. ISOHYETAL MAPPING OF STORMS

To generate isohyetal maps of each of the storms under study, use was made of the software package, SURFACE II, which is designed to display spatially distributed data. Input is in the form of a set of data points identified by geographic co-ordinates (latitude, x, and longitude, y) plus a third variable (z) which could be ground elevation, rainfall or any other feature that varies spatially. The basic form of the graphic display is an isometric map. A comprehensive description of SURFACE II is to be found in Sampson (1975).

To prepare the data for SURFACE II the computer was programmed to read the original tape and extract the information for each storm. Basic input to this program, SOFTA, comprises the date of the storm (or dates if the storm lasts longer than one day) and a list of the rainfall sections covered by the storm. This information was derived from maps, such as Fig. 3, prepared for each storm. The program selects all stations within the boundary of the storm and sums the rainfall over the duration of the event. In the case of five-day storms three runs of the program were required and two runs for the three-day storms.

Latitudes and longitudes of the stations were derived from station number in the following manner. A list was prepared of the westernmost section in each 'row', starting with section 273 and ending with section 1244 (see Fig. 2), together with the co-ordinates of the north-western corner of those sections. Latitude and longitude of the northwest corner of any section in the territory could then be derived by first placing it in the correct row and then establishing its displacement from the westernmost section at 30 minutes of arc per section. The co-ordinates of a station, relative to those of the north-west corner of the section, are uniquely determined by its position number (see footnote on page 1) and thus, given the number of a station, its latitude and longitude can be read by the computer.

Output from program SOFTA, comprising latitude, longitude (minutes of arc) and rainfall (1/10 mm) for each station within the storm boundary, was stored on disc for subsequent use by the contouring program, SURFACE II. Fig. 5 is an example of a storm isohyetal map produced by SURFACE II. The plot of the data points, which can be drawn separately or as an overlay to the isometric map, provides a useful guide to the reliability of the surface in areas where data are sparse.

5. DEPTH-AREA-DURATION ANALYSIS

The standard way of representing the areal distribution of storm precipitation is by depth-area curve. Fundamentally, the method involves determination of the maximum average depth of precipitation occurring within selected time intervals throughout the total storm period on areas encompassed by each closed isohyet. Thus, against a selected value on the area scale of the depth-area-duration graph, the value of depth read against a given duration curve represents the maximum volume of rain that occurred within that duration divided by the area value selected. The result represents therefore the maximum value of average-depth precipitation over a given area within a given period (duration) during the storm.

Planimetry was found to be the most satisfactory way of determining the areas enclosed by isohyets. Although computers can be programmed to do the job more rapidly, the manual method has distinct advantages. Individual storm cells can be readily identified by inspection of the isohyetal map. Separate depth-area curves for each cell can be constructed and it is the envelope of these curves that constitutes the maximum depth-area curve for the storm as a whole. Unreliable information for example, from cells centred on a single isolated station, shows up on inspection of the plot of stations and can be ignored.

Since the storm isohyetal maps produced by SURFACE II are based on a co-ordinate system of latitude and longitude in minutes of arc the units of the planimetred areas have to be converted from square minutes of arc to square kilometres. A simple conversion formula, based on a mean Earth diameter of 6367 km is:

Area (km) enclosed by
one square minute of arc = 3,43 cos Ø .... (1)

where Ø is the latitude in degrees.

A single conversion factor was computed for each storm according to the latitude of the storm centre. In this way errors of overestimation in areas south of the chosen latitude would tend to be balanced by errors of underestimation in areas north of that latitude. Furthermore, since the maximum north-south range of any storm was never more than about 5^{o}, the maximum error was always less than 2%.

Table 2 sets out the depth-area calculation for the three-day storm displayed in Fig. 5. (For improved accuracy, the actual working map was drawn to a much larger scale). Depth-area curves for the one-, three- and five-day rainfalls of this storm are plotted on Fig. 6. To ensure uniformity in the frequency analyses all the depth-area curves were extrapolated to cover an area of 100 000 km^2.

Table 2 Calculation of depth-area curve

Isohyet (mm)	Area enclosed (km^2)	Incremental area (km^2)	Ave. rain (mm)	Volume of rain ($10^3 m^3$) incremental	total	Depth of rain (mm)
175	0					
160	590	590	167	98 530	98 530	167
140	1330	740	150	111 000	209 530	158
120	7560	6230	130	809 900	1 019 430	135
100	14500	6940	110	763 400	1,782 830	123
80	27500	13000	90	1 170 000	2 952 830	107
60	53800	26300	70	1 841 000	4 793 830	89

6. REGIONAL SUB-DIVISION

Subdivision of the country into meteorologically homogeneous regions is necessary not only so that the storm data can be statistically analysed but also so as to define the areas within which storms may be transposed for design purposes.

The mean annual rainfall map, Fig. 7, provides the primary basis for regionalisation. Areas of low mean annual precipitation (MAP) are less likely to experience the same number or type of storms as areas of high MAP. As the major proportion of the MAP in SWA/Namibia is generally made up of quite a small number of relatively severe storms, it may be concluded that, compared with an area of high MAP, a low rainfall area experiences either lower frequency of occurrence of severe storms or lower rainfall per storm event or both.

Fig. 2 shows all the sections for which rainfall data were available, and therefore the area for which storms could be analysed. Owing to the rapid fall-off in MAP from east to west it would not be permissible to transpose storm data from the interior to the coastal region. An approach to design storm determination in the coastal region is discussed later. In the remainder of the country MAP increases from south to north so that regional boundaries could coincide with lines of latitude.

To establish an optimum number of regional sub-divisions, however, three options were tested:

i) the whole country was treated as a single region,
ii) the country was divided into two regions by the 22^{o}S line of latitude,
iii) the country was divided into three regions by latitudes 21^{o}S and 24^{o}S.

Comparison of the results indicated that sub-division into two regions, apart from the coastal strip, was satisfactory (see Fig. 8).

7. DEPTH-AREA-DURATION-FREQUENCY ANALYSIS

The prerequisite of data homogeneity has been discussed but some attention must be paid also to the statistical independence of the events to be analysed.

In the process of storm selection, which was aimed at choosing all the major storms that had occurred in the thirty-year period 1947 - 1976, it follows that in some of the wet years more than one event would have been abstracted for analysis while in some of the drier years no events were accepted. In the analysis of events such as floods and droughts (which are resultant rather than causative events) it is usual to select events that are separated by a stated minimum time period, to ensure mutual independence. In the current study all storms were deemed to have been independent events since it is a matter for conjecture whether either onset or magnitude of a storm is significantly influenced by the occurrence of an event a week or so beforehand.

The storm data abstracted therefore conform to the requirements of a partial duration series as distinct from an annual series (requiring selection of a single event for each year). Unless one is concerned with events of high frequency (low return period) the difference between the recurrence interval or return period (measured in years) determined by the two sampling procedures is small. If T_a and T_p are return periods based on the annual series and the partial duration series respectively, then, at relatively large values, $T_a - T_p$ is approximately half a year (Langbein, 1949). For example, an event estimated from a partial duration series to have a return period of 50 years would be found to have a return period of 50,5 years if calculated from the annual series.

Choice of frequency distribution was facilitated by plotting the ranked storm data on a variety of probability papers. The results indicated the most appropriate to be the Gumbel distribution for which the cumulative density function (c.d.f.) is given by:

$$f(x) = -a + cy \qquad \text{.................... (2)}$$

in which the reduced

variate $y = -\ln\left(-\ln\left(1-\frac{1}{T}\right)\right)$

T = return period

$c = \frac{\sqrt{6}}{\pi}\sigma$

$a = \gamma c - \mu$

σ = standard deviation

μ = mean

γ = 0,57721.... (Euler's constant)

In fitting the data to the Gumbel distribution, the return period T (years) is usually calculated according to the Weibull plotting position formula, viz:

$$T= \frac{n + 1}{m}$$

where m is the rank in the descending array and n the number of years of record analysed. Gumbel probability paper is constructed with co-ordinates to a natural scale for the observed variate f(x) (in this context, depth of precipitation) and on the horizontal axis a non-linear scale in T such that the reduced variate equation (2) plots to a linear scale.

The first step in the frequency analysis of the depth-area-duration curves for each region was to select a range of areas, viz. 100, 200, 500, 1000, 2000, 5000, 10 000, 20 000, 50 000 and 100 000 km^2. For each area, corresponding average precipitation depths were ranked in descending order and assigned plotting positions according to the Weibull formula. A straight line was then fitted to the data for each area and duration to yield the appropriate frequency distribution. Fig. 9 illustrates some typical plots of storm depth against return period. The close agreement of the data points with the fitted straight lines provides visual corroboration of the suitability of the Gumbel c.d.f. to represent the frequency distribution of data of this type.

8. CO-AXIAL DIAGRAMS

For each of the trial regions (see Fig. 8) precipitation values were read from plots such as those in Fig. 9 for recurrence intervals of 5, 10, 20, 50 and 100 years, for each duration (one, three and five days) and for each selected area of storm. The results were condensed for convenience of the user into the single coaxial diagram shown in Fig. 10. Construction of the coaxial diagram follows:

As shown in Fig. 10(a) the three-day depth-area-frequency values for a region are first plotted on semi-log paper without the parametric lines denoting return period. The vertical axis (precipitation to natural scale) is then rotated counterclockwise through 90°. If precipitation is now read on the new horizontal axis, a 45° line through the origin in the second quadrant will represent the three-day duration parameter. To fill in the parameter lines for other durations the procedure is as follows:

On the horizontal lines drawn through each plotting position in the first quadrant, and extended into the second quadrant, as shown in Fig 10 (b), are plotted the equivalent one-day and five-day precipitation depths. Straight line rays are interpolated by eye to represent the duration parameter in the second quadrant. As may be seen, the scatter about these lines is fairly narrow.

As shown in Fig. 10 (c),the positions of the parametric lines representing recurrence interval are then optimized by plotting, in the first quadrant, new positions for the one- and five-day durations such that all scatter about the lines representing duration is eliminated. The process is the same as before, except that one now enters the coaxial diagram in the left-hand quadrant and plots in the right-hand quadrant. There are now three points for each plotting position in the first quadrant and optimum parametric lines of return period can be drawn such that the scatter of the plotted points is minimised, as shown in Fig. 10(c).

Parametric lines for two- and four-day durations are derived by interpolation. The rays in the second quadrant of Fig. 10 are graphical representations of mathematical ratios, provided they pass through the origin - which they do. For any combination of return period and area, therefore, the precipitation depth for a given duration may be expressed as a factor multiplied by, say, the one-day duration depth. If these factors, or ratios, are plotted against duration, a line drawn through the points can be used to interpolate the two- and four-day ratios, which can in turn be employed to construct the corresponding parametric lines of duration. Fig. 11 illustrates such a graph. By plotting duration to a logarithmic scale the growth of rainfall with time can be fairly accurately represented by a straight line.

Final selection of regional boundaries was facilitated by visual comparison of the six coaxial diagrams, i.e. for each of the trial regions depicted on Fig. 8. A marked difference was noted between the coaxial for storms north of 22^{o} and that for storms south of this latitude. However, when the country was split into three regions, there appeared to be a negligible difference between the diagram for the central region bounded by latitudes 21^{o} and 24^{o} and that for the region south of 24^{o}S. It was therefore decided, at least for the interior, to adopt a sub-division into only two regions, viz. north and south of latitude 22^{o}S. The coaxial diagrams applicable to these two regions are presented as Figs. 12 and 13. Fig. 14 is the coaxial diagram based on analysis of all storms in SWA/Namibia, i.e. without regional sub-division. Information from this diagram was employed to derive a general curve relating areally averaged rainfall to point rainfall. Derivation of this curve is explained presently.

9. EXTENSION OF POINT RAINFALL ANALYSIS

HRU Report no. 3/79 described in detail the analysis of daily maximum point rainfalls for SWA/Namibia, resulting in the presentation of the coaxial diagram from which can be estimated extreme rainfalls of durations ranging from six minutes to one day for return periods from two to a hundred years. It is necessary now to extend the point rainfall study to cover durations of up to five days so that point rainfalls can be compared with areally averaged rainfalls over a full range of storm durations.

Analysis of three- and five-day rainfalls at each station proceeded along similar lines to those described for the one-day extremes in HRU Report 3/79. Since a relationship had already been established in the earlier study between MAP and extreme one-day rainfall, the precipitations during storms of longer duration were related to the one-day rainfall in the same way. For each record analysed the 3-day to 1-day and 5-day to 1-day ratios were computed for return periods of 2, 5, 10, 20, 50 and 100 years. Although there appeared to be, on average, a slight increase in the ratios with increasing return period the trend was sufficiently slight to be ignored. There was, however, a significant tendency for stations having relatively high MAP to exhibit higher ratios than those for stations having low MAP, although there was appreciable variation from station to station (see Fig. 15).

Notwithstanding the fairly wide scatter of points on Fig. 15 the trend of increasing multiple-day rainfall with increasing MAP is logical from a consideration of the causative precipitation. In areas of very low MAP, atmospheric conditions favourable for rain are not likely to persist for very long. As one proceeds into areas of higher and higher MAP, conditions for more prolonged rain are bound to be enhanced. A simple analysis of average numbers of rain days (per year) at locations of differing MAP would illustrate the point. Further proof could be had from comparison of the coaxial diagrams, Figs. 12 and 13. The left-hand quadrant of Fig. 12 (northern or high rainfall zone) indicates a more rapid increase of rainfall with storm duration than does Fig. 13 which is applicable to the southern or low rainfall region.

The smooth curves in Fig. 15 result from fitting to the data equations of the form

$$y = a + b \log x \qquad \text{................. (3)}$$

where y is the ratio of the multiple-day to the one-day rainfall
x is the MAP and
a and b are constants associated with a particular duration.

Curves for two- and four-day ratios were interpolated on graphs similar to Fig. 11 for a range of MAP values.

Finally, Fig. 16 was constructed. The upper two quadrants of this four-quadrant coaxial diagram are an exact replica of Fig. 10 from HRU Report no. 3/79. The lower two quadrants, based on relationships determined by the present analysis, enable one to estimate point rainfall for any recurrence interval anywhere in SWA/Namibia for durations of two to five days.

0. AREAL REDUCTION FACTORS

A simplified approach to storm design is to estimate an areal reduction factor (ARF) which, when applied to the appropriate point rainfall value for the given return period, will yield the average precipitation over the problem area. This method is best suited to relatively small areas (up to say 1000 km^2). As a large-area storm analysis was not possible for the coastal strip, because of inadequacy of data, the method just described offers a way out for this region. The method of computing ARF follows.

First, the highest point rainfall at the peak of each storm cell was identified for all storms analysed. Next, point rainfalls (for each duration) were ranked in descending order, assigned plotting positions and plotted on Gumbel paper as shown on Fig. 17. The fitted lines can be construed as frequency distributions of rainfall averaged over a zero area, as distinct from those for finite areas as displayed on Fig. 9.

The coaxial diagram, Fig. 14, depicts the results of a depth-area-duration-frequency analysis of all storms studied and can therefore be compared with the depth-duration-frequency analysis of maximum point rainfalls indicated by Fig. 17. Average rainfalls over areas ranging from 100 to 100 000 km^2 and return periods from 2 to 100 years were read from Fig. 14 for durations of one, three and five days. Comparison with equivalent point rainfalls (Fig. 17) revealed no correlation between ARF and return period. Furthermore, the computed ARF's appeared to be independent of duration, hence the only parameter influencing ARF was the obvious one, namely area. Fig. 18 depicts the relationship between ARF and area. Although the curve is extended to cover areas up to 100 000 km^2 it would be unwise to adopt this method for such large areas (see later). In any event areas of interest along the coastal strip, for which this graph is primarily intended, are unlikely to exceed a few thousand square kilometres.

11. DESIGN APPLICATIONS

A comparison between the point rainfall diagram (Fig. 16) and the coaxial diagrams for the two regions (Figs. 12 and 13) reveals what, at first glance, appears to be an anomaly. For comparatively small areas the regional graphs yield higher rainfalls for given return periods than those given by the point rainfall diagram. The reason can be ascribed to differences of approach between the analysis of large-area storms (the regional method) and that of small-area storms (the point-rainfall method). The two methods are described in what follows.

Regionalization in the inland area implies that a storm in one of the regions could have occurred anywhere within the boundaries of that region. When designing a storm over a particular area of interest (e.g. river catchment area), the inherent assumption in using coaxial diagrams such as Figs. 12 and 13 is that all storms in that region were centred over the area of interest. This assumption is bound to lead to over-design especially on relatively small areas. As the area increases, however, the degree of over-design diminishes and tends to zero as the storm area approaches that of the region as a whole.

By contrast, the point rainfall-ARF approach would tend towards under-design, especially as the storm area increases because the inherent assumption now is that only storms centred on the area of interest are relevant. This can be explained by the fact that point rainfall analyses are confined to falls measured by a single gauge, whereas heavier falls occurring possibly as near as a few kilometres away may have been ignored.

The two different methods of storm design therefore represent diametrically opposed approaches. The storm region method allows maximum flexibility in storm transposition whereas the point rainfall-ARF method permits no transposition whatever. An accurate way of overcoming the problem would be to re-analyse all the major storms situated - but not necessarily centred - over the area of concern. The depth-area calculations would have to be confined of course to events within the boundaries of the problem area. The process would be extremely tedious and probably not worth the extra accuracy achieved.

It is therefore important that for the design of small-area storms the point-rainfall-ARF method (Figs. 16 and 18) should be given the greater weight whereas when designing large-area storms the user should give maximum weight to the appropriate regional coaxial diagram (Figs. 12 or 13).

Fig. 19 is offered to assist the designer to accord weights suitable to results derived from the two different methods. An example of how Fig. 19 may be employed is described below. (In the coastal region one would have no option but to refer to Figs. 16 and 18).

Example:

Estimate the 1:50 year one-day rainfall averaged over a 5000-km^2 area situated in the Southern region of SWA/Namibia where average MAP is 200 mm.

1)	50-year point rain (Fig. 16)	: 120 mm
	ARF (Fig. 18)	: 0,71
	∴ Average rain	= 0,71x120 = 85 mm
2)	Average rain - South region (Fig.13)	: 110 mm
3)	Weighted average (Fig. 19)	= 85x0,32+110x0,68
		= 102 mm

DOCUMENTATION

Appendix A contains the user's manual for program SOFTA and other relevant documentation.

Appendix B comprises a library of storms and should provide valuable guidance to the engineer who may wish to design a large-area storm for flood determination purposes.

ACKNOWLEDGEMENT

Dr. Ann Henderson-Sellers of Liverpool University developed the computer programs employed in this study during her sojourn at the HRU from July - September 1979. She also contributed many valuable ideas on the methodology to be adopted for this research work.

REFERENCES

1. Richardson, B.F.C. and Midgley, D.C. *Analysis of SWA-Namibia rainfall data*, HRU Report No. 3/79 August 1979.
2. Sampson, R.J. *Surface II Graphics System*, Kansas Geol. Survey, Lawrence, Kansas 1975.
3. Langbein, W.B. *Annual floods and the partial-duration flood series*. Trans. Amer. Geophys. Union, Vol. 30, 1949

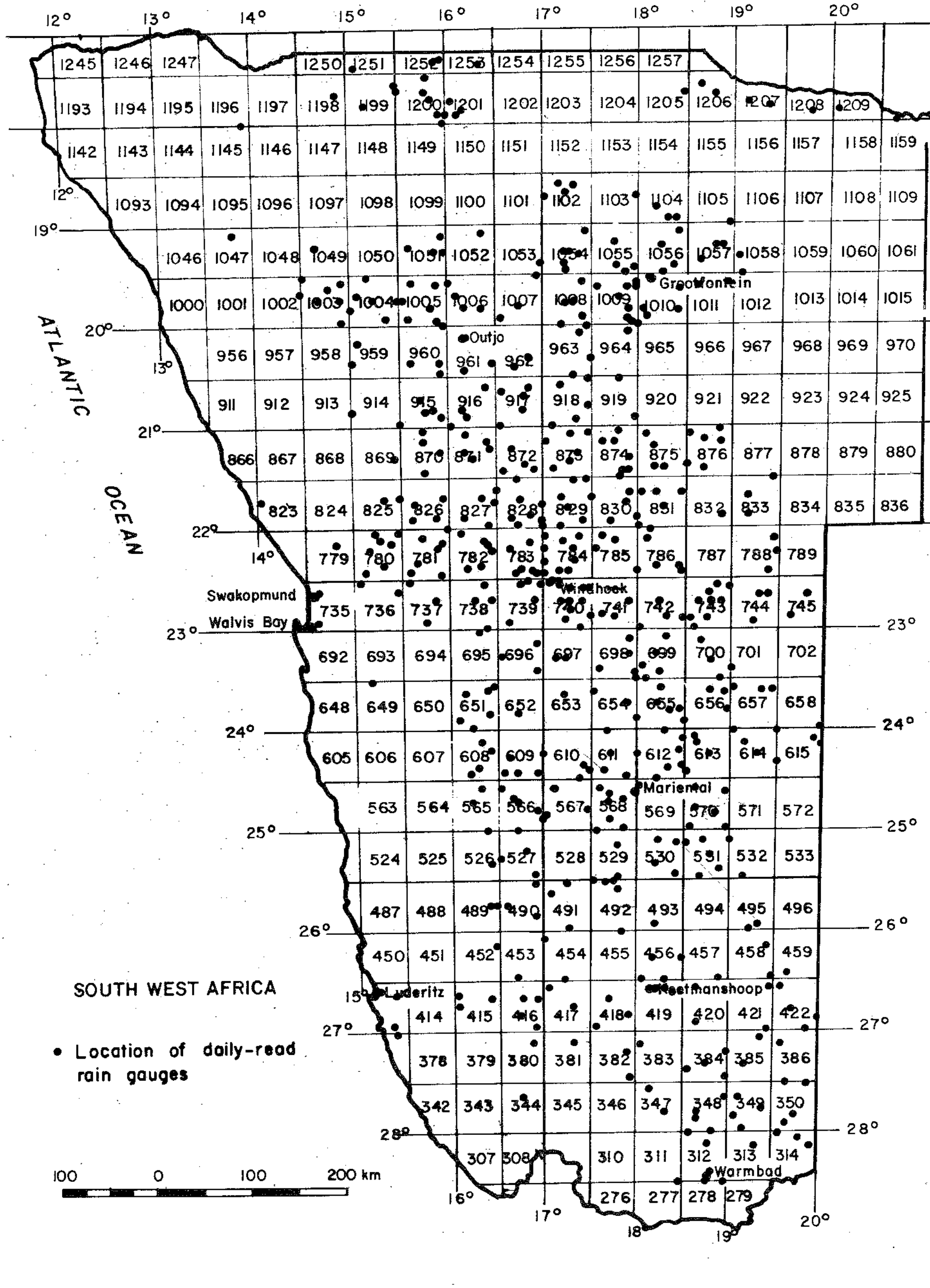


Fig. 1 Distribution of rainfall stations

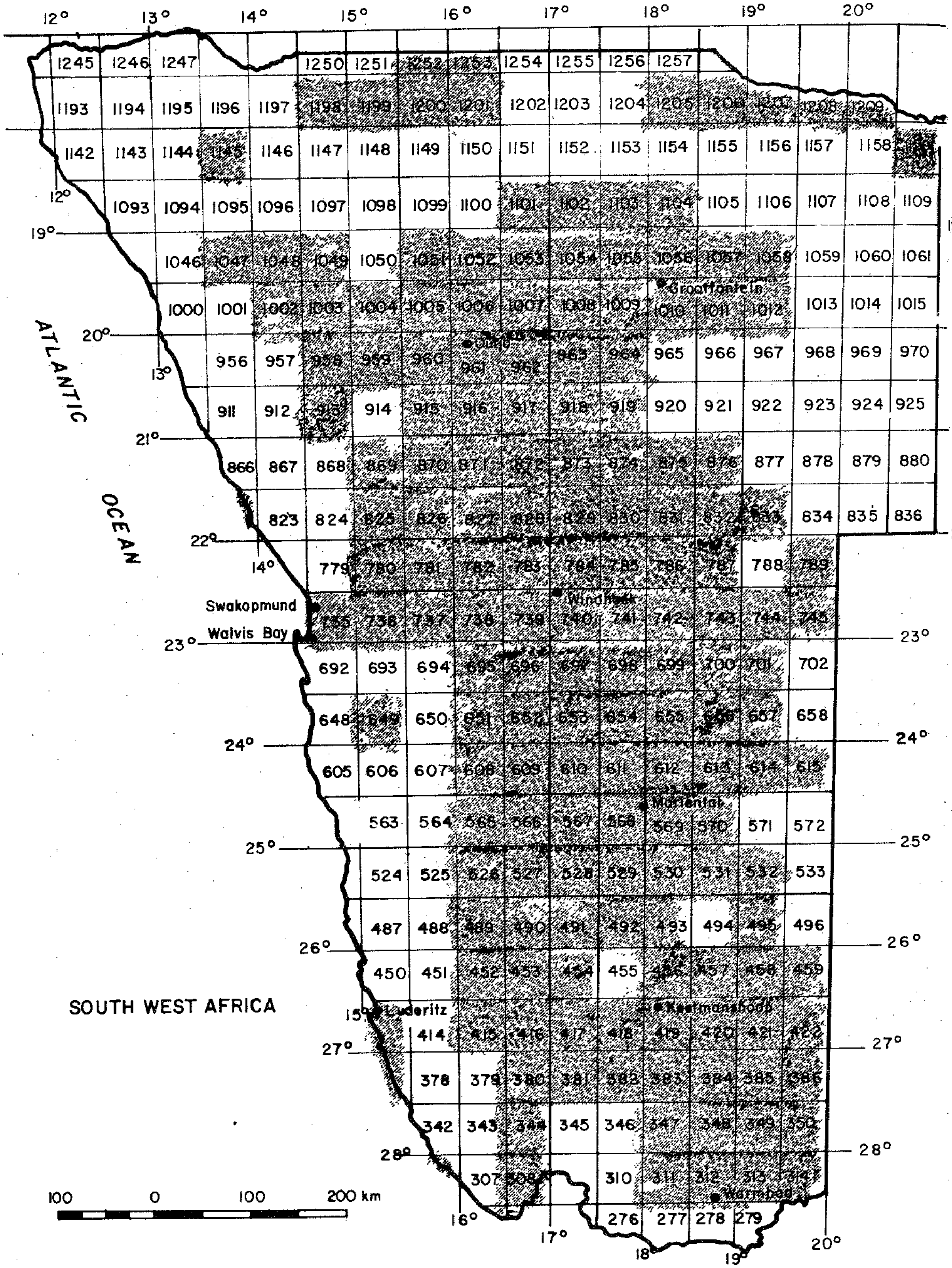


Fig. 2 Distribution of sections with rainfall data

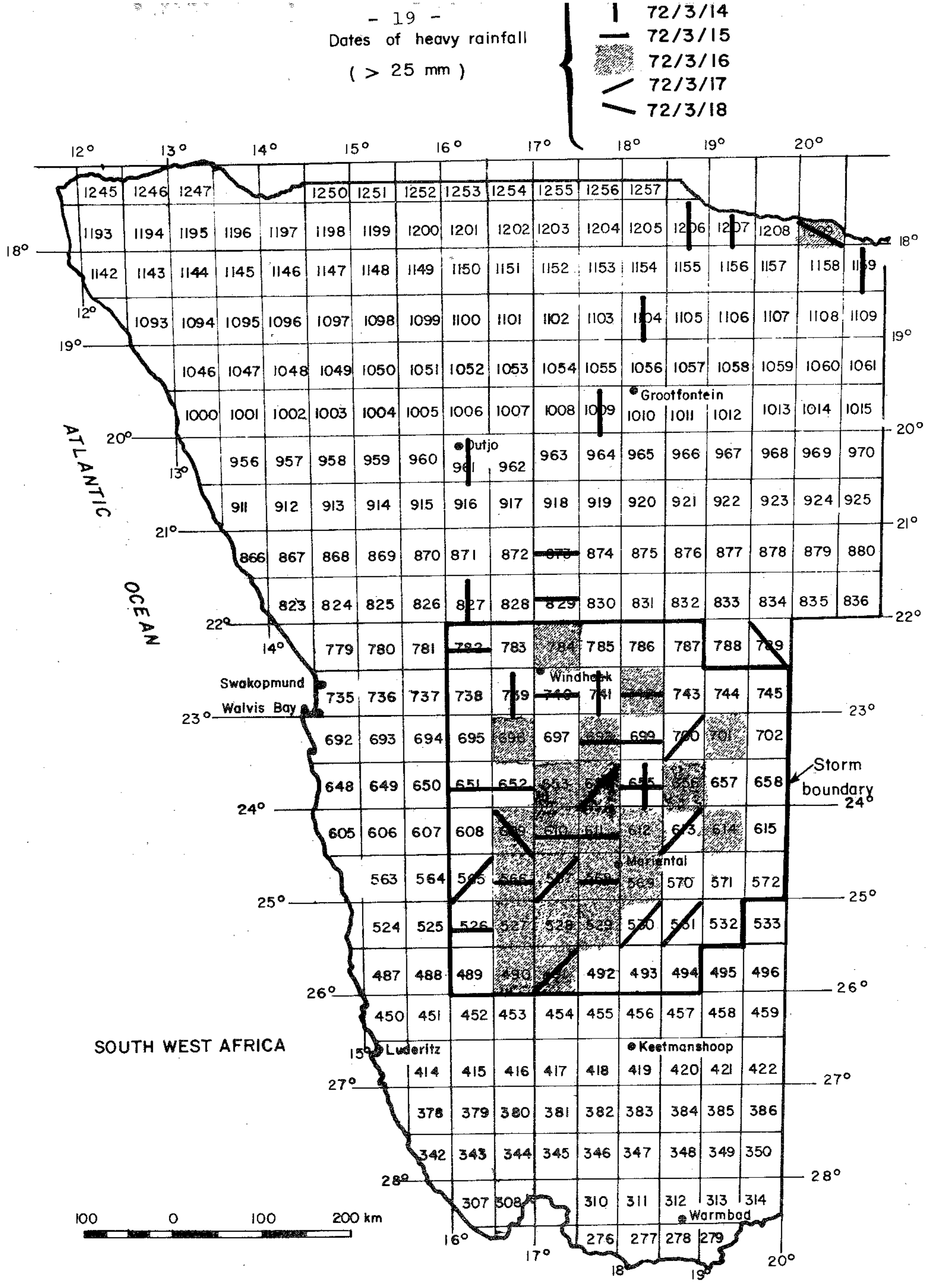


Fig. 3 Example of plot to aid delineation of storm boundary

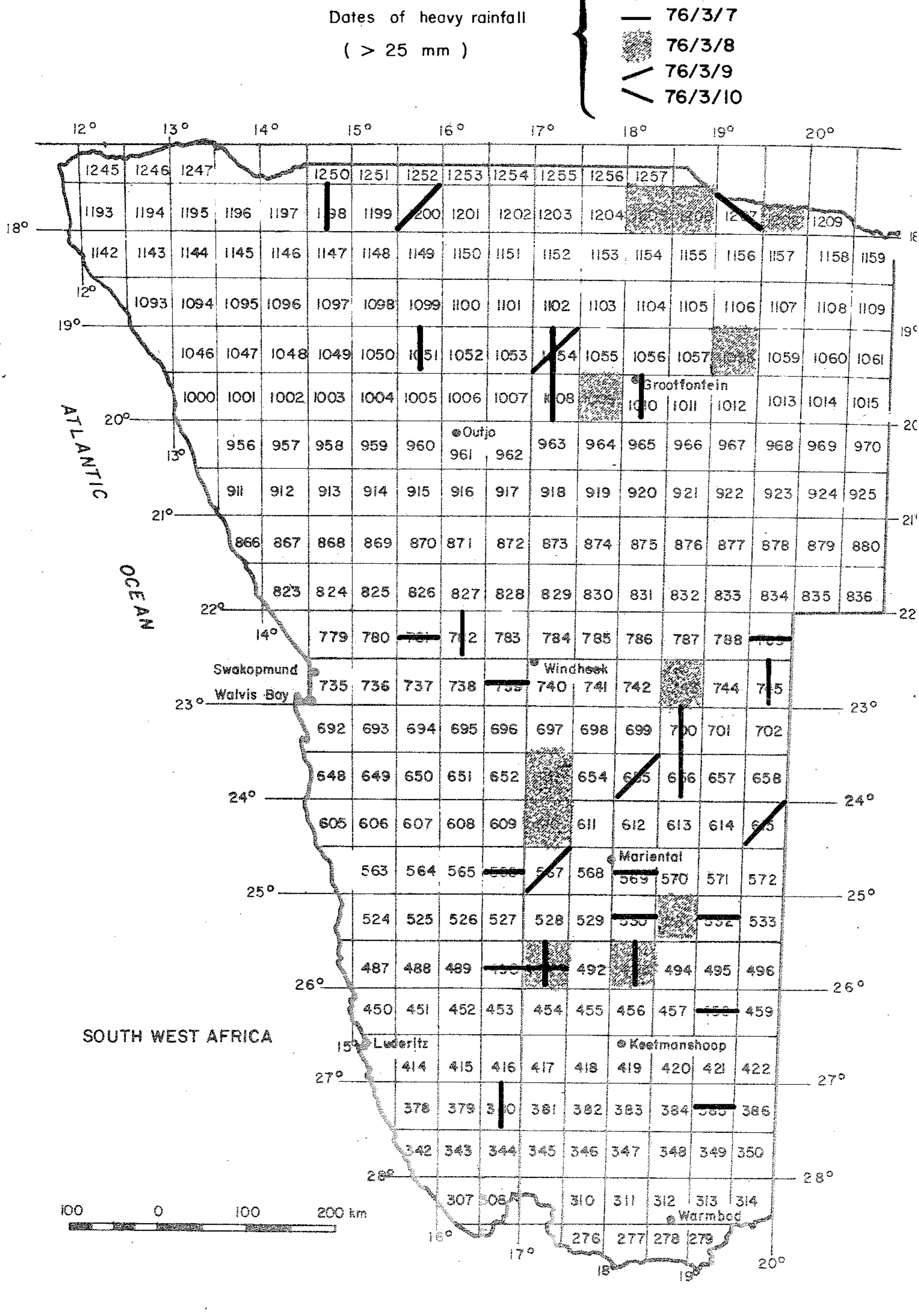


Fig. 4 Example of plot showing rejected storm

SWA THREE - DAY STORM DATE 72/03/16
PLOT NO. 2 DATE 2/21/80 TIME 14:06:21

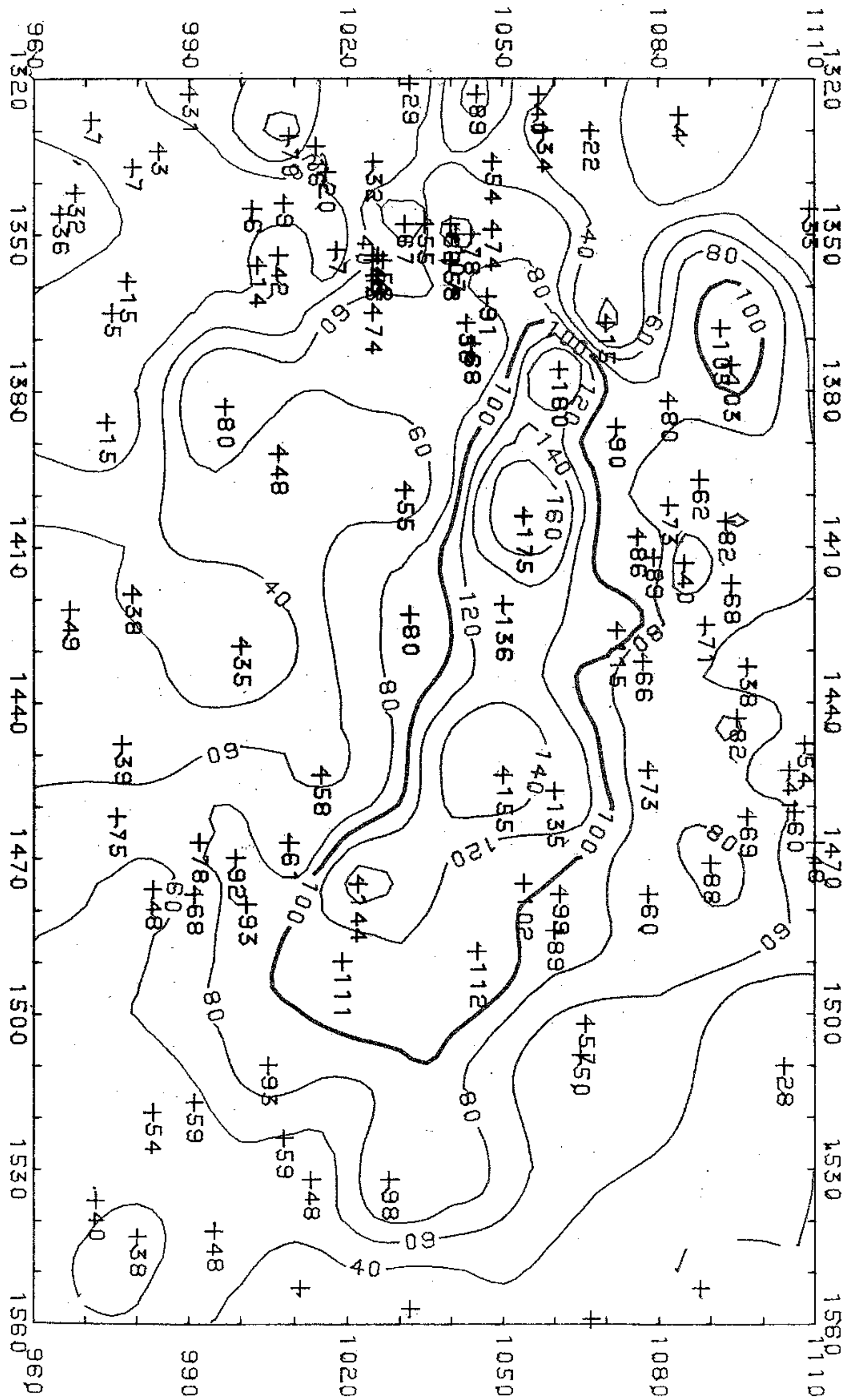


Fig. 5 Example of plot from SURFACE II

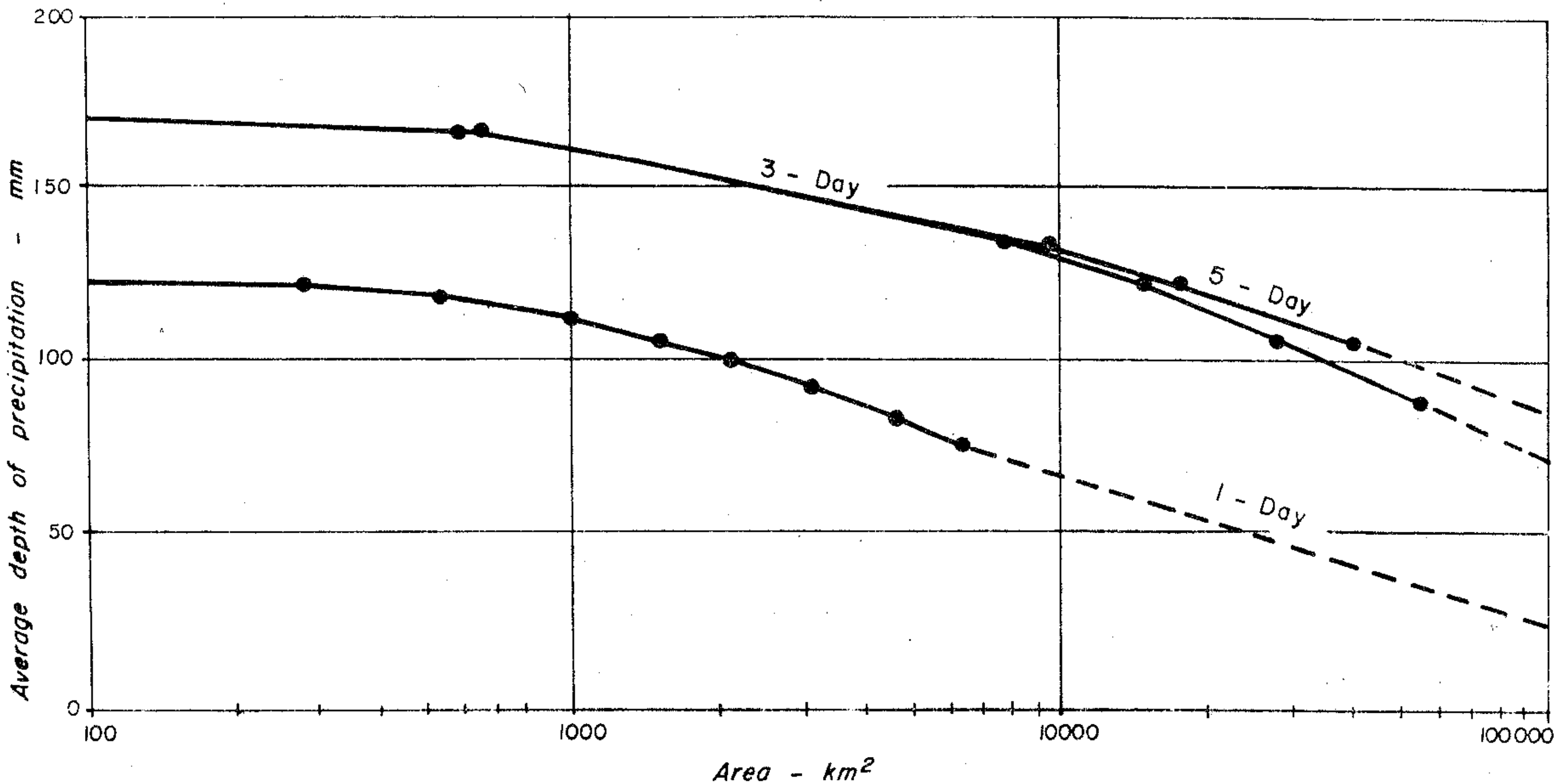


Fig. 6 Depth-Area-Duration curves for storm of 16/3/72

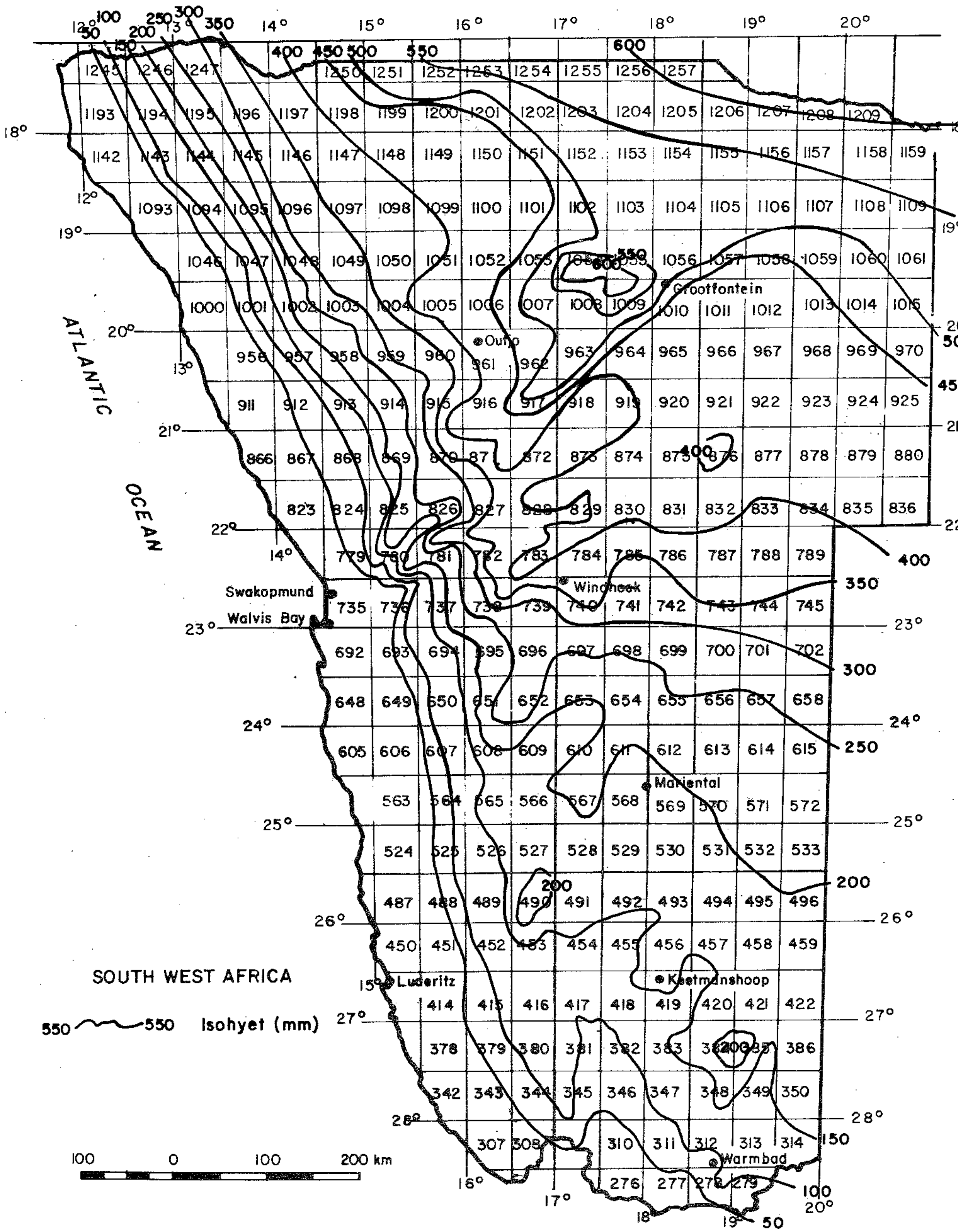


Fig. 7 Mean Annual Rainfall isohyetal map

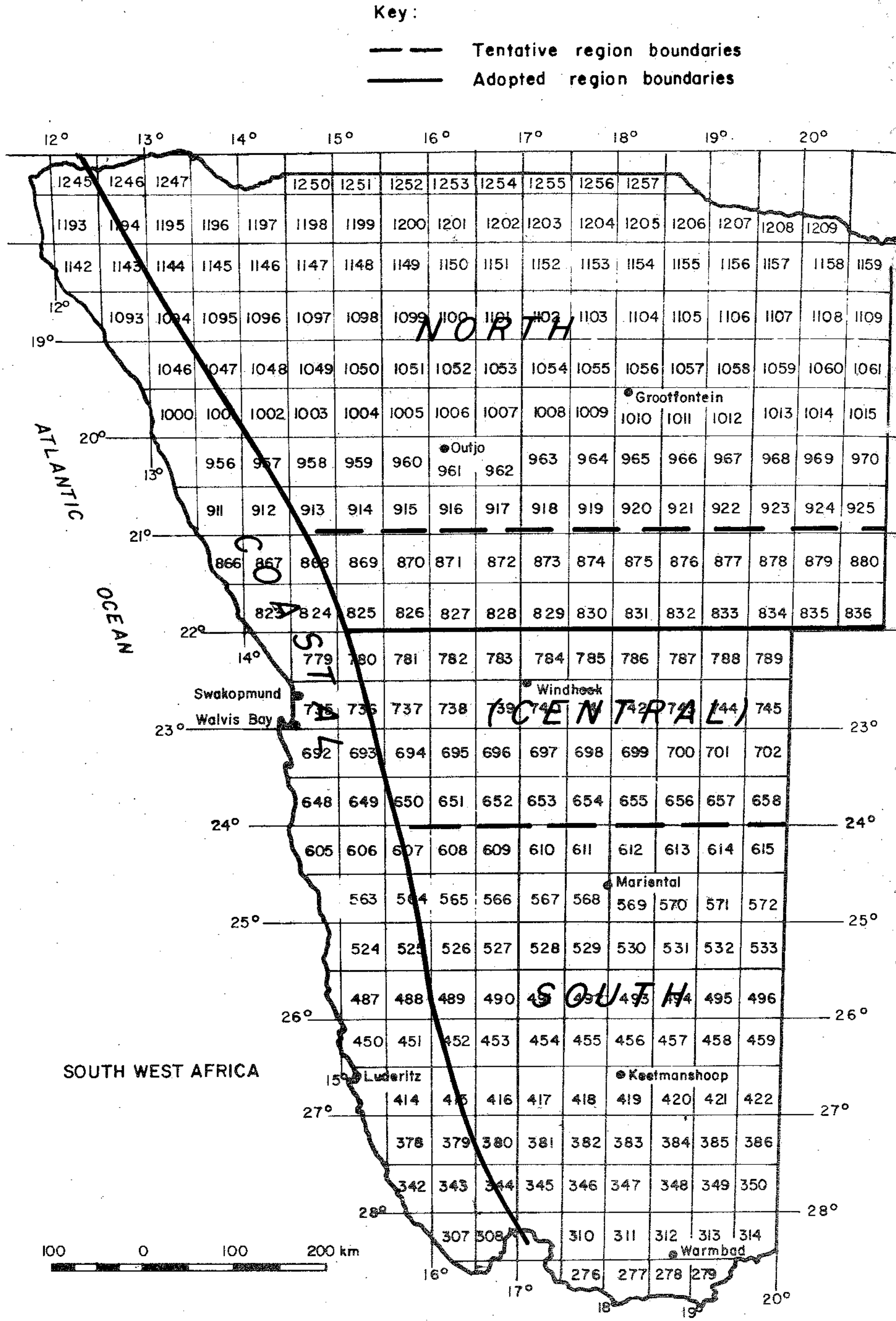


Fig. 8 Regional Sub-divisions

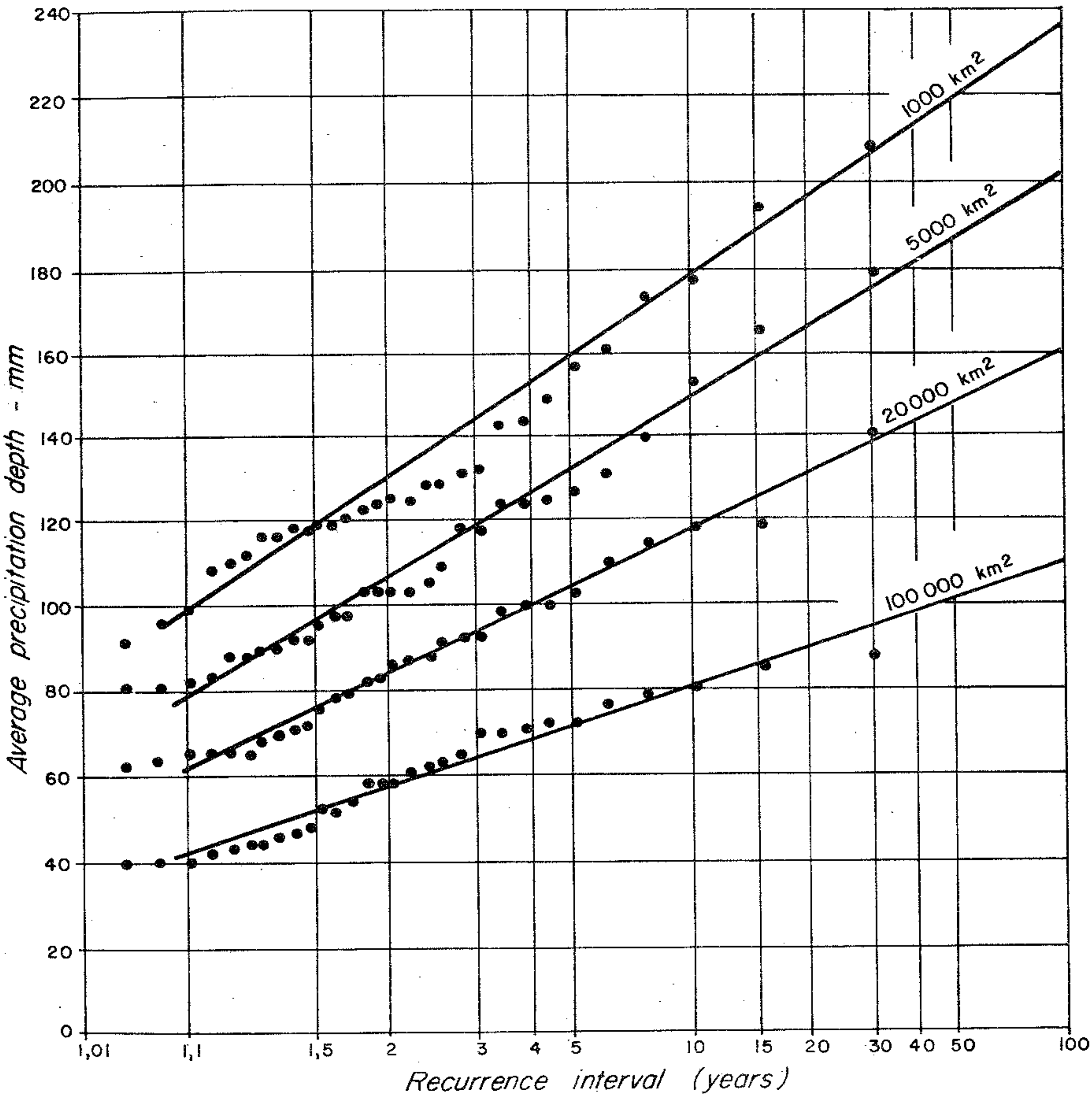


Fig. 9 Example of frequency plot for selected duration with storm area as parameter

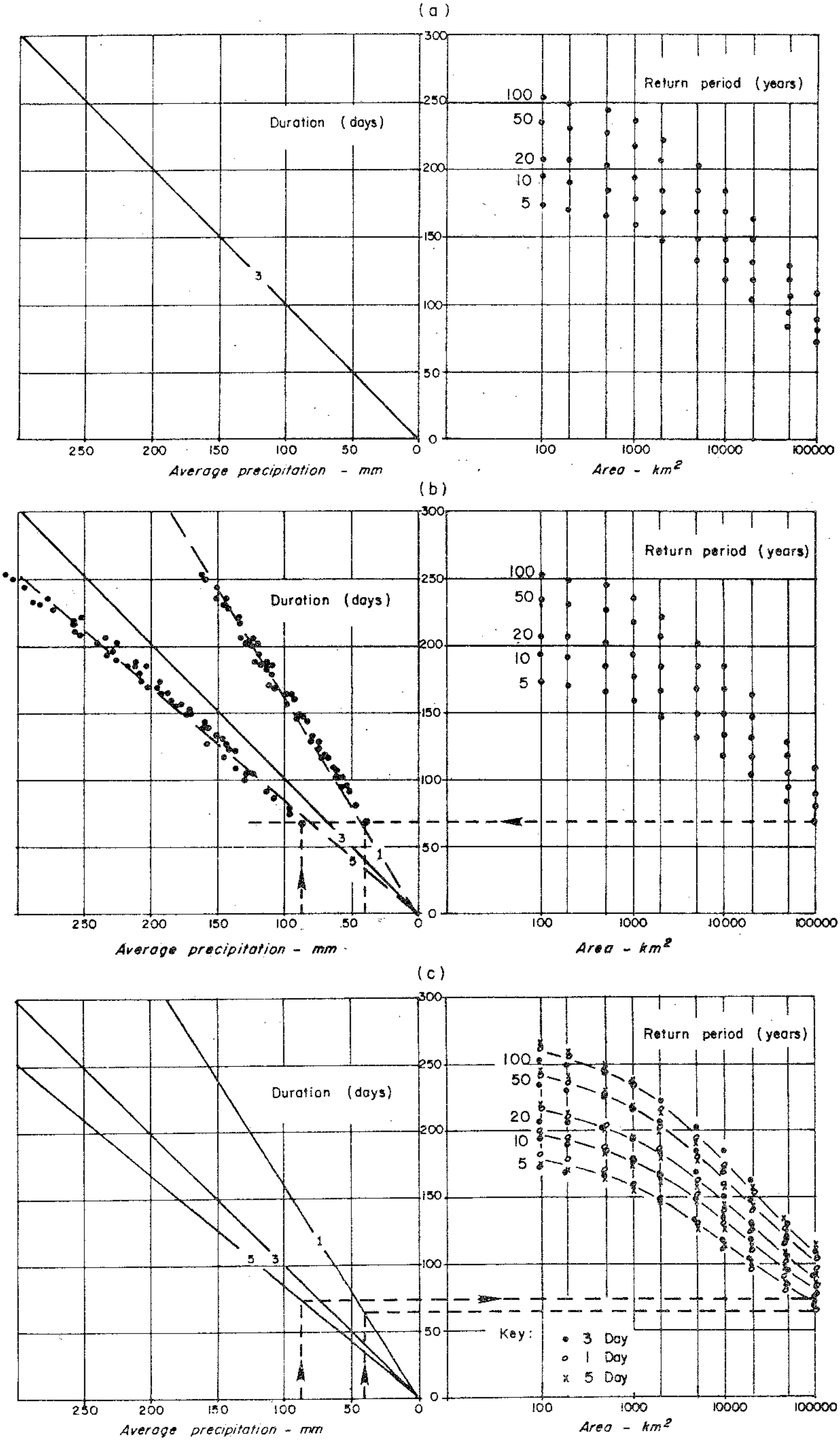


Fig. 10 Construction of co-axial diagram

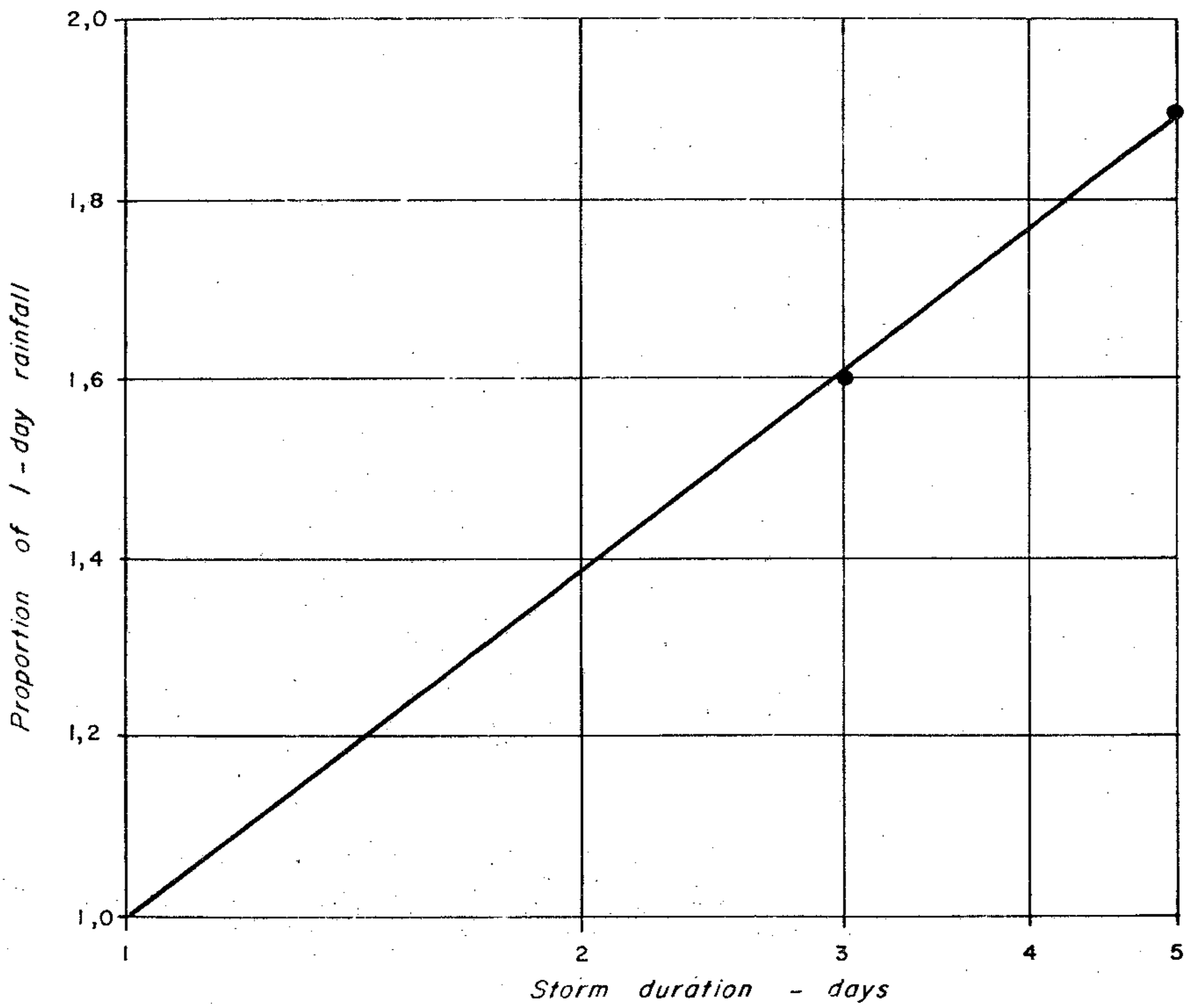


Fig. 11 Interpolation of two- and four-day ratios

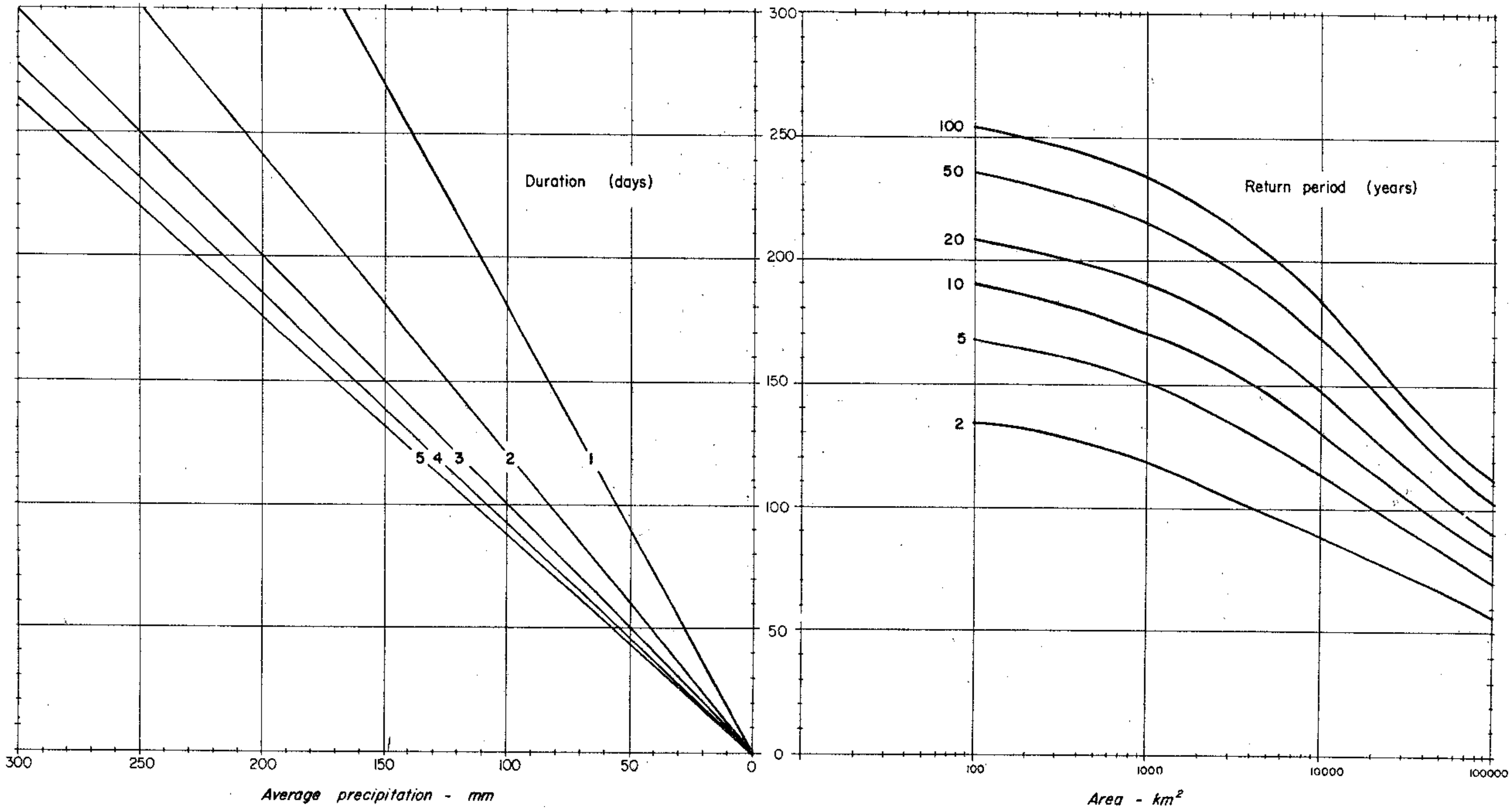


Fig. 12 Depth-duration-frequency-area-relationship: North Region

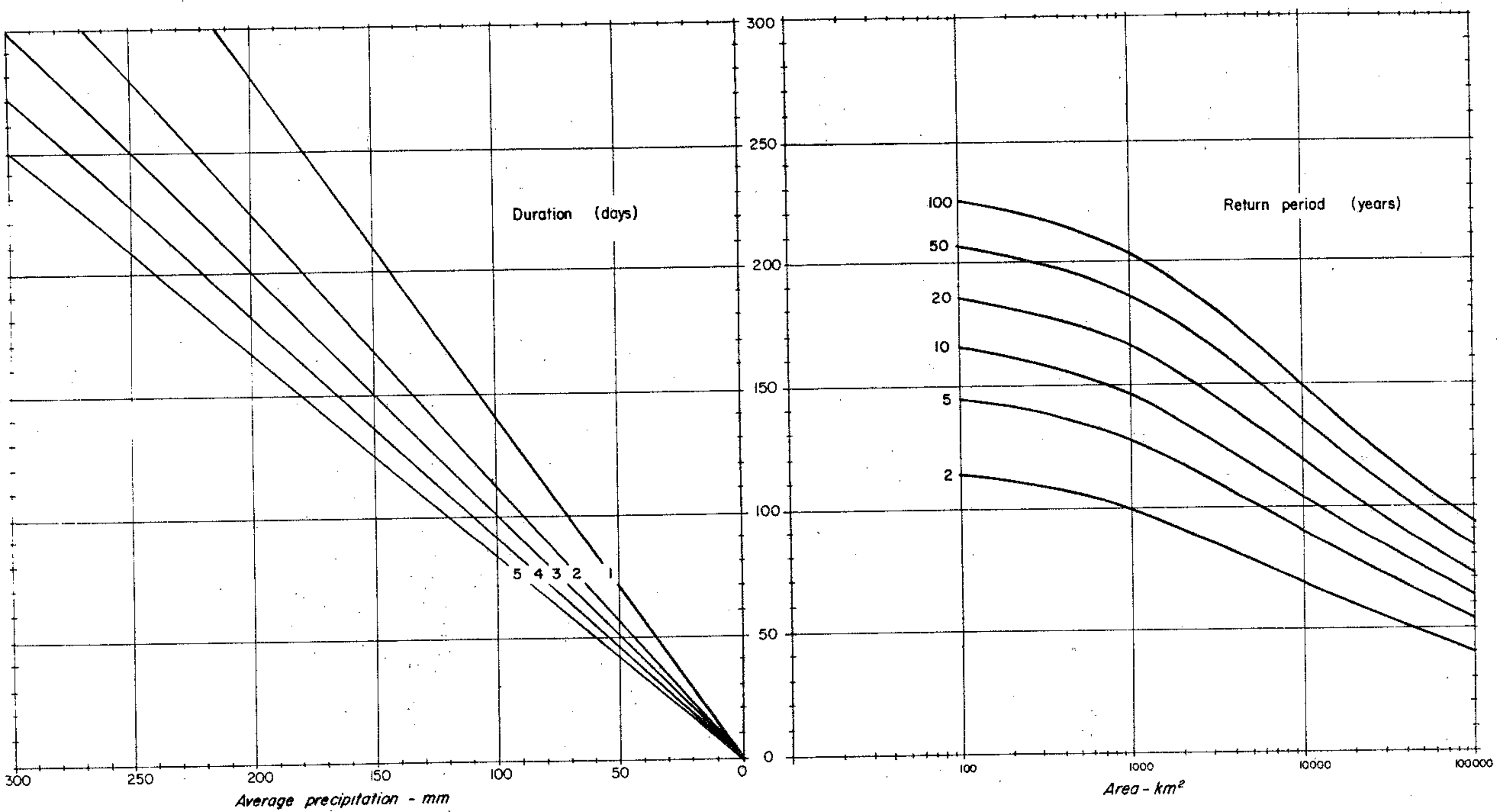


Fig. 13 Depth-duration-frequency-area relationship: South Region

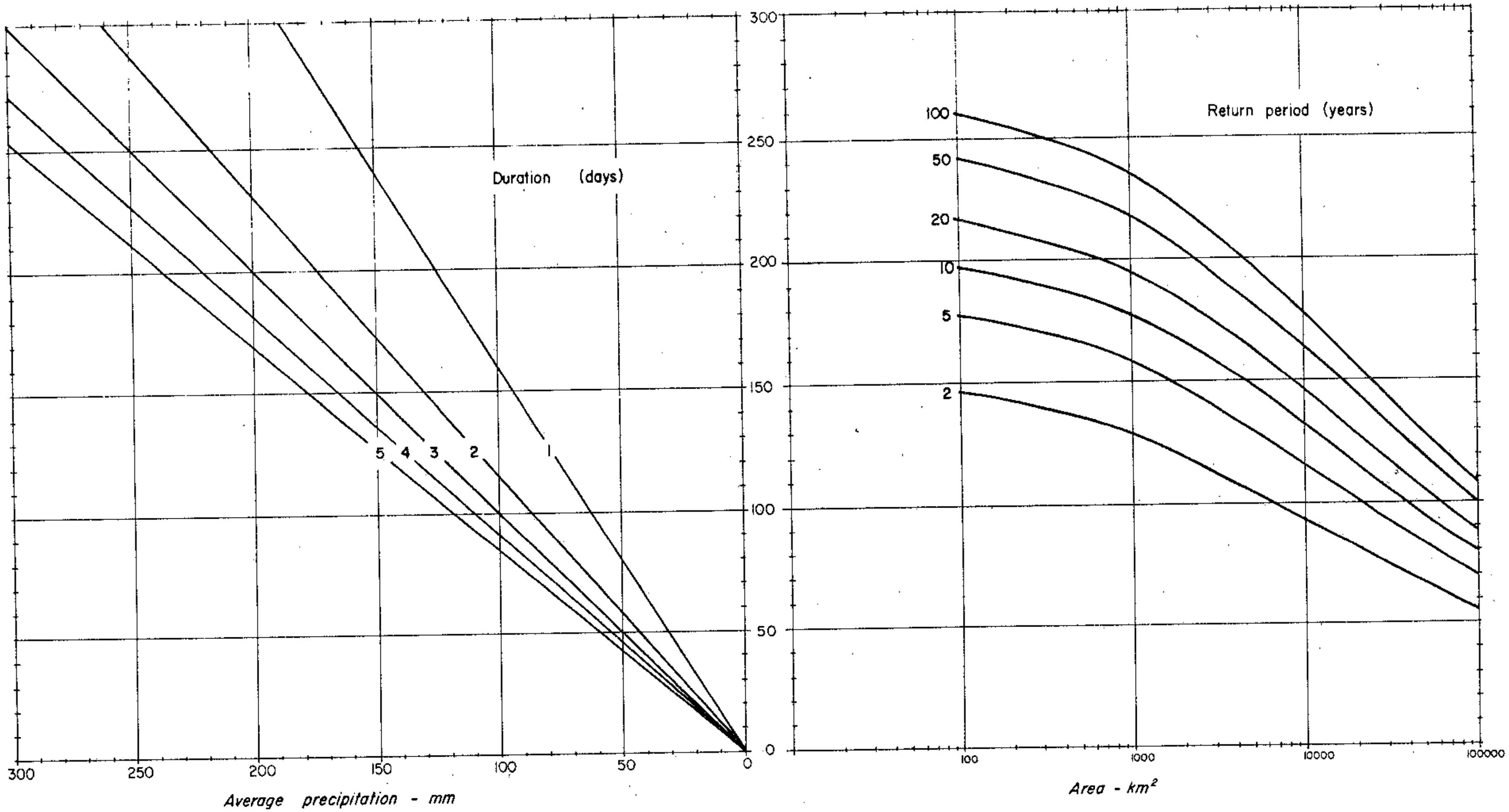


Fig. 14 Depth-duration-frequency area relationship for SWA-Namibia as a whole

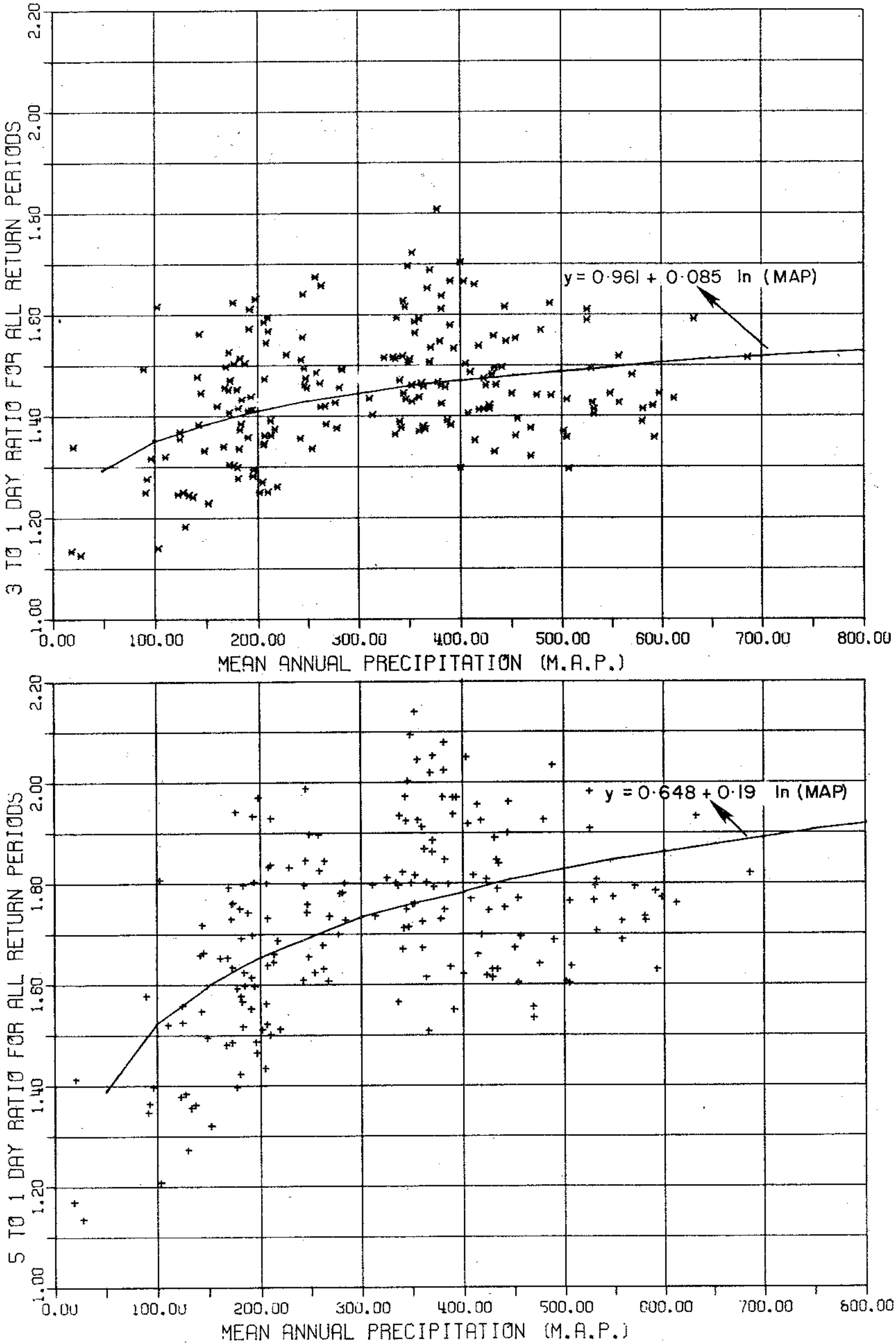


Fig. 15 Ratios of 3-day:1-day and 5-day:1-day point rainfall extremes

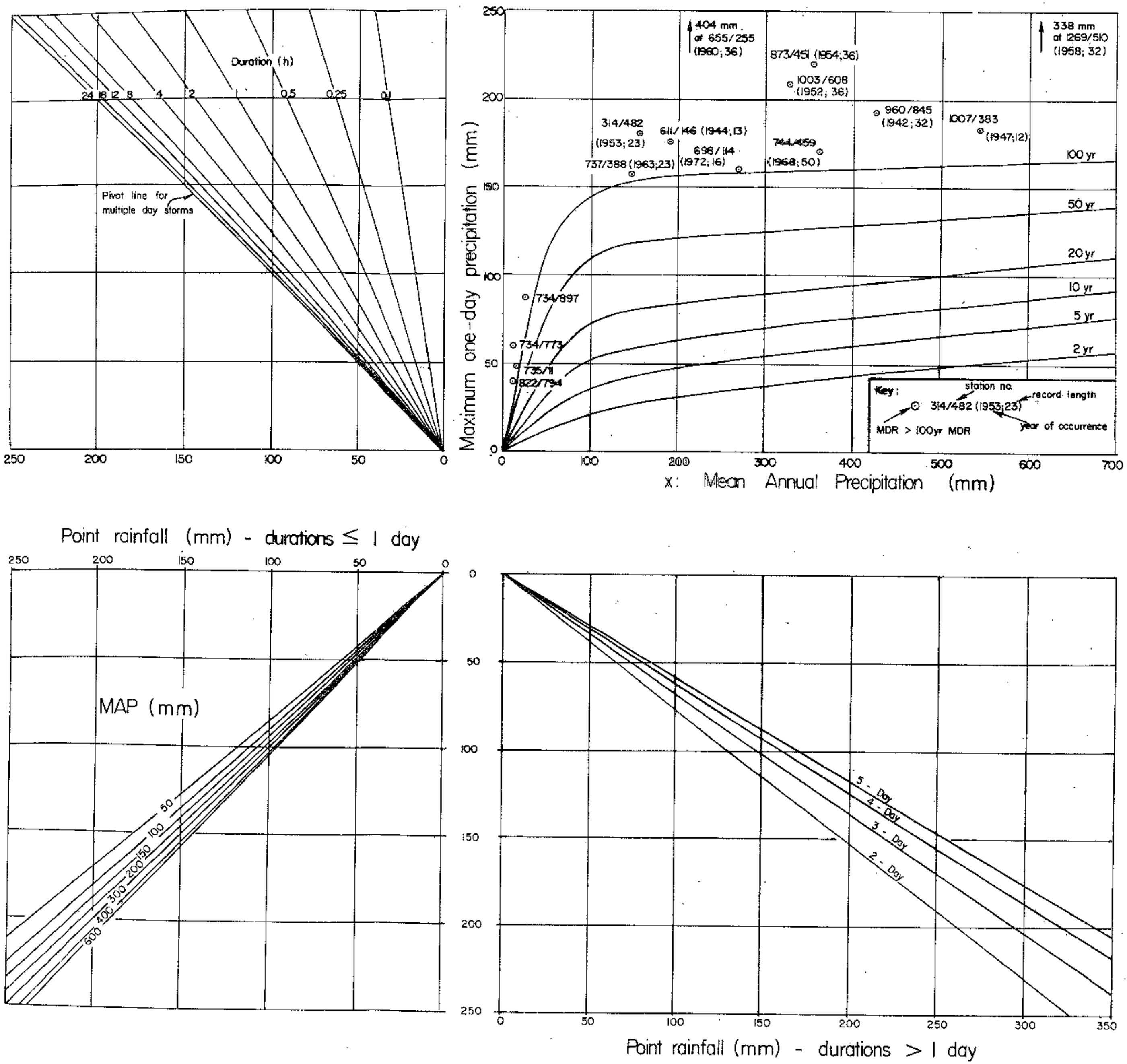


Fig. 16 Depth-duration-frequency relationship for point rainfall

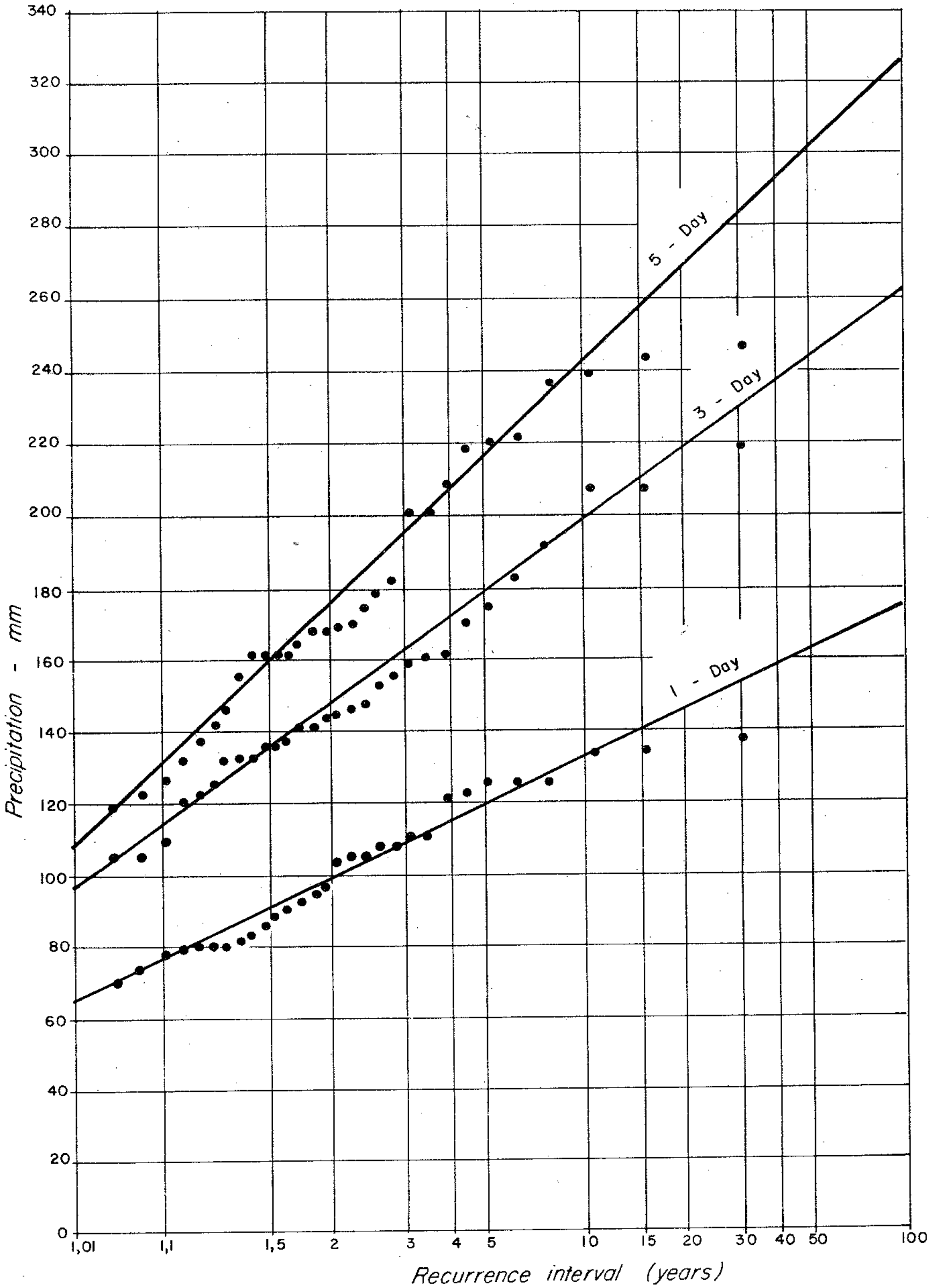


Fig. 17 Frequency analysis of highest point rainfalls in 1-, 3- and 5- day storms

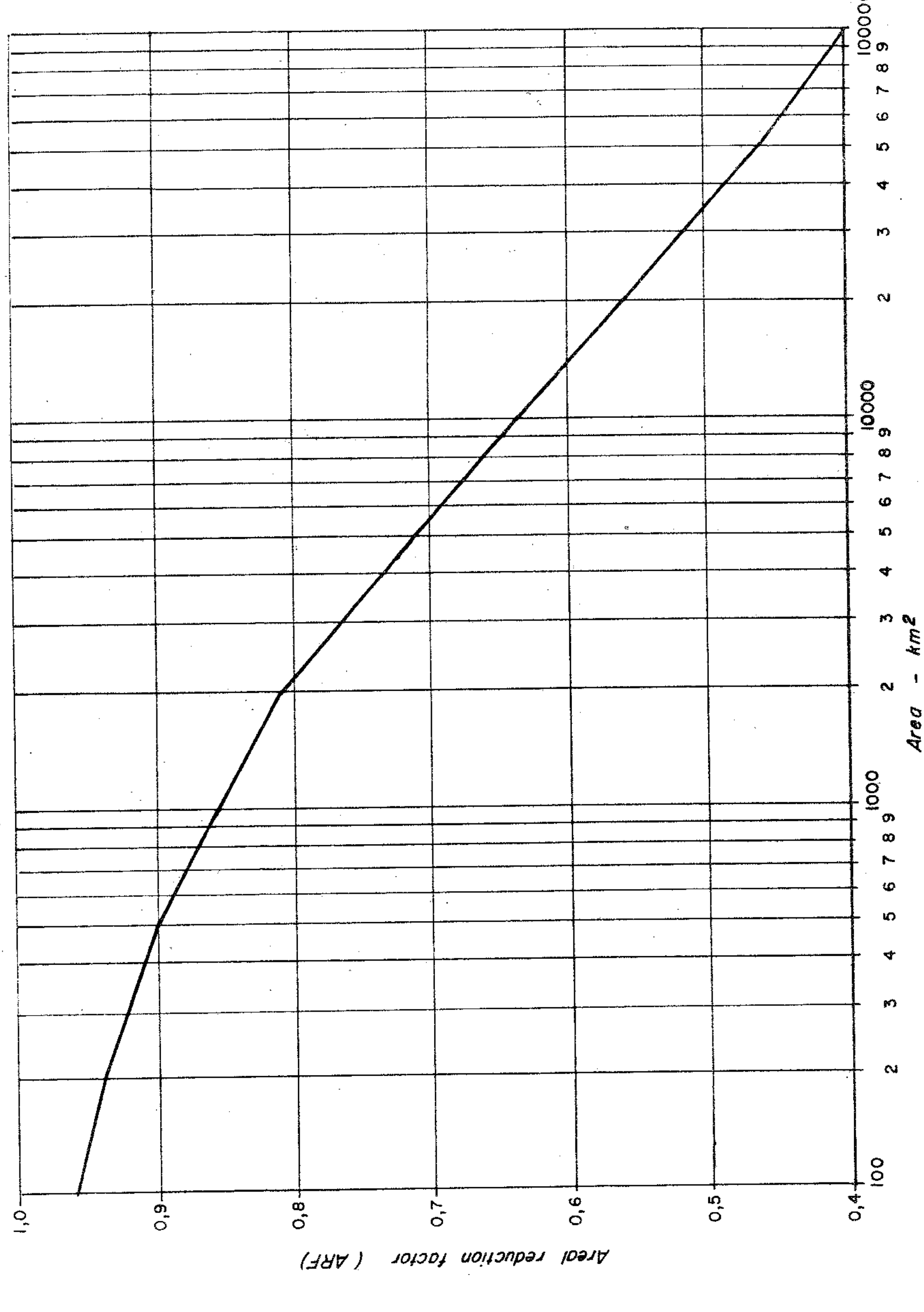


Fig. 18 Area reduction factor

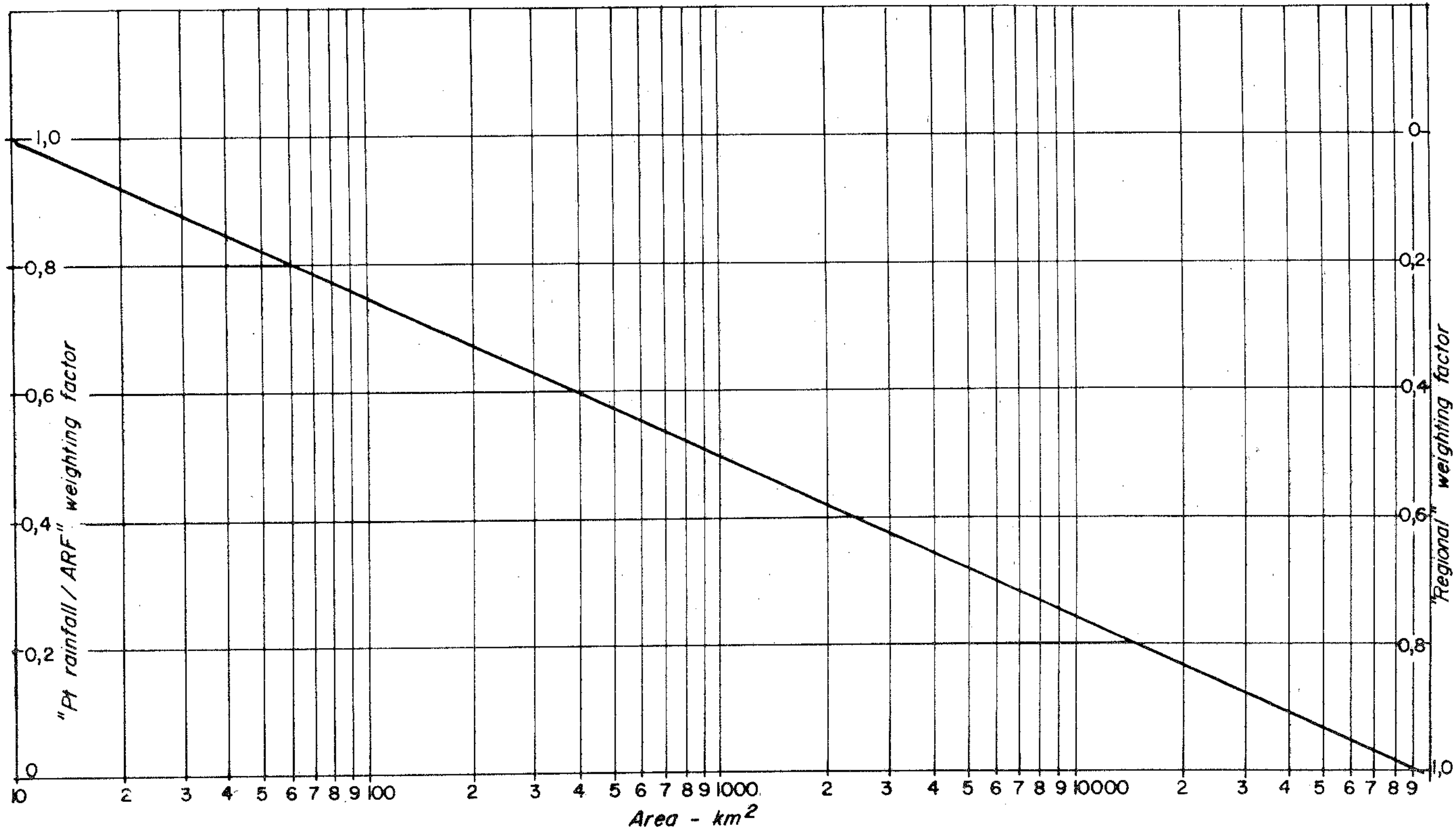


Fig. 19 Weighting Factors "Point Rainfall/ARF" method and "Regional" method

APPENDIX A

COMPUTER PROGRAMS

Three of the computer programs employed in this study were written with the sole object of identifying the date and location of major large-area storms, viz:

- SWSTOR : Scans the tape for daily falls exceeding 25 mm and writes on to disc a matrix with each column constituting a list of dates of heavy rainfall (i.e. >25mm) at a particular representative station.
- RANK : Searches the output file from SWSTOR and writes out, in chronological order, each date of high rainfall and the number of stations recording more than 25mm
- SEARCH : Scans the file created by SWSTOR and picks out stations that yielded more than 25mm on each of five consecutive days.

Output from these programs has been retained on file at the HRU; it is therefore most unlikely that a need will arise for SWSTOR, RANK and SEARCH to be run again. Accordingly, this appendix does not contain detailed descriptions (i.e. user's manuals) of these programs.

Program SOFTA, however, may be used to abstract storm data from the tape for virtually any period and location in SWA/Namibia. For instance, given the dates of known floods at a streamflow gauge, SOFTA can be employed to abstract the relevant data of the causative rainfall over the catchment. Such information would be required to develop design data and modelling techniques for the prediction of flood response in SWA/Namibia.

Output from SOFTA, comprising latitude, longitude and rainfall for each station within a pre-selected boundary, is stored in a format suited to the requirements of the contouring program SURFACE II. Therefore, a brief guide to the use of SURFACE II in the preparation of isohyetal storm maps is presented hereunder. A fully comprehensive user's manual on SURFACE II is to be found in *Surface II Graphics System* (Sampson, 1975).

Operation of program SOFTA

Primary input to SOFTA is the magnetic tape HRUSWA, containing 572 records of daily rainfall. The format of this tape is similar to that of tape SWADRN, described in detail in Appendix B of HRU Report No. 3/79. The sole difference between the two tapes is that SWADRN is a labelled tape (one label per section) whereas HRUSWA is an unlabelled tape.

The other standard input to SOFTA comprises the index of sections situated on the west coast of SWA/Namibia together with the co-ordinates of the north-western corner of those sections. This data set, called ANNINDEX, is displayed in Table A.1.

Table A.1 Data set no. 4 required by program SOFTA (file ANNINDEX)

1	273	1710	960
2	306	1680	930
3	341	1650	900
4	377	1620	900
5	413	1590	900
6	449	1560	870
7	486	1530	870
8	523	1500	870
9	562	1470	870
10	604	1440	840
11	647	1410	840
12	691	1380	840
13	734	1350	840
14	778	1320	840
15	822	1290	810
16	866	1260	810
17	910	1230	780
18	955	1200	780
19	999	1170	750
20	1045	1140	750
21	1092	1110	720
22	1141	1080	690
23	1192	1050	690
24	1244	1020	690

Additional information required by SOFTA is listed in Table A.2. These data, read from file 5, comprise a list of storm dates and a tabulation of sections defining the limits of the area to be searched for storm data.

Table A.2 Input data for program SOFTA

Data set number	Line number	Format	Symbol	Units	Description
2	(Tape HRUSWA)				Rainfall data
4*	1-24	I2	INDEX(L,1)	-	Sequence number
		I5	INDEX(L,2)	-	Section number
		I5	INDEX(L,3)	minutes	Section latitude
		I5	INDEX(L,4)	minutes	Section longitude
5	1	I2	LST	days	Duration of storm
	2-(LST+1)	I2	IYR	years)	
		I2	IMON	months)	Dates of storm
		I2	IDAY	days)	
	(LST+2)	I2	LINES	-	Number of rows of sections
	(LST+3)-	I2	LIMIT(I,1)	-	L.H. section in row
	(LST+LINES+2)	I2	LIMIT(I,2)	-	R.H. section in row

* Data set no 4 is file ANNINDEX, displayed in Table A.1

The source listing of program SOFTA is presented as Table A.3. A typical sample of input data, together with the Job Control Language (JCL) required to execute the program, is listed in Table A.4 and the corresponding output is displayed in Table A.5. The stored output is retained on disc for use by SURFACE II. This output is written to file no. 1 (see JCL in Table A.4).

Table A.3 Source listing of program SOFTA

```
C   **********    MAIN PROG    **  SOFTA   ***   **********
C
      COMMON/ANN/M,N,MM,M4,N1
      DIMENSION LIMIT(15,2),IYR(10),IMON(10),IDAY(10)
C
C
C  READ RAINFALL TAPE ON MM.. MY INPUT ON M ..WRITE ON N
C     TAPE OUTPUT FOR CONTOUR PLOT ON N1=1,  READ INDEX FROM M4=4
C
      M=5
      N=6
      MM=2
      M4=4
      N1=1
      READ(M,9999) LST
      DO 14 L=1,LST
14    READ(M,9998) IYR(L),IMON(L),IDAY(L)
 9998 FORMAT(3I2)
C
C  LIMITS FOR INDIVIDUAL STORM BY SECTION NUMBERS
C     LINES=NO OF ROWS
C
      DO 11 I=1,15
      DO 12 J=1,2
   12 LIMIT(I,J)=0
   11 CONTINUE
      READ(M,1000) LINES
 1000 FORMAT(I2)
      DO 10 I=1,LINES
   10 READ(M,2000) (LIMIT(I,J),J=1,2)
 2000 FORMAT(2I4)
C
C  CHECK
C
      WRITE(N,3000) LINES
      DO 20 I=1,LINES
   20 WRITE(N,4000) (LIMIT(I,J),J=1,2)
 3000 FORMAT(//20X,'CHECK  *******  LINES= ',I2/)
 4000 FORMAT(10X,2I4)
C
C
      IF(LINES.LE.15) GO TO 30
      WRITE(N,5000)
 5000 FORMAT(//1X,'TOO MANY ROWS - STOP')
      STOP
   30 IWID=LIMIT(1,2)-LIMIT(1,1)
      DO 60 I=2,LINES
   60 IF((LIMIT(I,2)-LIMIT(I,1)).GT.IWID) IWID=LIMIT(I,2)-LIMIT(I,1)
      IF(IWID.LE.10) GO TO 40
      WRITE(N,6000)
 6000 FORMAT(//1X,'TOO MANY COLUMNS - TOO WIDE - STOP')
      STOP
   40 CONTINUE
C
      CALL STORM(IYR,IMON,IDAY,LINES,LIMIT,IWID,LST)
      STOP
      END
```

Table A.3 continued

```
      SUBROUTINE STORM(IYR,IMON,IDAY,LINES,LIMIT,IWID,LST)
      COMMON/ANN/M,N,MM,M4,N1
      DIMENSION JYR(900),MON(900),JTOT(900),ND(10),NP(10)
      DIMENSION LIMIT(15,2),LAIN(1500,3)
      DIMENSION INDEX(24,4),IYR(10),IMON(10),IDAY(10)
C
      DATA BL /1H /
C
      ILL=0
      K=0
      IFIN=1
      JSTAF=0
      JSECF=0
      DO 40 I=1,1500
      DO 50 J=1,3
   50 LAIN(I,J)=0
   40 CONTINUE
      IRAIN=2
C
      DO 12 L=1,LST
12    WRITE(N,2000) IYR(L),IMON(L),IDAY(L)
 2000 FORMAT(/5X,'DATE IS ',I3,'/',I3,'/',I3//)
C
C  USE BILL'S METHOD FOR DATA READING
C
C
  600 CONTINUE
      IF(K.LT.899) GO TO 601
      JYR(1)=JYR(899)
      MON(1)=MON(899)
      JTOT(1)=JTOT(899)
      K=1
  601 K=K + 1
      READ(MM,1000,END=999) JYR(K),MON(K),JTOT(K),(ND(I),NP(I),I=1,10),
     1KSEC,KPOS,KYR,KMON,LYR,LMON,B
 1000 FORMAT(2I2,I6,10(I3,I4),T1,2I4,2(I5,I3),2X,A1)
C     IF(JYR(K).GT.80) JYR(K)=JYR(K) - 100
C
      IF(B.EQ.BL) GO TO 800
C
C  HEADER OF SOME TYPE GO TO 800    ELSE DATA
C
      IF(IFIN.EQ.1) GO TO 600
      GO TO 801
C
C  HEADER TEST
C
  800 CONTINUE
C
C  NEW STATION??
C
      IF(KPOS.EQ.JSTAF) GO TO 600
C
C  YES
C
      IF(IFIN.EQ.1) GO TO 700
C     WRITE(N,3011)
 3011 FORMAT(/10X,'NO DATA')
  700 CONTINUE
      IFIN=0
```

Table A.3 continued

```
C
C   NEW SECTION
C
       JSECF=KSEC
       JSTAF=KPOS
C
       ILL=ILL +1
       IF(ILL.EQ.573) GO TO 999
C
C    CHECK FOR LAST SECTION IN AREA
C
       IF(KSEC.GT.LIMIT(LINES,2)) GO TO 999
C
       IF(KSEC.LT.LIMIT(1,1)) GO TO 600
       IYES=0
       DO 51 I=1,LINES
    51 IF((JSECF.GE.LIMIT(I,1)).AND.(JSECF.LE.LIMIT(I,2))) IYES=I
       IF(IYES.NE.0) GO TO 60
       LAIN(IRAIN,1)=0
       GO TO 600
    60 CONTINUE
       LREM=0
C
C      WRITE(N,3010) KSEC,KPOS
  3010 FORMAT(////10X,'SECTION ',I4,2X,'STATION(POSITION)',I4/)
       LAIN(IRAIN,1)=JSECF
       LAIN(IRAIN,2)=JSTAF
       GO TO 600
   301 CONTINUE
C
C   *****  DATA *********
C
C
C
       DO 14 L=1,LST
       IF((JYR(K).EQ.IYR(L)).AND.(MON(K).EQ.IMON(L))) GO TO 825
       GO TO 14
   825 CONTINUE
       LREM=L
C
C   CHECK FOR DAILY
C
       ITOT=0
       DO 20 I=1,10
       IF(NP(I).LT.0) GO TO 22
    20 ITOT=ITOT + ND(I)
       IF(ITOT.GT.0) GO TO 21
C      WRITE(N,2050) JYR(K),MON(K)
  2050 FORMAT(/'************ NO DAILY VALUES 19',I2,2X,'MONTH ',I2/)
       IFIN=0
       GO TO 14
    22 CONTINUE
    21 CONTINUE
C
C   SEARCH FOR DAY
C
       IF(LAIN(IRAIN,1).EQ.0) GO TO 26
       DO 25 I=1,10
       IF(ND(I).NE.IDAY(L)) GO TO 25
       IF(NP(I).LT.0) GO TO 25
C      WRITE(N,3010) NP(I)
       LAIN(IRAIN,3)=NP(I)+LAIN(IRAIN,3)
```

Table A.3 continued

```
C
   26 CONTINUE
   14 CONTINUE
      IF(LREM.NE.LST) GO TO 600
      IFIN=1
      IF(LAIN(IRAIN,1).EQ.0.OR.LAIN(IRAIN,3).EQ.0) GO TO 600
      IRAIN=IRAIN+1
      IF(IRAIN.LE.1500) GO TO 93
      WRITE(N,9300)
 9300 FORMAT(/1X,'ARRAY RAIN TOO SMALL  STOP')
      STOP
   93 CONTINUE
C
      GO TO 600
  600 WRITE(N,6070)
 6070 FORMAT(/1X,'DATA ENDS'/)
      LAIN(1,1)=IRAIN-2
C
C
      DO 62 L=1,24
   62 READ(44,6063) (INDEX(L,J),J=1,4)
 6063 FORMAT(I2,3I5)
C
      MESS=LAIN(1,1)+1
      WRITE(6,4099) LAIN(1,1)
4099  FORMAT(/10X,'LENGTH OF FILE = ',I3/)
C
      DO 61 I=2,MESS
   61 CALL COORD(LAIN(I,1),LAIN(I,2),INDEX)
C
C
      WRITE(N,4000)
 4000 FORMAT(/10X,'RAIN ARRAY',10X,'LAT  LONG RAIN'/)
      DO 60 I=2,MESS
      WRITE(N1,4011) (LAIN(I,J),J=1,3)
 4011 FORMAT(3I5)
   60 WRITE(N,4010) (LAIN(I,J),J=1,3)
 4010 FORMAT(30X,3I5)
C
C
      RETURN
      END
      SUBROUTINE COORD(ISEC,IPOS,INDEX)
      DIMENSION INDEX(24,4)
      DO 10 L=1,24
      IF(INDEX(L,2).LE.ISEC) GO TO 10
      LL=L - 1
      GO TO 20
   10 CONTINUE
      LL=24
   20 LATS=INDEX(LL,3)
      LONS=INDEX(LL,4) + (ISEC - INDEX(LL,2)) * 30
      LONG=LONS + ((IPOS + 29) / 30)
      LATG=LATS + IPOS + 30 - (LONG - LONS)*30
      ISEC=LATG
      IPOS=LONG
      RETURN
      END
```

Table A.4 Input data and Job Control Language for execution of program SOFTA

```
//RCJSOFTA JOB 12,CLASS=K
/*SETUP          TAPE=(HRUSWA,NO RING,NL)
/*JOBPARM R=43,LINES=9999
//STORM EXEC FORTXCLG,REGION=512K,TIME.GO=20
//FORT.SYSIN DD *
C  **********  MAIN PROG    **  SOFTA   ***  **********
        .
        .
        .
        .
        .
        .
        .          (Source listing of SOFTA: see Table A.3)
        .
        .
        .
        .
     END
/*
//GO.FT05F001 DD *
 3
720315
720316
720317
 8
 489 494
 526 532
 565 572
 608 615
 651 658
 695 702
 738 745
 782 787
//GO.FT02F001 DD UNIT=TAPE,DISP=OLD,LABEL=(,NL),
// VOL=SER=HRUSWA,DCB=(RECFM=FB,LRECL=80,BLKSIZE=6400)
//GO.FT04F001 DD DSN=ACM.HRU012.TEMP(ANNINDEX),DISP=SHR,
// LABEL=(,,,IN)
//GO.FT01F001 DD DSN=ACM.HRU012.TEMP(LT720316),DISP=OLD,
// LABEL=(,,,OUT)
//GO.FT06F001 DD SYSOUT=A
//
```

Table A.5 Output from program SOFTA

```
                    CHECK  *******   LINES=   8

        459 464
        526 532
        565 572
        608 615
        651 655
        695 702
        735 745
        782 787

   DATE IS   72/   3/  15


   DATE IS   72/   3/  16


   DATE IS   72/   3/  17


DATA ENDS

        LENGTH OF FILE = 135

        RAIN ARRAY              LAT   LONG  RAIN

                                 1536   972   404
                                 1543   950   380
                                 1542   995   450
                                 1553  1011   320
                                 1532  1013   455
                                 1532  1025   330
                                 1557  1032   310
                                 1559  1067   390
                                 1553  1058   155
                                 1513   983   545
                                 1517   931   590
                                 1510  1005   332
                                 1524  1003   595
                                 1508  1065   505
                                 1502  1066   575
                                 1510  1104   286
                                 1507  1112   335
                                 1527  1117   155
                                 1500  1139   230
                                 1523  1146   145
```

Table A.5 continued

1476	983	480
1477	991	585
1478	1001	835
1490	1013	1110
1475	1022	1140
1466	1045	1121
1475	1054	1020
1484	1060	800
1477	1061	800
1477	1075	600
1471	1090	860
1476	1117	550
1493	1131	215
1477	1132	368
1462	976	750
1445	977	300
1467	992	750
1470	999	920
1467	1009	610
1454	1015	556
1454	1050	1550
1457	1060	1350
1453	1078	755
1445	1095	820
1462	1097	695
1453	1105	415
1461	1106	600
1448	1108	542
1467	1110	484
1445	1116	605
1455	1123	740
1442	1141	406
1445	1147	335
1456	1154	278
1445	1169	550
1461	1171	250
1447	1183	190
1454	1198	500
1422	967	495
1419	979	365
1423	1000	352
1423	1032	800
1421	1050	1365
1426	1072	1150
1432	1077	660
1412	1079	590
1413	1085	400
1425	1089	710
1417	1094	685
1433	1097	355
1435	1111	495
1417	1125	556
1411	1129	610
1422	1130	480
1431	1136	655
1416	1142	300
1422	1160	350
1336	974	155
1392	1007	455
1389	1031	555

Table A.5 continued

All

1404	1054	1750
1387	1072	900
1408	1076	360
1382	1052	805
1402	1082	735
1397	1088	625
1405	1033	820
1400	1127	555
1404	1141	650
1365	975	53
1359	978	150
1354	1007	420
1353	1018	70
1355	1025	450
1365	1025	742
1355	1040	585
1367	1043	580
1371	1044	680
1362	1047	913
1376	1061	1601
1367	1070	155
1368	1092	1050
1375	1094	1035
1377	1114	555
1369	1122	100
1360	1123	420
1357	1133	344
1368	1135	395
1379	1154	507
1359	1156	420
1375	1175	687
1361	1135	210
1346	965	360
1342	968	320
1337	979	70
1334	984	30
1323	990	310
1345	1002	65
1344	1008	90
1331	1009	705
1333	1014	160
1321	1032	290
1348	1035	550
1348	1040	620
1323	1045	885
1336	1048	545
1330	1058	345
1330	1067	220
1327	1084	45
1345	1109	330
1331	1115	250
1324	1117	200
1343	1119	430
1342	1134	130
1348	1138	210

Operation of program SURFACE II

There are altogether more than sixty user commands associated with SURFACE II. These commands allow the user to specify which plot option to perform, how large to make the display, how to calculate values in the grid matrix, where to find the input data, how to read the data, and so forth. Associated with most commands is a list of parameters, many of which have pre-assigned values and it is not necessary to define them unless the user wishes to change their pre-assigned values.

A brief description of the twelve user commands employed by the author to construct isohyetal storm maps is given in Table A.6.

Table A.6 SURFACE II commands

Command	Description
TITL	Accepts a 60-character alphanumeric phrase which is used to label the printed output and any plots that are produced by SURFACE II.
IDXY	Reads sample data points, ID labels and posting symbols into an array in memory.
BOX	Draws and labels tick marks around the border of a posting or a contour map.
POST	Generates a posting of the sample data points
CINT	Specifies the spacing, annotation and labelling of contour lines.
GRID	Generates a grid matrix of estimated Z values from irregularly spaced X,Y,Z sample data points.
EXTR	Defines the X and Y limits of a grid matrix, or the boundaries of a posting.
SIZC	Specifies the physical size of a contour map or posting created on a plotter.
DEVI	Prepares the plotting device to accept instructions.
CONT	Generates the instructions used by the plotting device to make a contour map from the grid matrix.
PERF	Initials processing of SURFACE II commands
STOP	Halts execution of SURFACE II.

An example of a job set-up to run SURFACE II is presented as Table A.7. The first parameter of IDXY gives the number of data points to be read in (148), while the last parameter is the format of the data - '(2F5.0, F5.1)'. The Box parameters indicate that tick marks should be made every 10 units with every third tick labelled. The third parameter of CINT gives the increment between contours (20mm) while the first three parameters of GRID indicate that the distance between rows and columns of the grid matrix is 5 minutes of arc. The four parameters of EXTR are respectively X-minimum, X-maximum, Y-minimum and Y-maximum of the boundary of the plot (1320, 1560, 960, 1110).

The parameters of SIZC give the scale of the plot as 32 units per inch. The data in the form of latitude, longitude (minutes of arc) and rainfall (1/10 mm) constitutes the stored output from SOFTA (see Table A.5).

Table A.7 Example of job set-up required for execution of SURFACE II

```
//WVPSURF2 JOB 12,CLASS=A,MSGLEVEL=(0,0)
/*JOBPARM R=43
// EXEC SURFACE2
//CONTROL DD *
TITLE  SWA THREE - DAY STORM DATE 72/03/16
IDXY   148,20,3,,,,,,,,'(2F5.0,F5.1)'
BOX    10,3,10,3,
POST   0,0,0.1,0.1,1
CINT   0,0,20,0,1,,0,
GRID   1,5,5,0,
EXTR   1320,1560,960,1110
SIZC   0,32,
DEVICE 5,'BILL',9999,29,,
CONT
PERFORM
STOP
//DATA DD *
 1536  972  404   )
 1543  980  380   )
         .        )
         .        )  X,Y,Z matrix produced by SOFTA
         .        )        (see Table A.5)
 1342 1134  130   )
 1348 1138  210   )
//                )
```

Table A.8 lists the printed output from SURFACE II, while Figs. A.1 and A.2 display the plotted contour map and posting of data respectively.

Table A.8 Printed output from SURFACE II

```
SWA THREE - DAY STORM DATE 72/03/16                              DATE  3/25/80  TIME 14:12:57

        ********** INPUT X-Y-Z DATA POINTS **********

        THE NUMBER OF INPUT VARIABLES IS      3

        X IS VARIABLE  1
        Y IS VARIABLE  2
        Z IS VARIABLE  3
        IDENT. WILL BE SET TO SAMPLE NUMBER
        NO VARIABLE SPECIFIED FOR MAP SYMBOL

        NO CHECK WILL BE MADE FOR MISSING DATA

        FORMAT OF DATA IS (2F5.0,F5.1)

        THE NUMBER OF DATA POINTS TO BE READ IS    148

        THE X-Y-Z DATA POINTS WILL BE READ FROM FILE  20

        NO SUBSET SPECIFIED

        ************************************************

        THE X-MINIMUM OF X-Y-Z DATA IS          1321.00000000
        THE X-MAXIMUM OF X-Y-Z DATA IS          1559.00000000

        THE Y-MINIMUM OF X-Y-Z DATA IS           965.00000000
        THE Y-MAXIMUM OF X-Y-Z DATA IS          1198.00000000

        THE Z-MINIMUM OF X-Y-Z DATA IS             3.00000000
        THE Z-MAXIMUM OF X-Y-Z DATA IS           175.00000000

          148 X-Y-Z DATA POINTS SAVED

        NO ROTATION OF AXIS


SWA THREE - DAY STORM DATE 72/03/16                              DATE  3/25/80  TIME 14:13:19

        ********** GRID GENERATION **********

        NUMBER OF X-Y-Z DATA POINTS IS    148

        THE X-MINIMUM OF X-Y-Z DATA IS          1321.00000000
        THE X-MAXIMUM OF X-Y-Z DATA IS          1559.00000000

        THE Y-MINIMUM OF X-Y-Z DATA IS           965.00000000
        THE Y-MAXIMUM OF X-Y-Z DATA IS          1198.00000000

        THE Z-MINIMUM OF X-Y-Z DATA IS             3.00000000
        THE Z-MAXIMUM OF X-Y-Z DATA IS           175.00000000

********     39 X-Y-Z DATA POINT(S) FOUND OUTSIDE EXTREMES OF GRID MATRIX

        ***** GRID MATRIX PARAMETERS *****

        THE X-VALUE AT LEFT   EDGE OF GRID MATRIX IS        1320.00000000
        THE X-VALUE AT RIGHT  EDGE OF GRID MATRIX IS        1560.00000000

        THE Y-VALUE AT BOTTOM EDGE OF GRID MATRIX IS         960.00000000
        THE Y-VALUE AT TOP    EDGE OF GRID MATRIX IS        1110.00000000

        THE DISTANCE BETWEEN COLUMNS IS                5.00000
        THE DISTANCE BETWEEN ROWS IS                   5.00000

        THE GRID MATRIX WILL HAVE   49 COLUMNS AND   31 ROWS

        SAMPLE DATA POINTS WILL BE RETAINED

        DUPLICATE DATA POINTS WILL BE AVERAGED

        NO DUPLICATE DATA POINTS FOUND

          148 X-Y-Z DATA POINTS WILL BE USED TO CALCULATE THE GRID MATRIX

        THE GRID NODES WILL BE CALCULATED USING A WEIGHTED AVERAGE OF THE NEAREST DATA POINTS

        SCALED INVERSE DISTANCE SQUARED WILL BE USED FOR THE WEIGHTING FUNCTION
```

Table A.8 continued

```
SWA THREE - DAY STORM DATE 72/03/16                                    DATE  3/25/80  TIME 14:13:38

      ****** SEARCH METHOD FOR PHASE 2 OF GRID ******

******** NO SEARCH METHOD SPECIFIED, NEAR WILL BE USED

      ****** NEAREST NEIGHBOR SEARCH ******

      NUMBER OF NEAREST NEIGHBORS IS     8

      MAXIMUM DISTANCE TO NEAREST SAMPLE DATA POINT IS          35.19697571

      MAXIMUM SEARCH RADIUS IS           55.65130615


SWA THREE - DAY STORM DATE 72/03/16                                    DATE  3/25/80  TIME 14:14:26

      ******** MAKE A CONTOUR MAP ********

      THE X-VALUE AT LEFT   EDGE OF GRID MATRIX IS          1320.00000000
      THE X-VALUE AT RIGHT  EDGE OF GRID MATRIX IS          1560.00000000

      THE Y-VALUE AT BOTTOM EDGE OF GRID MATRIX IS           960.00000000
      THE Y-VALUE AT TOP    EDGE OF GRID MATRIX IS          1110.00000000

      THE Z-MINIMUM OF THE GRID MATRIX IS             3.25037575
      THE Z-MAXIMUM OF THE GRID MATRIX IS           174.87094116

      THE GRID MATRIX HAS   49 COLUMNS AND   31 ROWS

      THE GRID MATRIX HAS    35 MISSING VALUES

      THE X-VALUE AT LEFT   EDGE OF CONTOUR MAP IS          1320.00000000
      THE X-VALUE AT RIGHT  EDGE OF CONTOUR MAP IS          1560.00000000

      THE Y-VALUE AT BOTTOM EDGE OF CONTOUR MAP IS           960.00000000
      THE Y-VALUE AT TOP    EDGE OF CONTOUR MAP IS          1110.00000000

      THE CONTOUR MAP WILL BE        7.50 INCHES WIDE BY        4.69 INCHES HIGH

      THE X-SCALE IS        32.0000 UNITS PER INCH
      THE Y-SCALE IS        32.0000 UNITS PER INCH

      ****** CONTOUR LEVELS AND ANNOTATION ******

      CONTOUR LEVELS WILL HAVE EQUAL SPACED INTERVALS

      THE REFERENCE CONTOUR LEVEL IS      0.0

      THE INCREMENT BETWEEN EQUAL SPACED CONTOUR LEVELS IS      20.00000

      THE MAXIMUM NUMBER OF CONTOUR LEVELS IS     13

      EVERY CONTOUR LEVEL WILL BE LABELED

      LABELS ON THE CONTOUR LINES WILL BE  0.10 INCHES HIGH

      LABELS WILL BE PRINTED WITHOUT A DECIMAL FRACTION

      LABELS WILL BE PRINTED A MINIMUM OF     3.00 INCHES APART

      EVERY    5TH CONTOUR LEVEL WILL BE DRAWN HEAVY
```

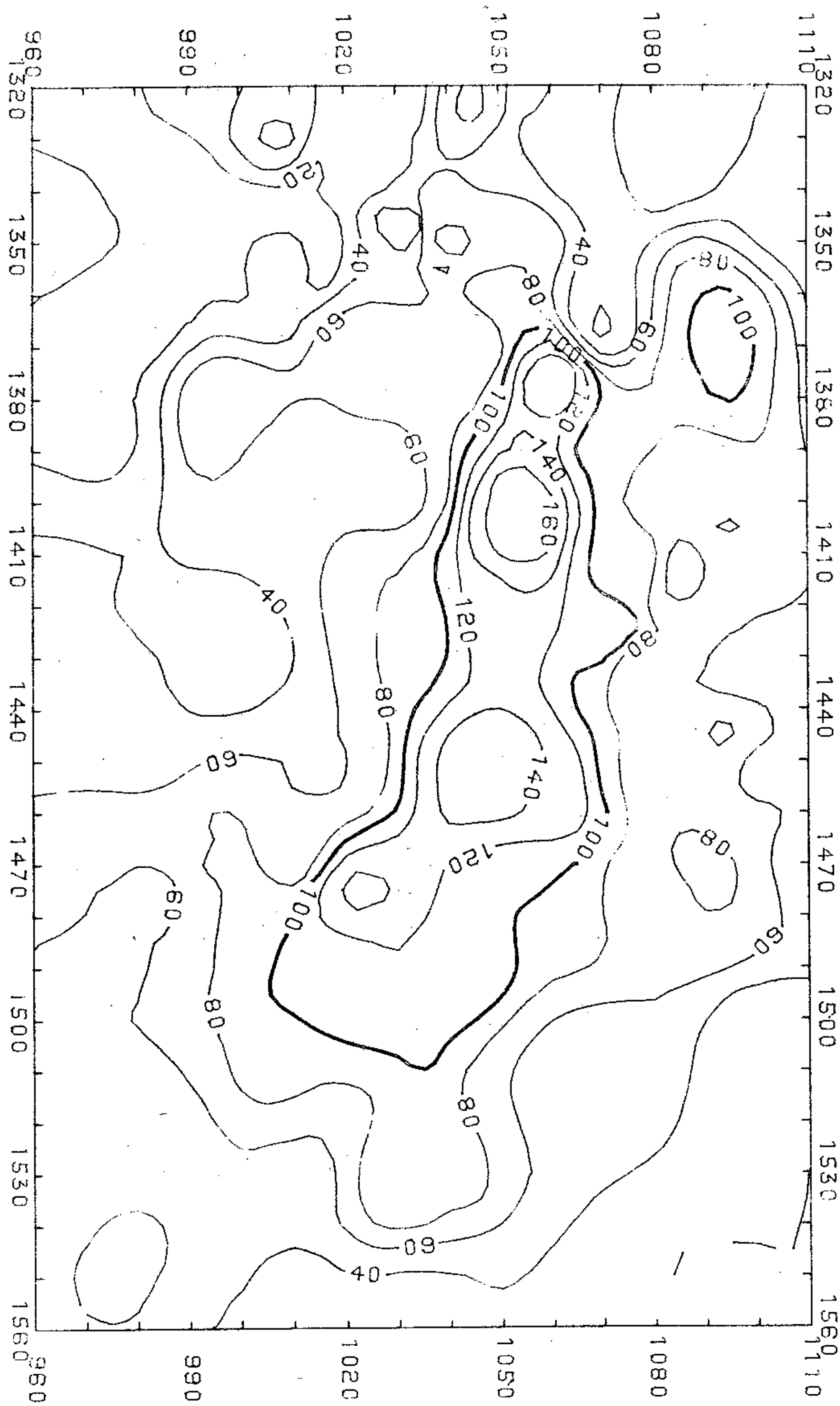
Table A.8 continued

```
SWA THREE - DAY STORM DATE 72/03/16                              DATE  3/25/80   TIME 14:15:05

        ******** MAKE POSTING OF X-Y-Z DATA POINTS ********

        THE NUMBER OF X-Y-Z DATA POINTS IS     148

        THE X-MINIMUM OF THE X-Y-Z DATA POINTS IS           1321.00000000
        THE X-MAXIMUM OF THE X-Y-Z DATA POINTS IS           1559.00000000

        THE Y-MINIMUM OF THE X-Y-Z DATA POINTS IS            965.00000000
        THE Y-MAXIMUM OF THE X-Y-Z DATA POINTS IS           1198.00000000

        THE Z-MINIMUM OF THE X-Y-Z DATA POINTS IS              3.00000000
        THE Z-MAXIMUM OF THE X-Y-Z DATA POINTS IS            175.00000000

        THE X-VALUE AT LEFT   EDGE OF POSTING IS            1320.00000000
        THE X-VALUE AT RIGHT  EDGE OF POSTING IS            1560.00000000

        THE Y-VALUE AT BOTTOM EDGE OF POSTING IS             960.00000000
        THE Y-VALUE AT TOP    EDGE OF POSTING IS            1110.00000000

        THE POSTING WILL BE        7.50 INCHES WIDE BY        4.69 INCHES HIGH

        THE X-SCALE IS       32.0000 UNITS PER INCH
        THE Y-SCALE IS       32.0000 UNITS PER INCH

        ****** POST PARAMETERS ******

        POINTS WILL BE LABELED WITH Z VARIABLE

        MAP SYMBOL WILL BE      0.10 INCHES HIGH

        LABEL ON MAP SYMBOL WILL BE      0.10 INCHES HIGH

        LABELS WILL BE PRINTED WITHOUT A DECIMAL FRACTION

        MAP SYMBOL  1 WILL BE USED FOR ALL DATA POINTS

        ****** BOX PARAMETERS ******

        TICK MARKS ALONG ALL EDGES OF BOX WILL BE LABELED

        THE NUMBER OF UNITS BETWEEN TICK MARKS ALONG X-AXIS IS          10.00000
        EVERY   3RD TICK MARK ALONG X-AXIS WILL BE LABELED

        THE NUMBER OF UNITS BETWEEN TICK MARKS ALONG Y-AXIS IS          10.00000
        EVERY   3RD TICK MARK ALONG Y-AXIS WILL BE LABLED

        REFERENCE VALUE FOR TICK MARKS AND LABELS ON X-AXIS IS            0.0
        REFERENCE VALUE FOR TICK MARKS AND LABELS ON Y-AXIS IS            0.0

        BOX LABELS WILL BE PRINTED WITHOUT A DECIMAL FRACTION

        LABELS AROUND BOX WILL BE      0.10 INCHES HIGH


SWA THREE - DAY STORM DATE 72/03/16                              DATE  3/25/80   TIME 14:14:28

        ****** CONTOUR PARAMETERS ******

        CONTOUR LINES WILL BE SMOOTHED BY PIECEWISE BESSEL INTERPOLATION

        DEPRESSION CONTOUR LINES WILL NOT BE ANNOTATED

        ****** BOX PARAMETERS ******

        TICK MARKS ALONG ALL EDGES OF BOX WILL BE LABELED

        THE NUMBER OF UNITS BETWEEN TICK MARKS ALONG X-AXIS IS          10.00000
        EVERY   3RD TICK MARK ALONG X-AXIS WILL BE LABELED

        THE NUMBER OF UNITS BETWEEN TICK MARKS ALONG Y-AXIS IS          10.00000
        EVERY   3RD TICK MARK ALONG Y-AXIS WILL BE LABLED

        REFERENCE VALUE FOR TICK MARKS AND LABELS ON X-AXIS IS            0.0
        REFERENCE VALUE FOR TICK MARKS AND LABELS ON Y-AXIS IS            0.0

        BOX LABELS WILL BE PRINTED WITHOUT A DECIMAL FRACTION
```

Table A.8 continued

```
***** SURFACE II COMMANDS AND ERROR REPORT *****    DATE  3/25/80  TIME 14:12:39     PAGE    1
-----------------------------------------------------------------------------------------------

                          ****** COMMANDS ******

   (    1) 'TITLE   SWA THREE - DAY STORM DATE 72/03/16                                      '
   (    2) 'IDXY    148,20,3,,,,,,,,'(2F5.0,F5.1)'                                           '
   (    3) 'BOX     10,3,10,3,                                                               '
   (    4) 'POST    0,0,0.1,0.1,1                                                            '
   (    5) 'CINT    0,0,20,0,1,,0,                                                           '
   (    6) 'GRID    1,5,5,0,                                                                 '
   (    7) 'EXTR    1320,1560,960,1110                                                       '
   (    8) 'SIZE    0,32,                                                                    '
   (    9) 'DEVICE 5,'BILL',9999,29,,                                                        '
   (   10) 'CONT                                                                             '
   (   11) 'PERFORM                                                                          '

   ****************************************************************************************

   START OF PLOTTING DEVICE      5

   ****************************************************************************************

                          ****** COMMANDS ******

   (   12) 'STOP                                                                             '


***** SURFACE II COMMANDS AND ERROR REPORT *****    DATE  3/25/80  TIME 14:15:17     PAGE    2
-----------------------------------------------------------------------------------------------

   ******** END OF SURFACE II EXECUTION ********

   NO WARNINGS AND/OR ERRORS FOUND DURING EXECUTION

   65536 WORDS AVAILABLE FOR DYNAMIC STORAGE ALLOCATION
    2328 (     3 PERCENT) WORDS USED BY PROGRAM

   ****************************************************************************************

   END OF PLOTTING - DEVICE      5 NUMBER OF PLOTS =      2

   ****************************************************************************************
```

SWA THREE - DAY STORM DATE 72/03/16
PLOT NO. 1 DATE 3/25/80 TIME 14:14:36



SWA THREE - DAY STORM DATE 72/03/16
PLOT NO. 2 DATE 3/25/80 TIME 14:15:06

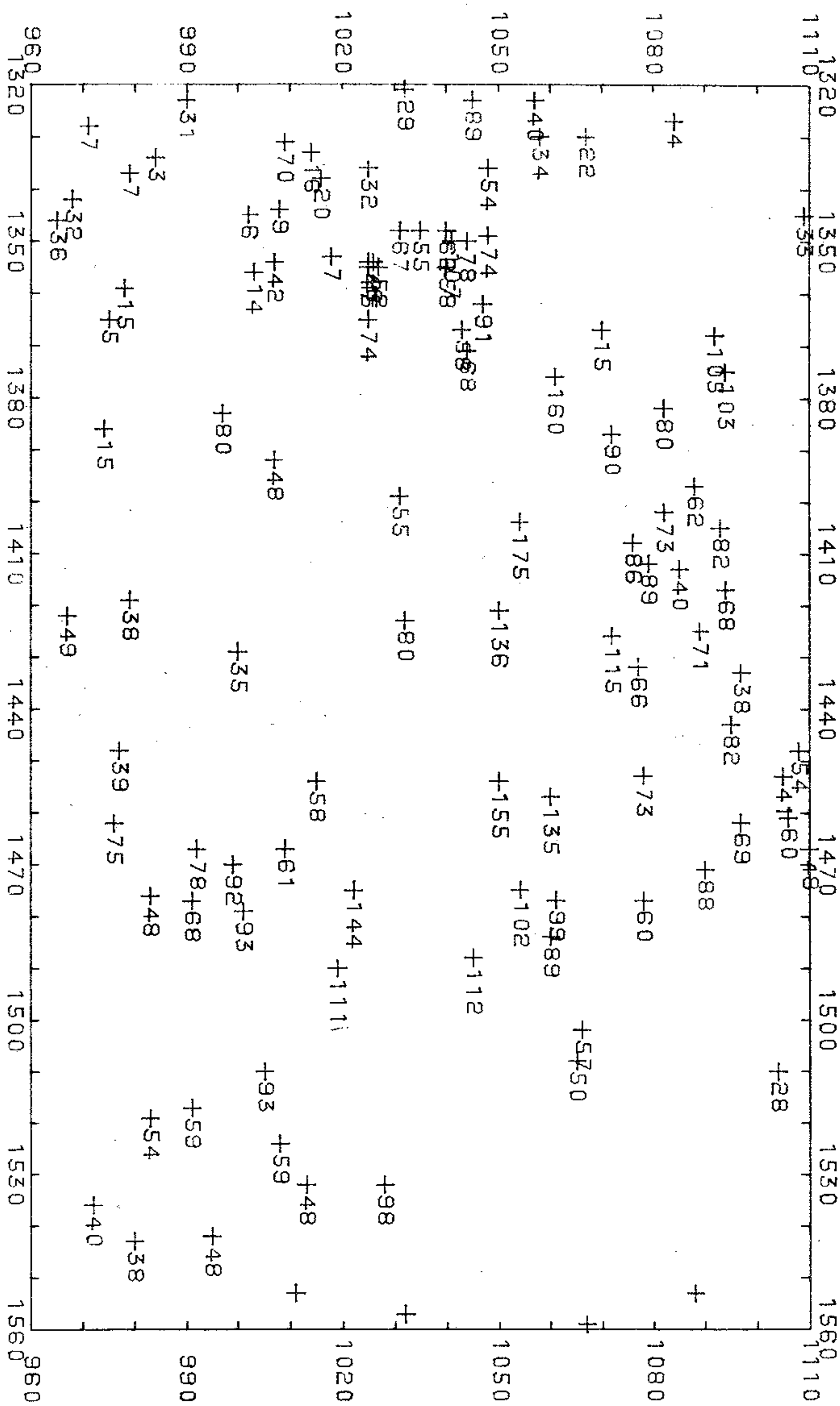


Fig. A.2 Example of posting of data points

APPENDIX B

STORM LIBRARY

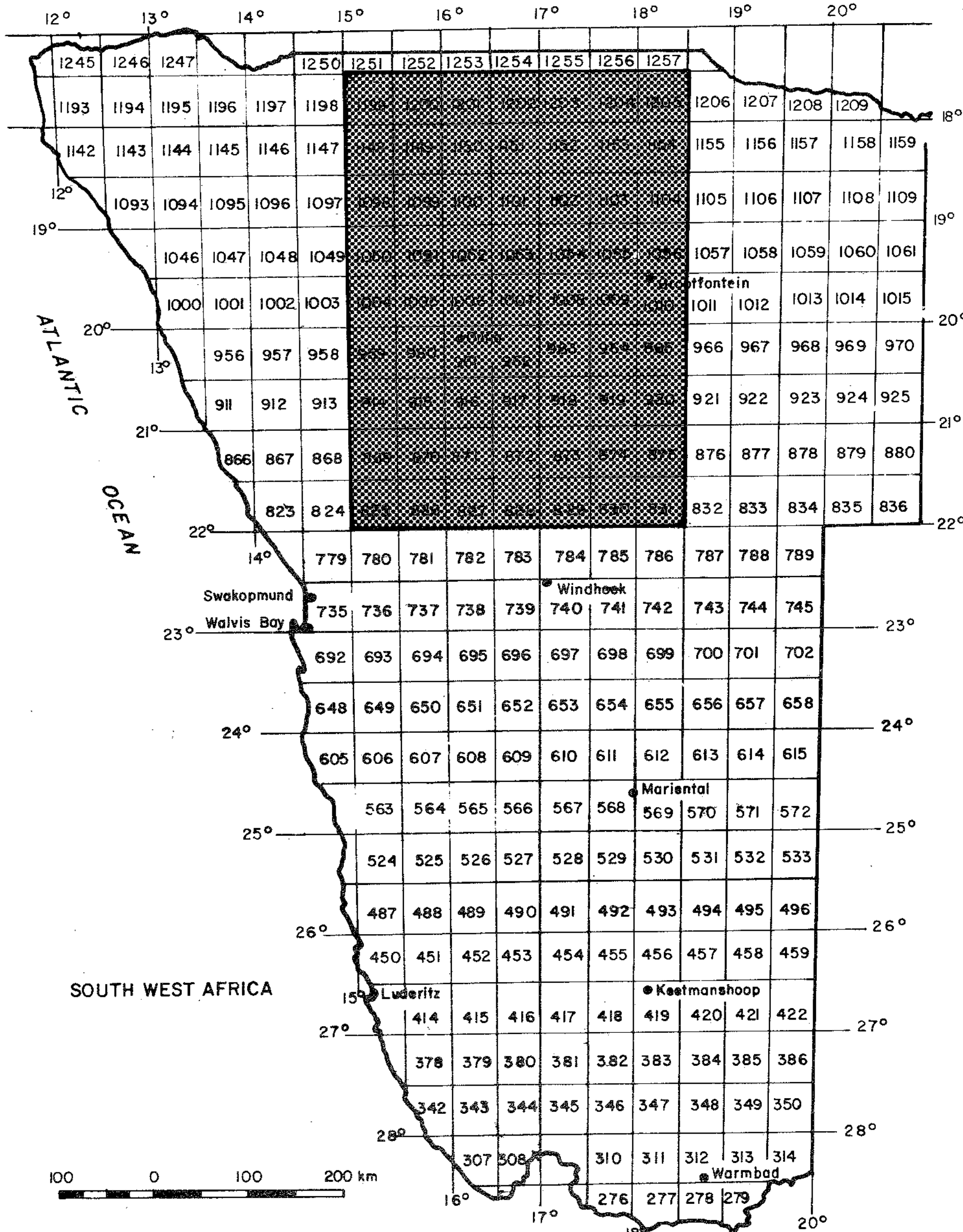
Table B.1 lists details of the thirteen most severe storms that have been selected from the complete set of 36 analysed in this study. Presented for each storm are the one-, three- and five-day isohyetal maps, as well as a key map showing the location of the storm.

Table B.1 Details of storms for which isohyetal maps are plotted

Storm	Date	Isohyetal map			Limits of plot (degree)			
		1-day	3-day	5-day	North	South	West	East
1*	47/12/23	√	√		17½	22	15	18½
2	50/01/12	√	√	√	18	22½	15	18½
3	50/02/21	√	√	√	18	22	15	18½
4	52/02/16	√	√	√	19	22	15	17½
5	53/02/05	√	√	√	19½	23	15½	19
6**	53/12/18	√			25½	29	17	19
7	56/02/08	√	√	√	21½	25½	16½	19
8	56/02/22	√	√	√	18½	20½	16½	19
9	60/02/23	√	√	√	19	23½	16½	19½
10	72/03/16	√	√	√	22	26	16	18½
11	74/01/12	√	√	√	18½	22	16½	19½
12	74/02/01	√	√	√	23½	27½	16½	20
13*	74/02/20	√	√		24	28	16½	20

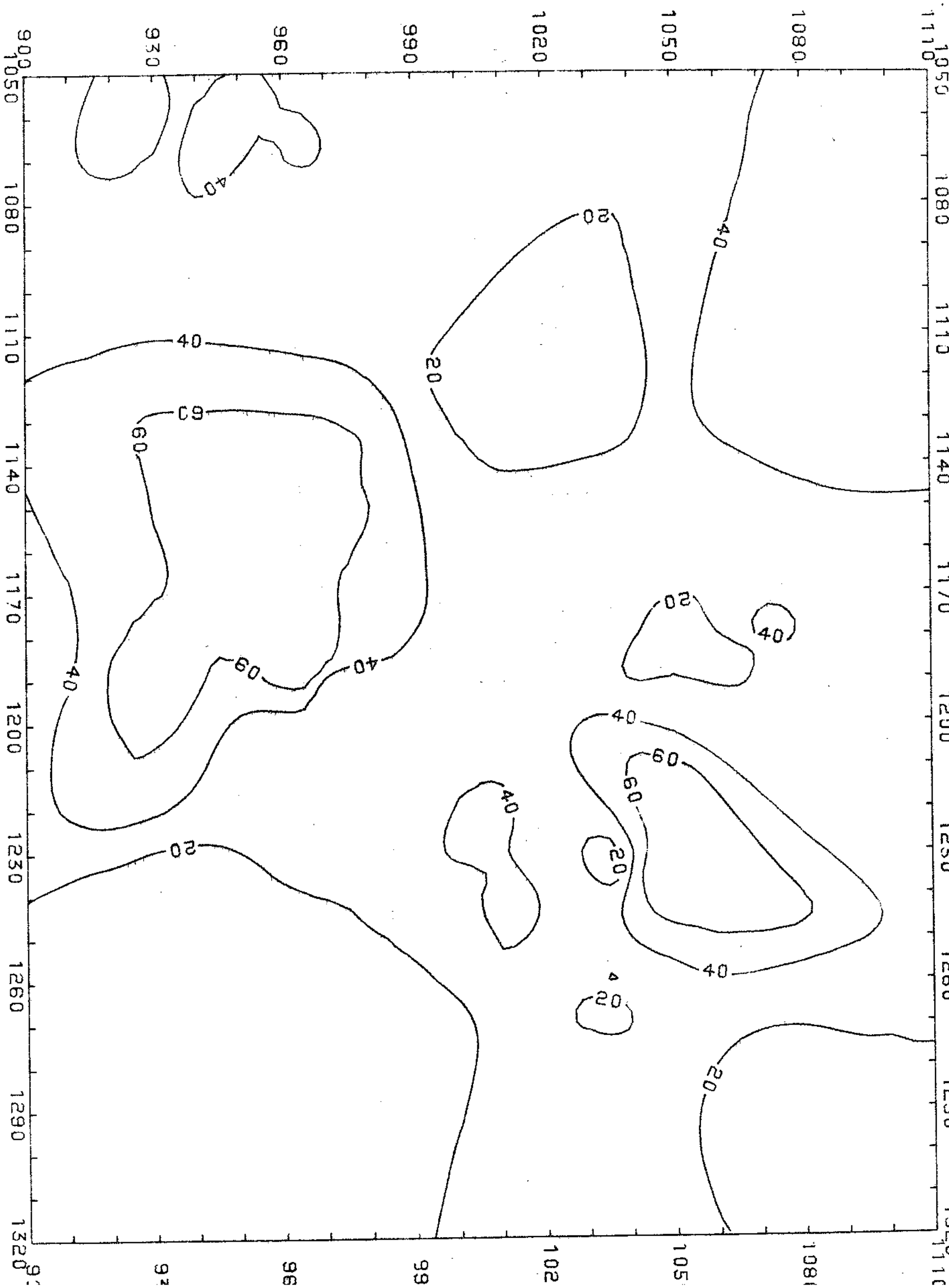
N.B. * 3-day storms
** 1-day storm

Storm I 47/12/23



B3

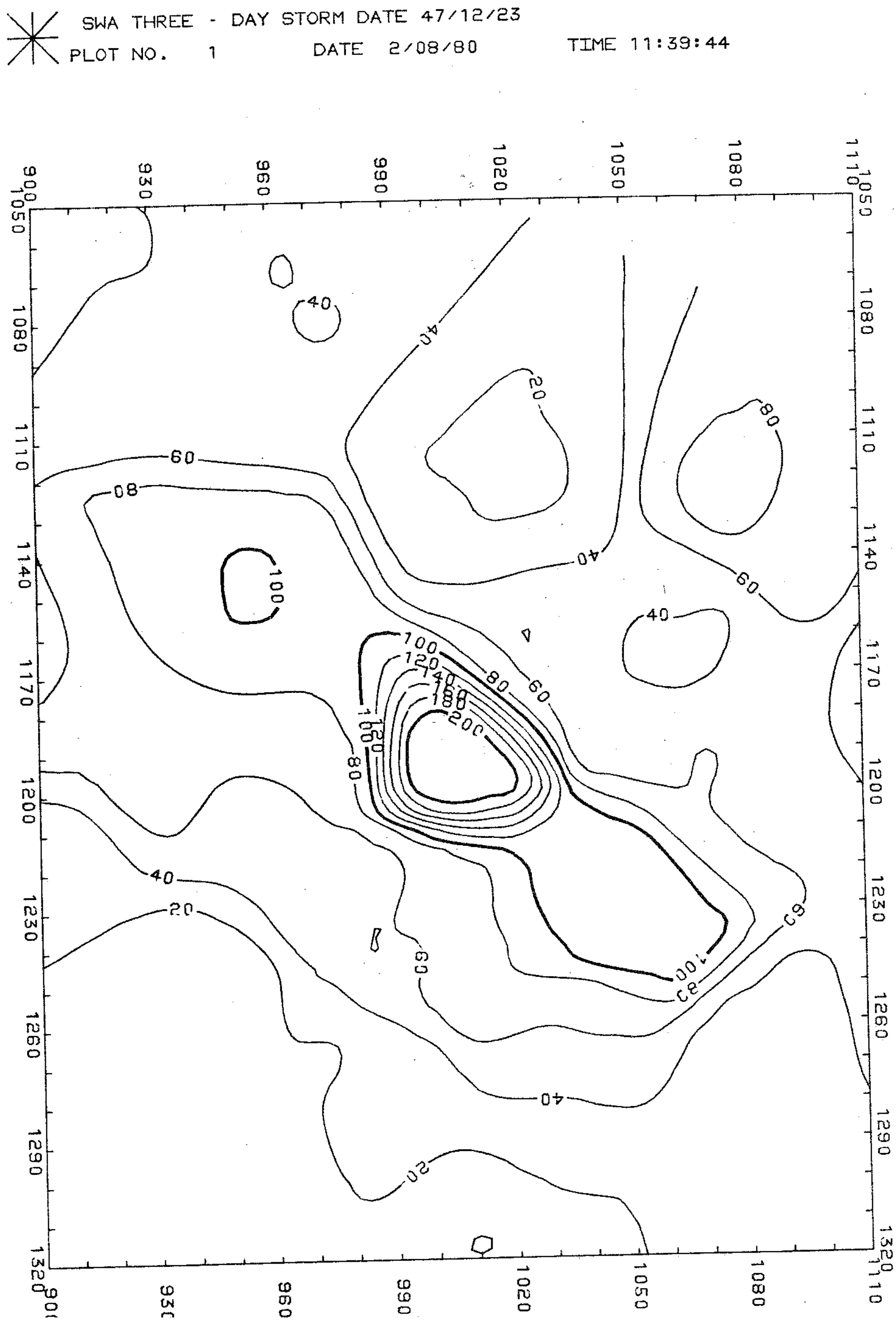
SWA ONE - DAY STORM DATE 47/12/23
PLOT NO. 1 DATE 2/08/80 TIME 11:34:51



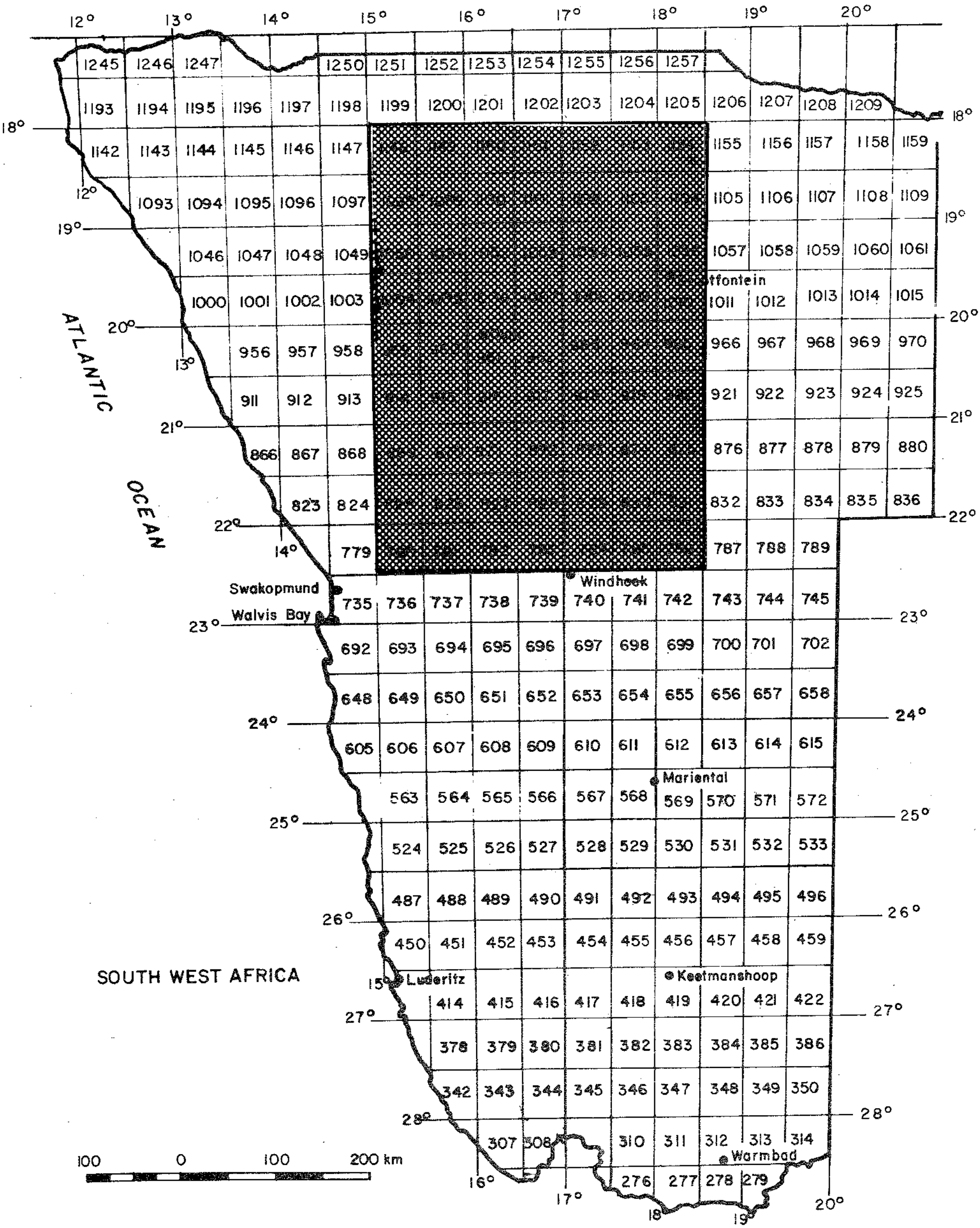
B4

SWA THREE - DAY STORM DATE 47/12/23

PLOT NO. 1 DATE 2/08/80 TIME 11:39:44

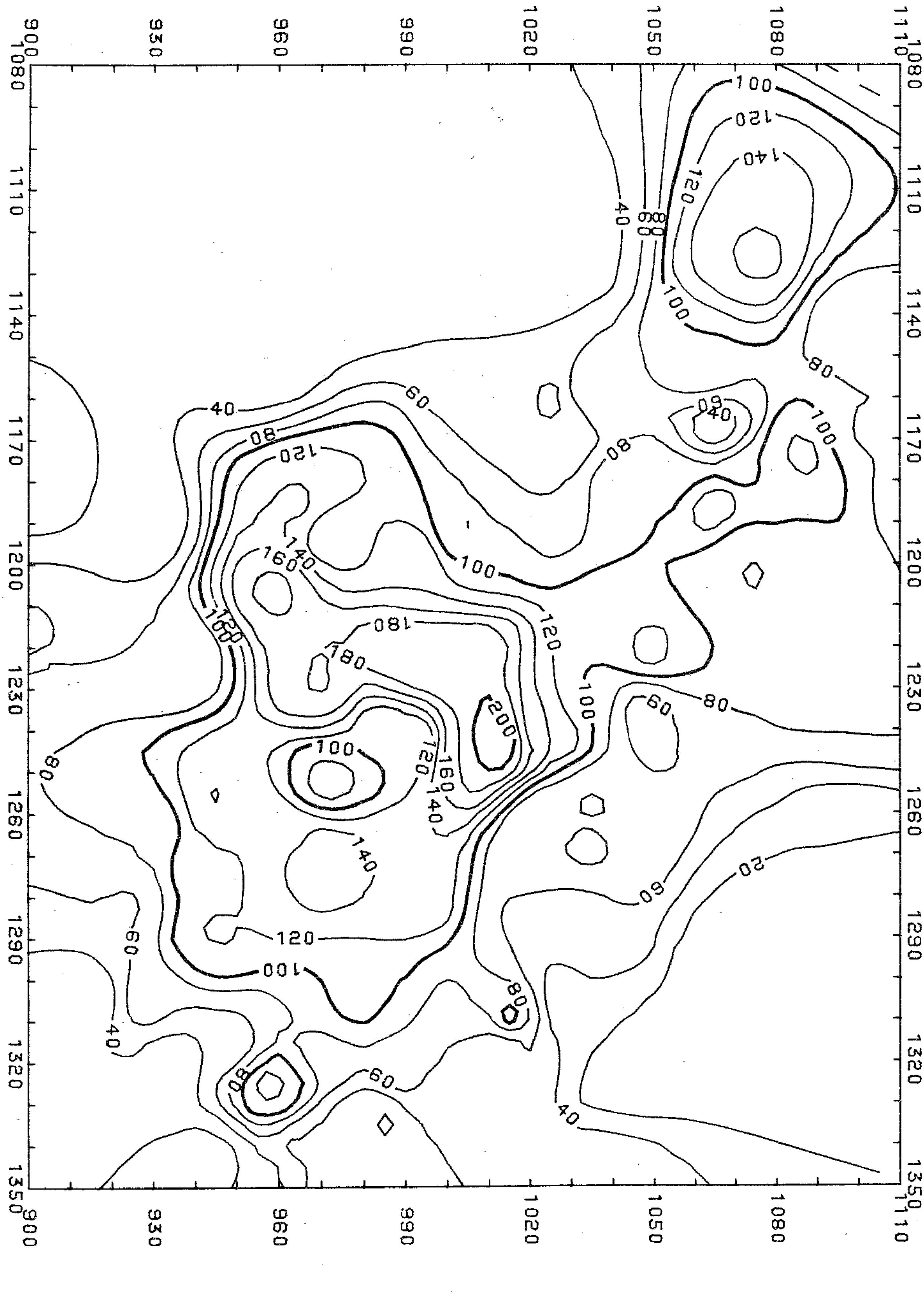


Storm 2 50/01/12



SWA FIVE - DAY STORM DATE 50/01/12

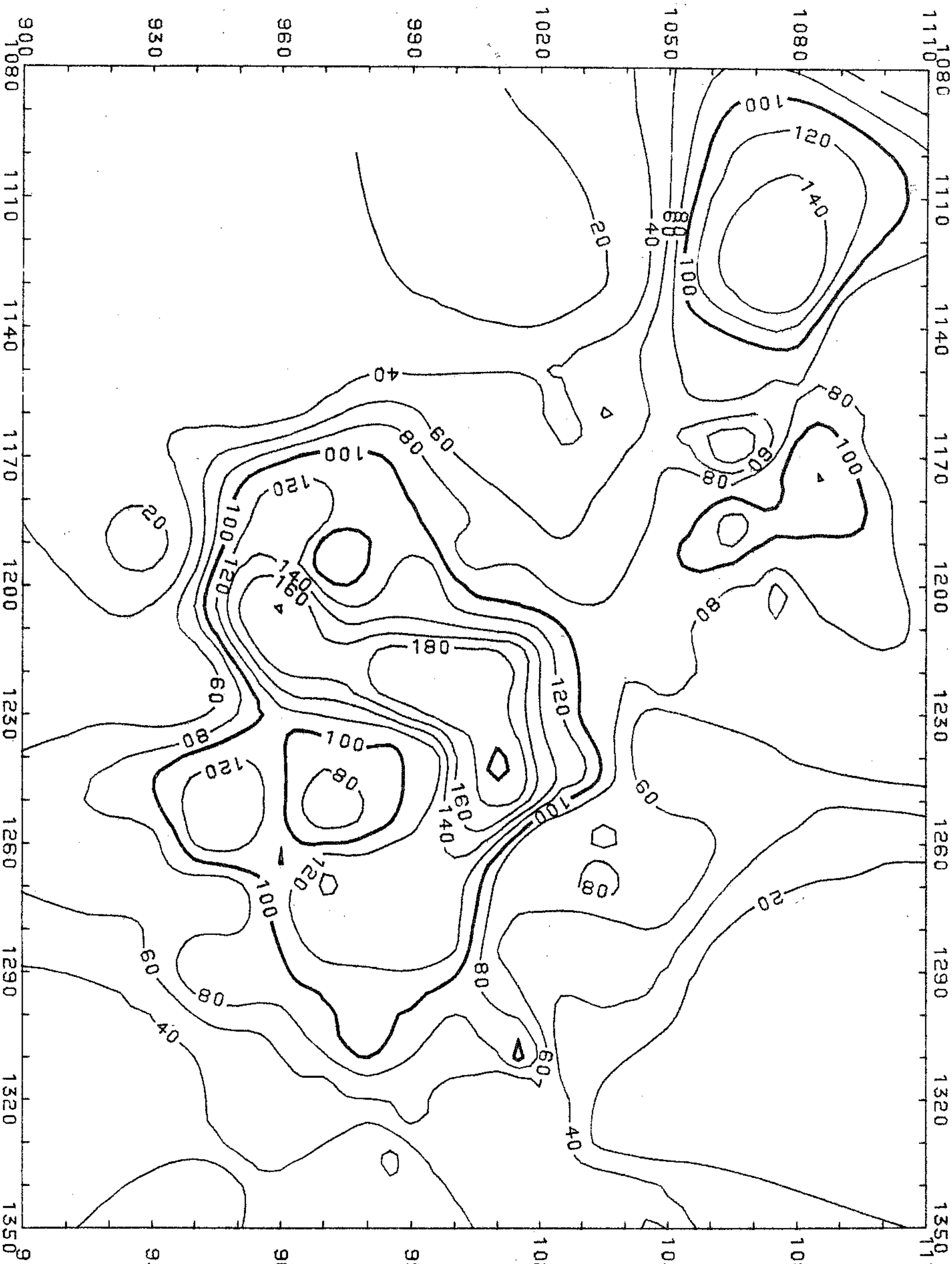
PLOT NO. 1 DATE 2/05/80 TIME 12:42:48



B7

SWA THREE - DAY STORM DATE 50/01/12

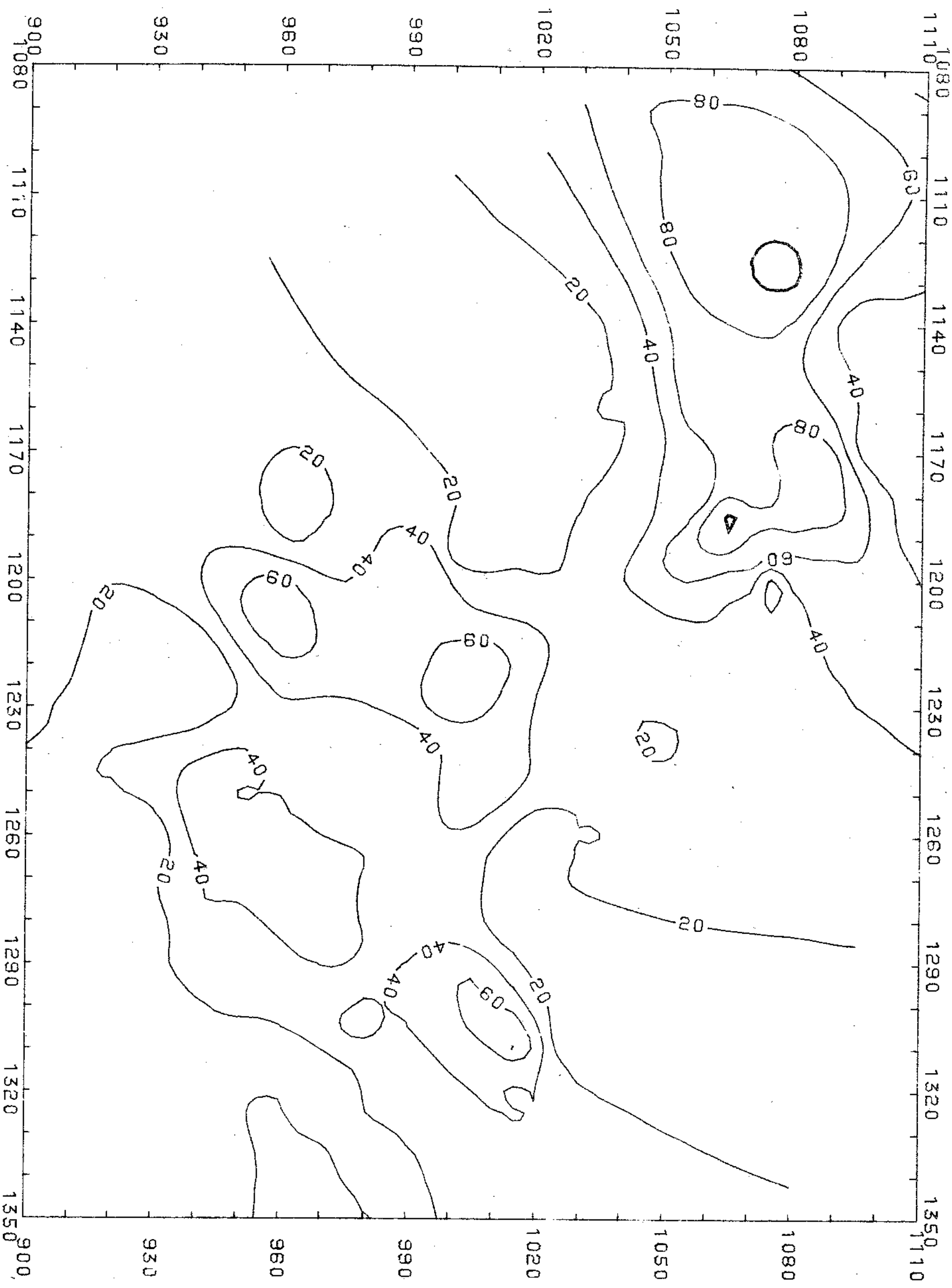
PLOT NO. 1 DATE 2/05/80 TIME 12:41:47



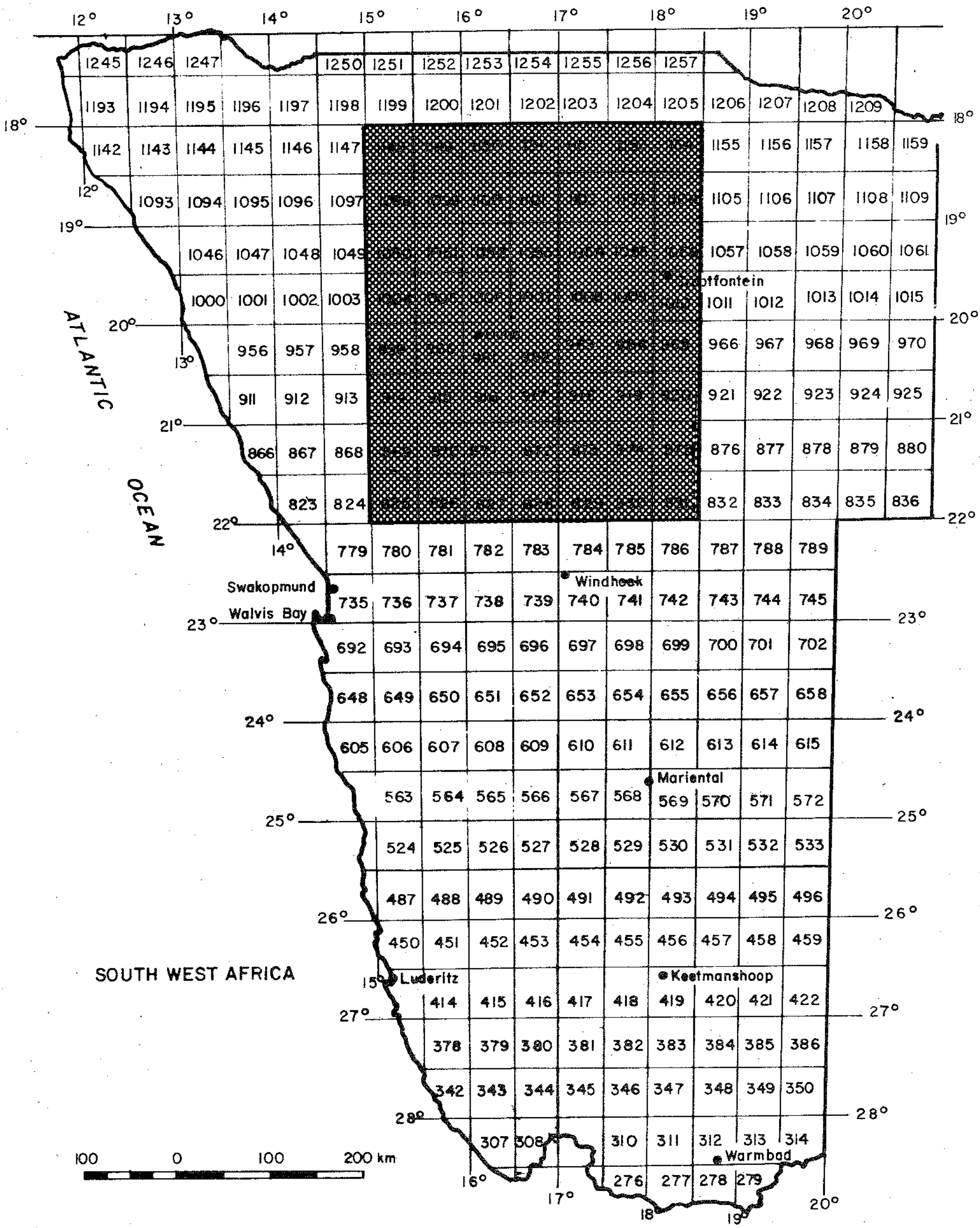
B8

SWA ONE - DAY STORM DATE 50/01/12

PLOT NO. 1 DATE 2/05/80 TIME 12:38:38

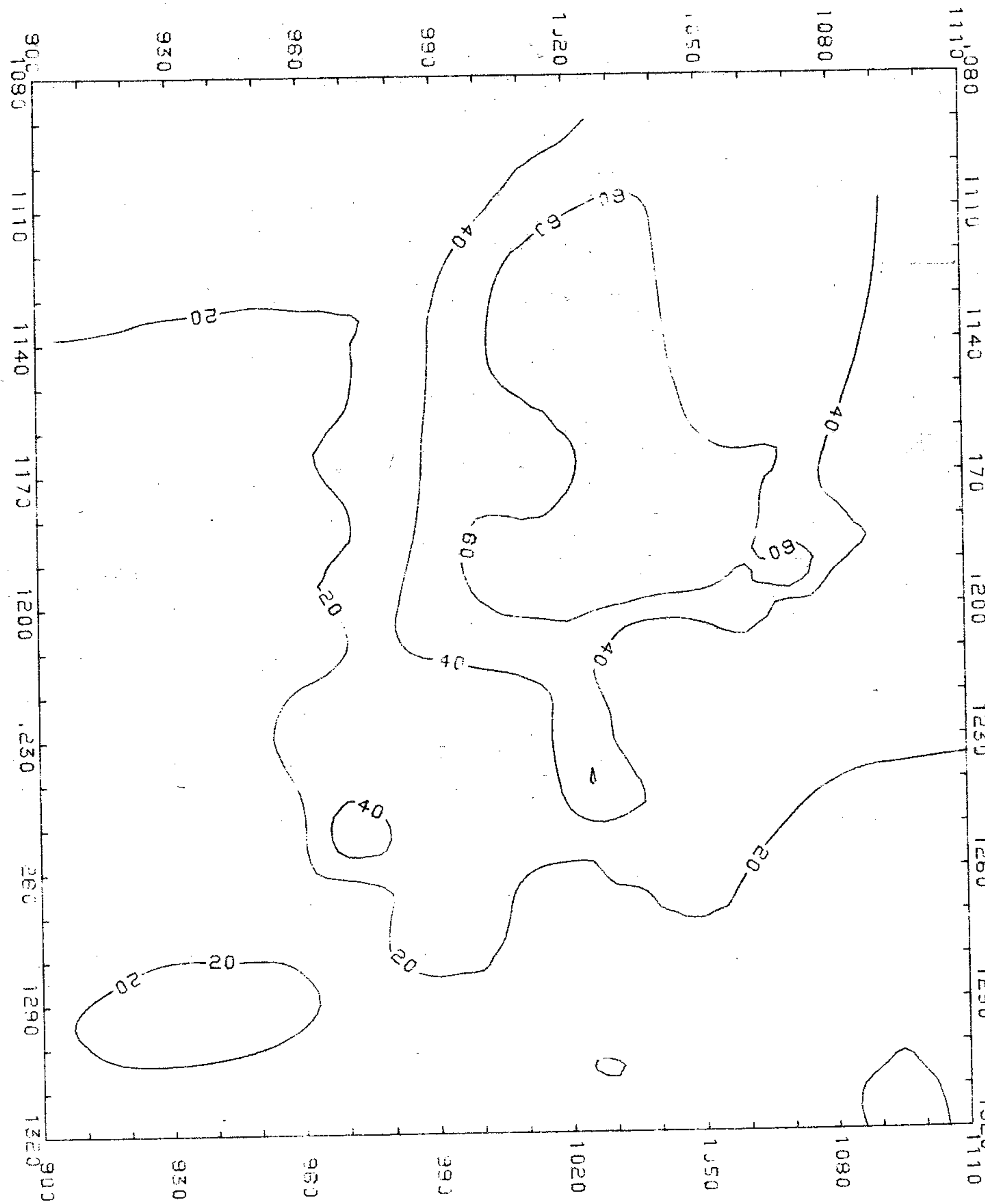


Storm 3 50/02/21

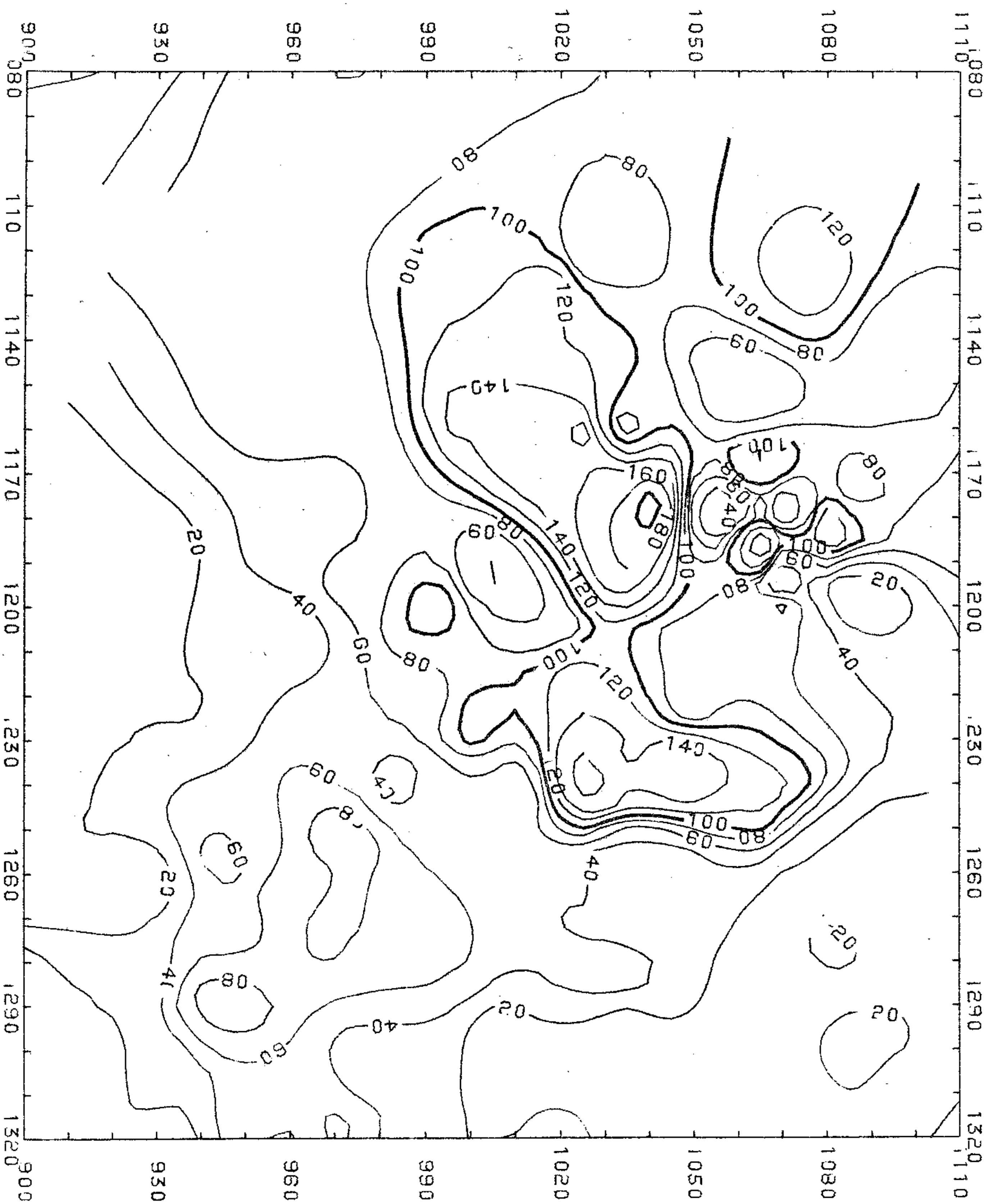


B10

SWA ONF - DAY STORM DATE 50/02/21
PLOT NO. 1 DATE 2/07/80 TIME 9:10:07

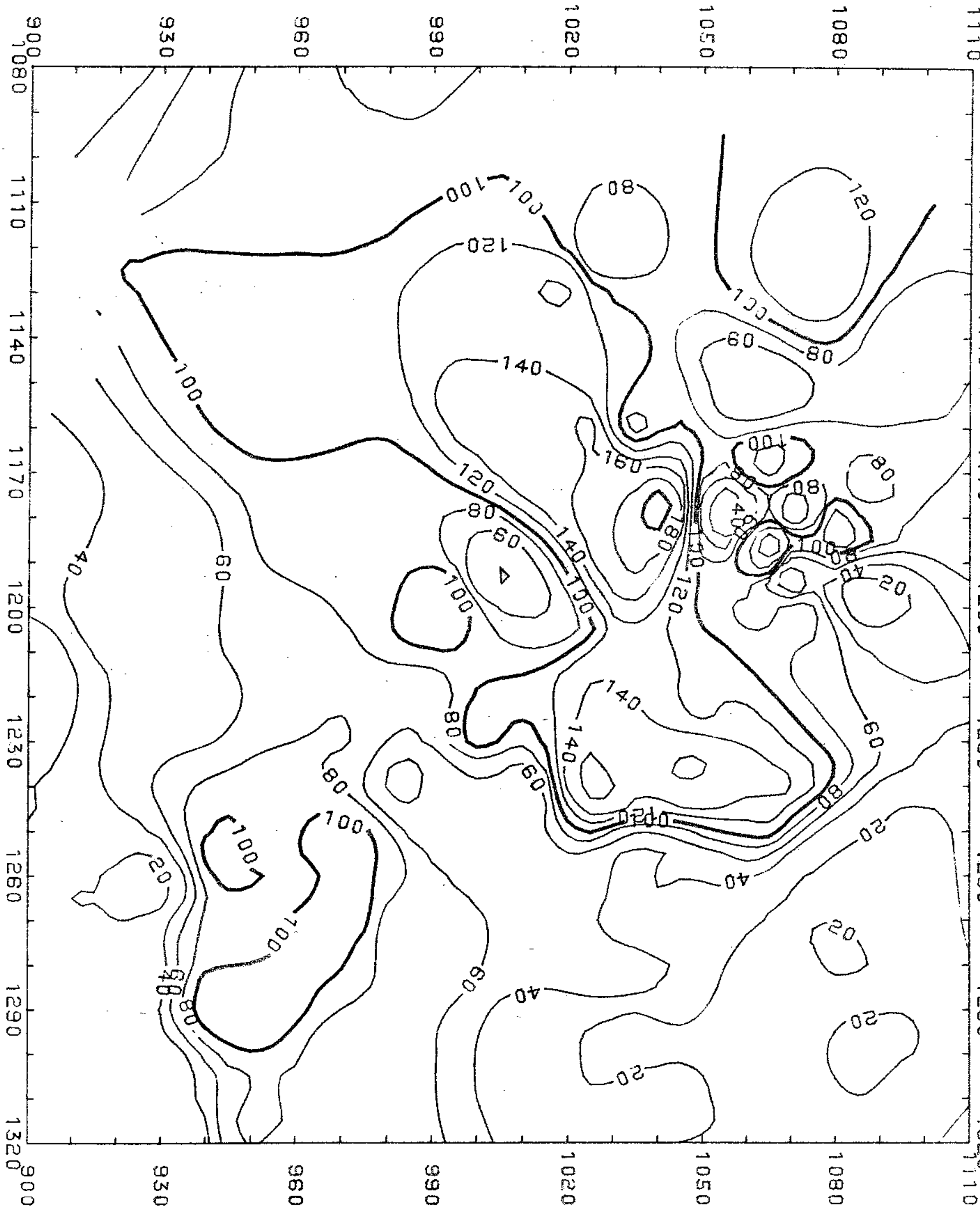


SWA THREE - DAY STORM DATE 50/02/21
PLOT NO. 1 DATE 2/07/80 TIME 9:13:45

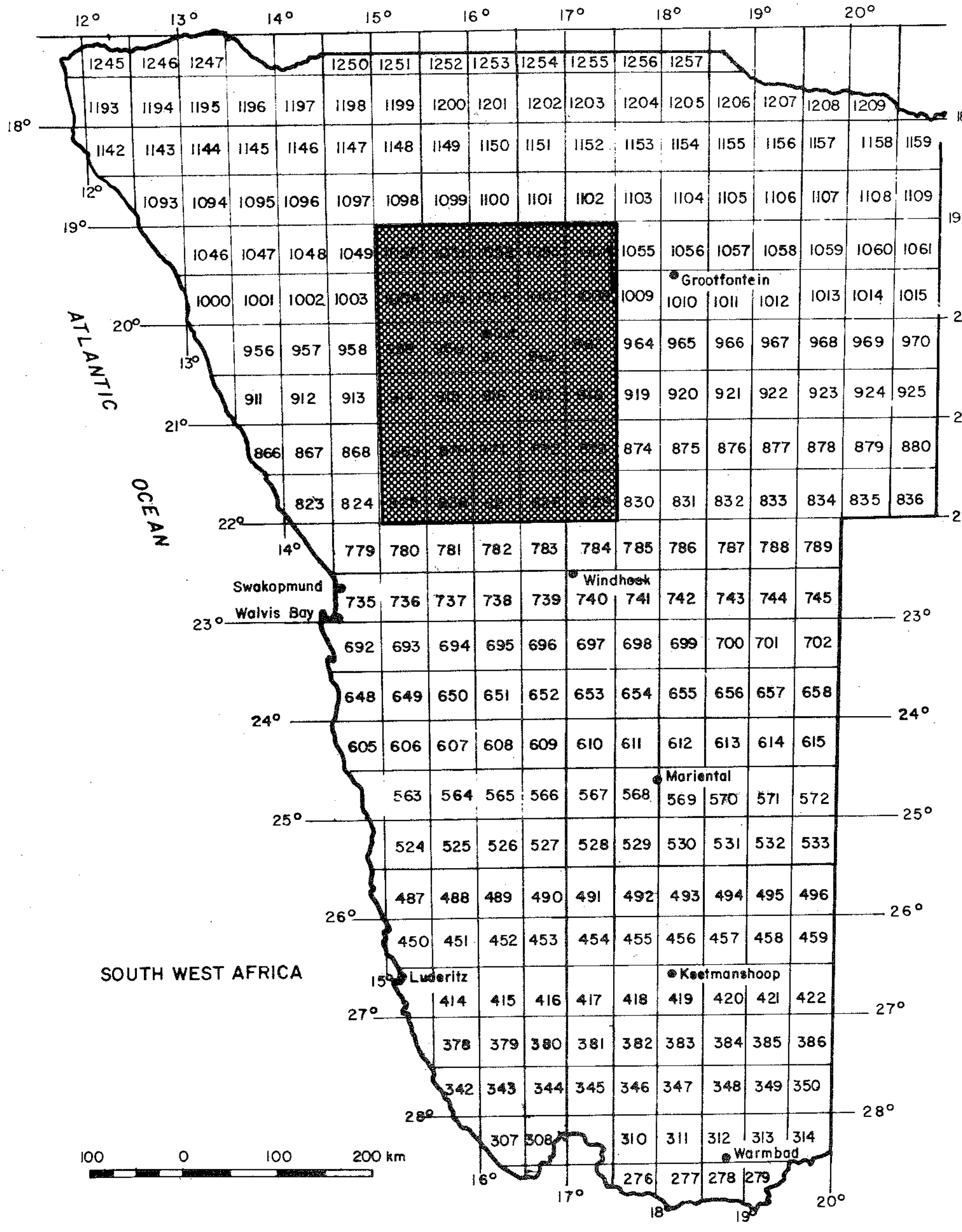


SWA FIVE - DAY STORM DATE 50/02/21

PLOT NO. 1 DATE 2/07/80 TIME 9:17:30

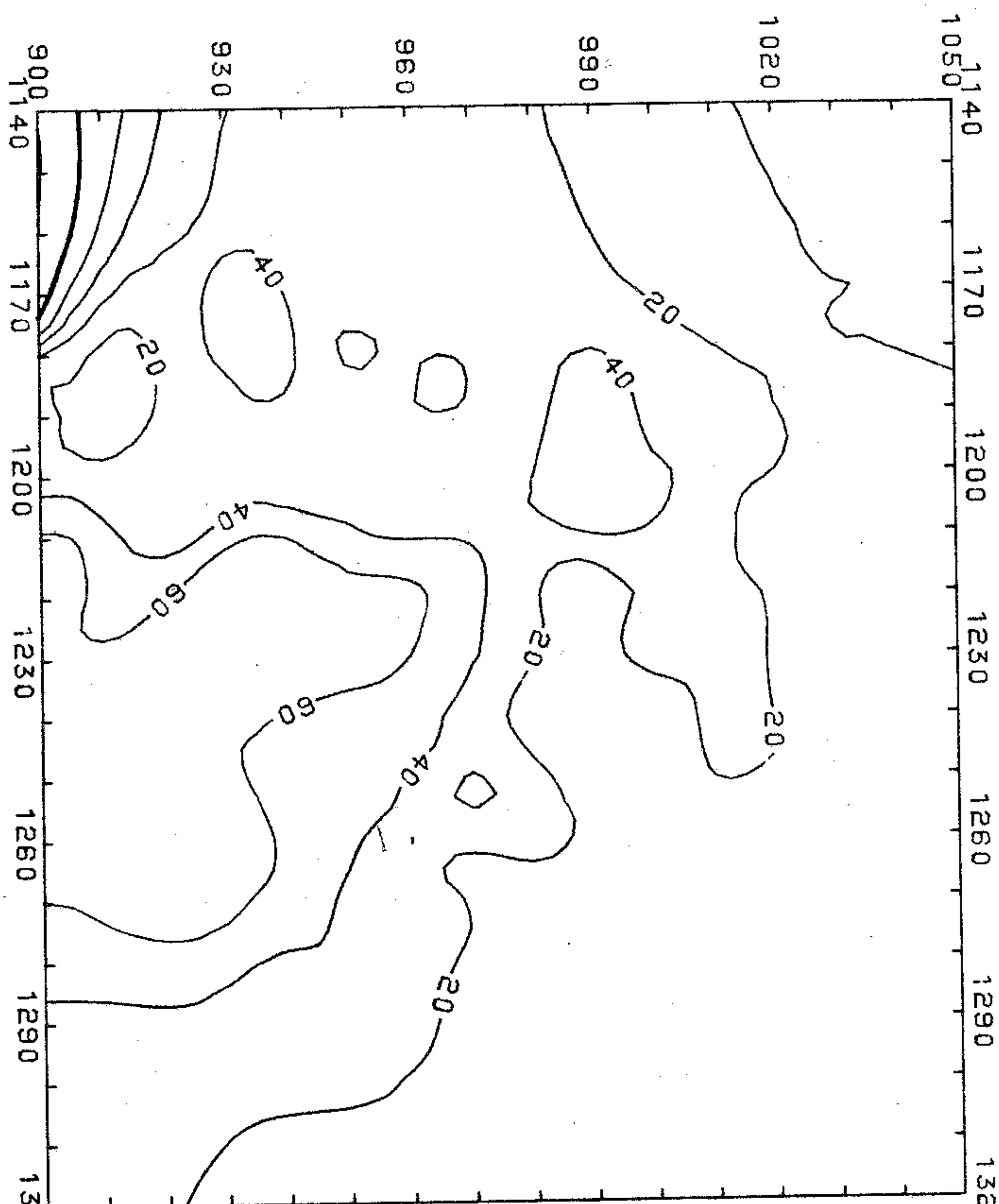


Storm 4 52/02/16



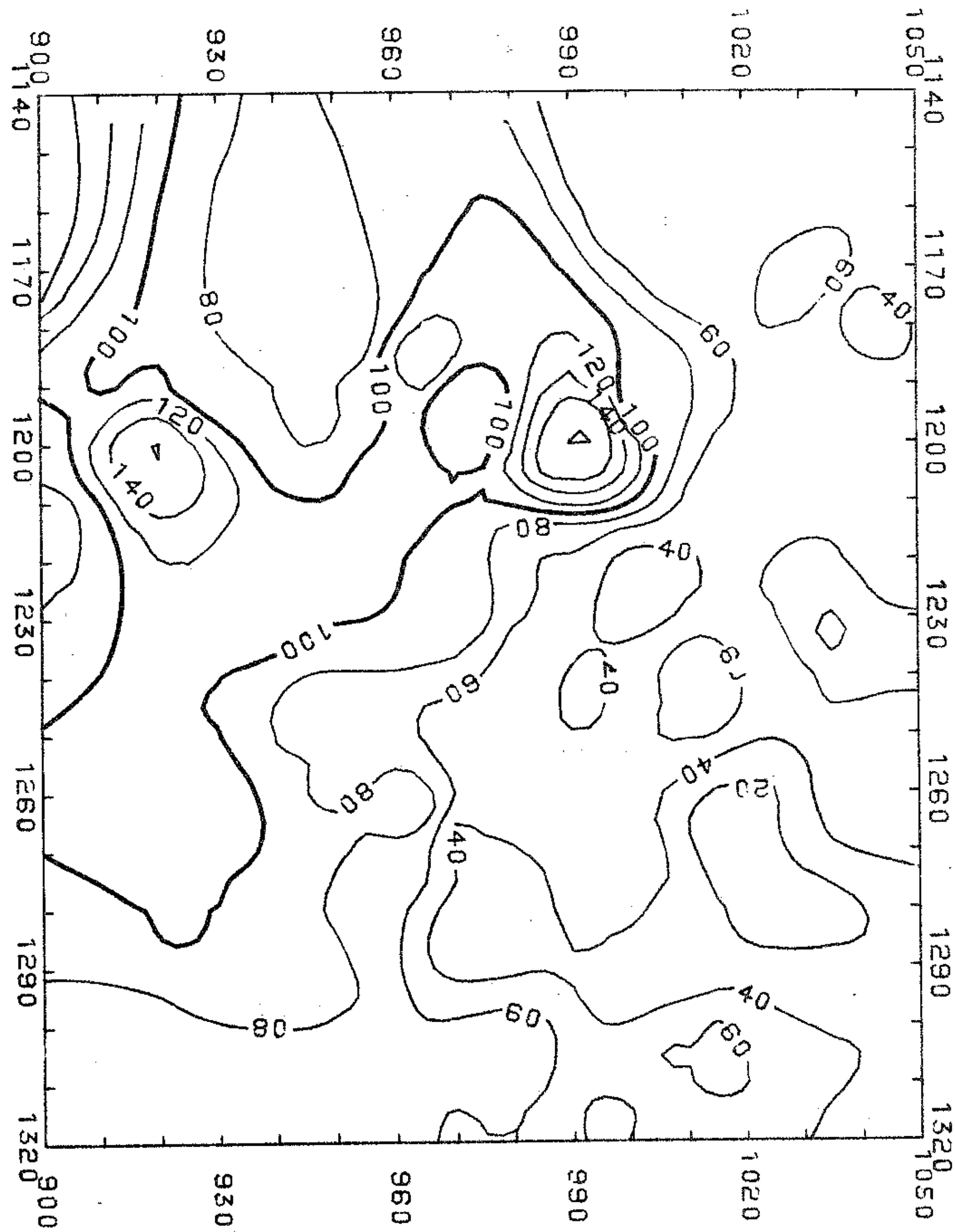
SWA ONE - DAY STORM DATE 52/02/16

PLOT NO. 1 DATE 2/08/80 TIME 11:42:33



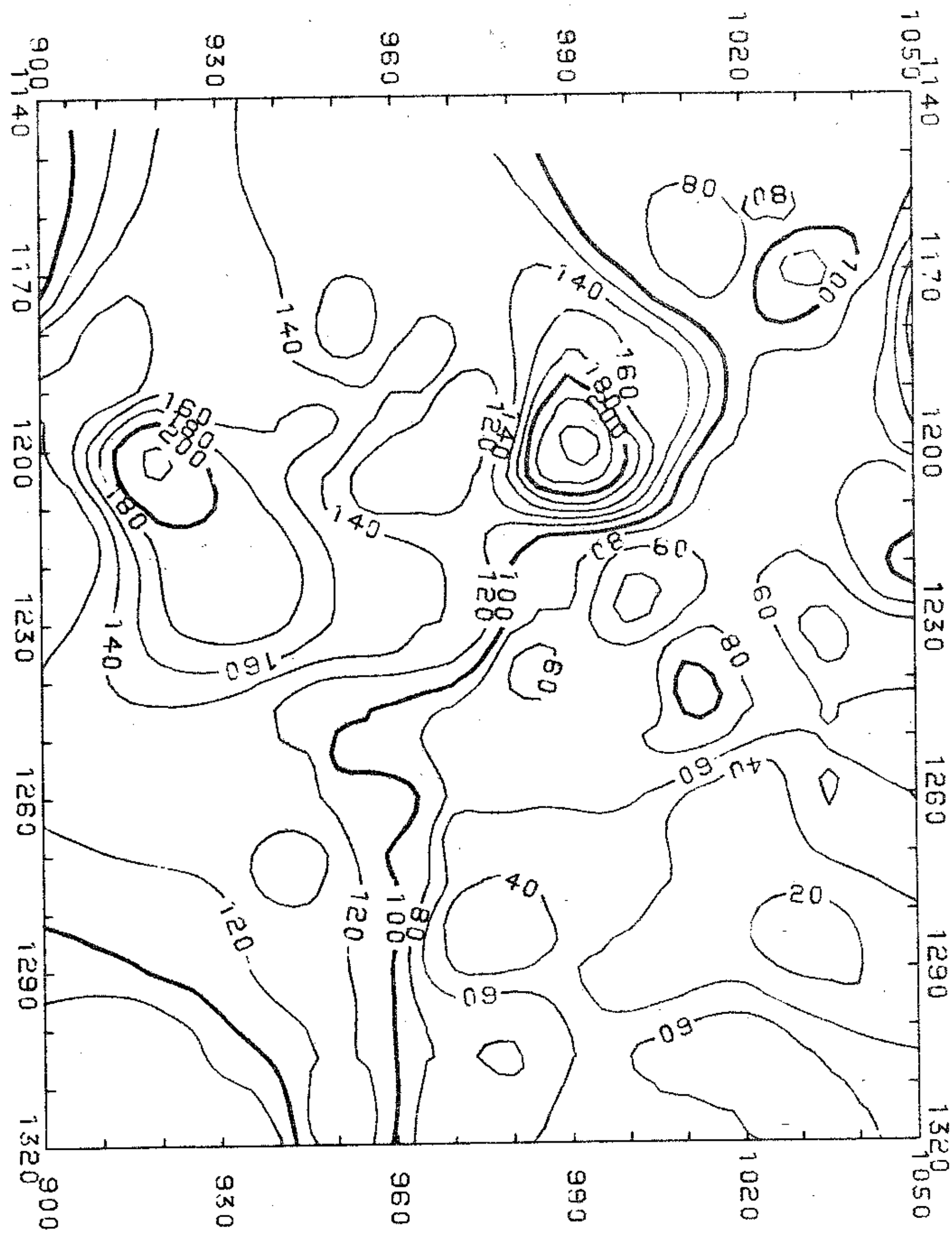
SWA THREE - DAY STORM DATE 52/02/16

PLOT NO. 1 DATE 2/08/80 TIME 11:46:15

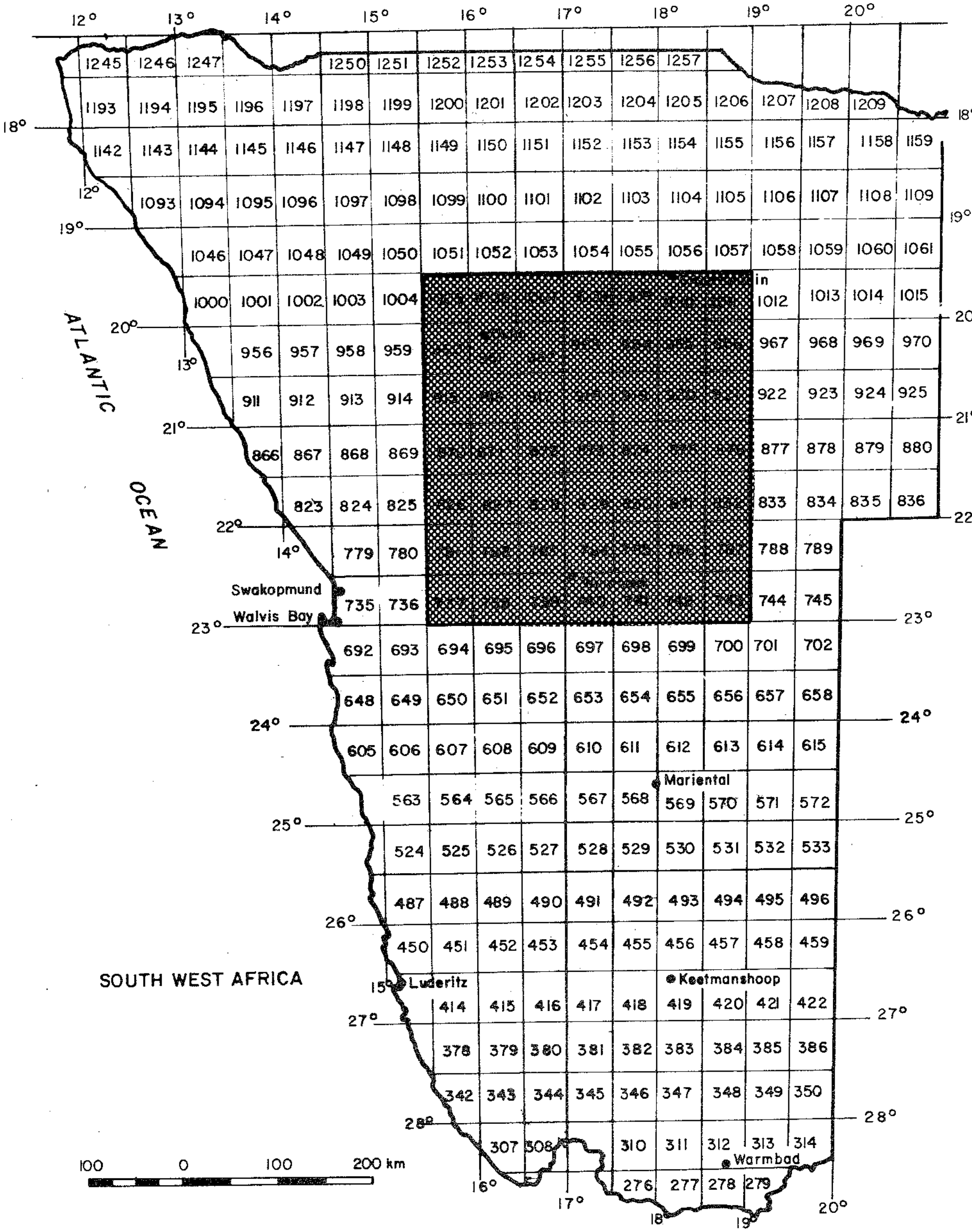


SWA FIVE - DAY STORM DATE 52/02/16

PLOT NO. 1 DATE 2/08/80 TIME 11:47:39

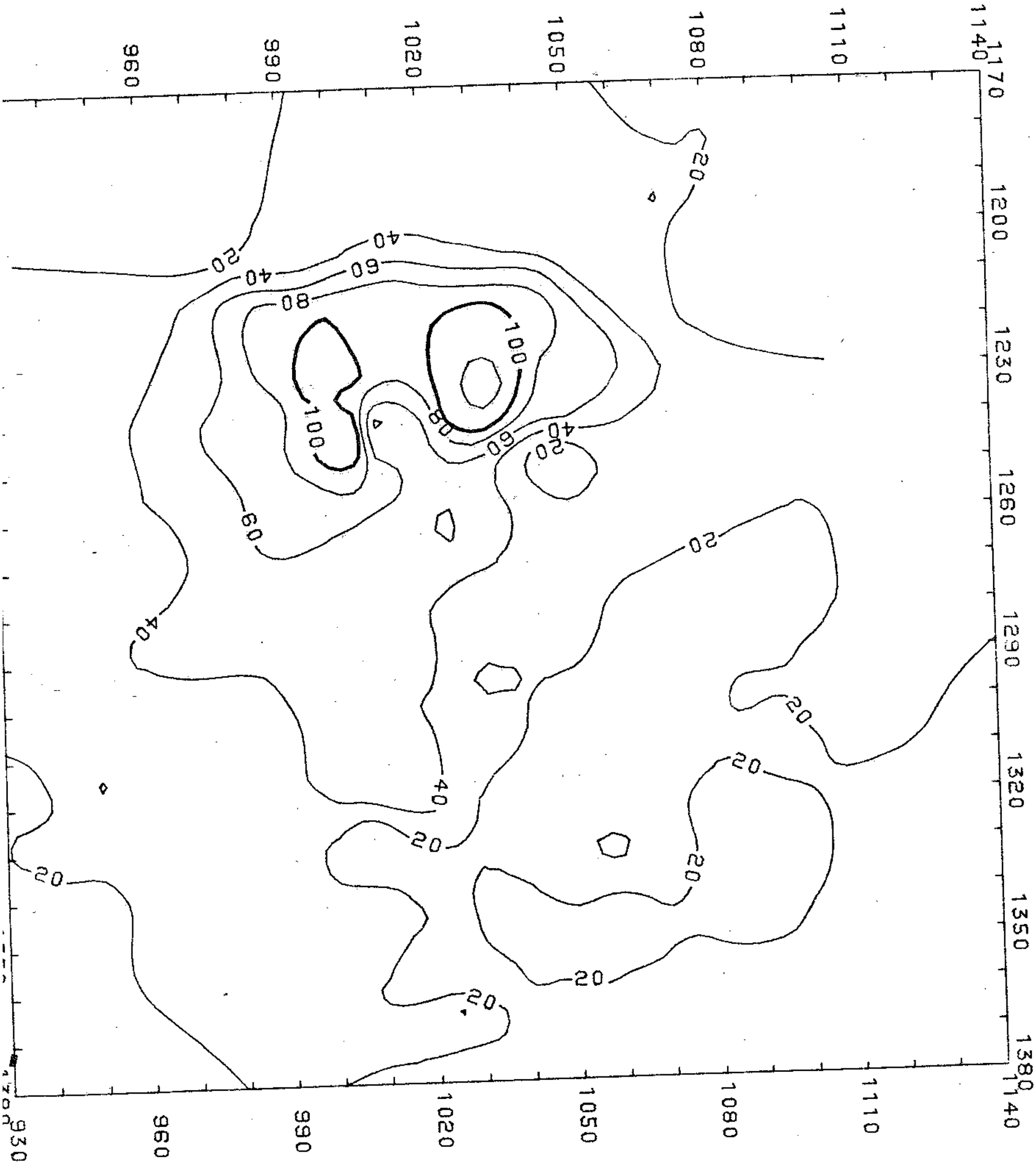


Storm 5 53/02/05



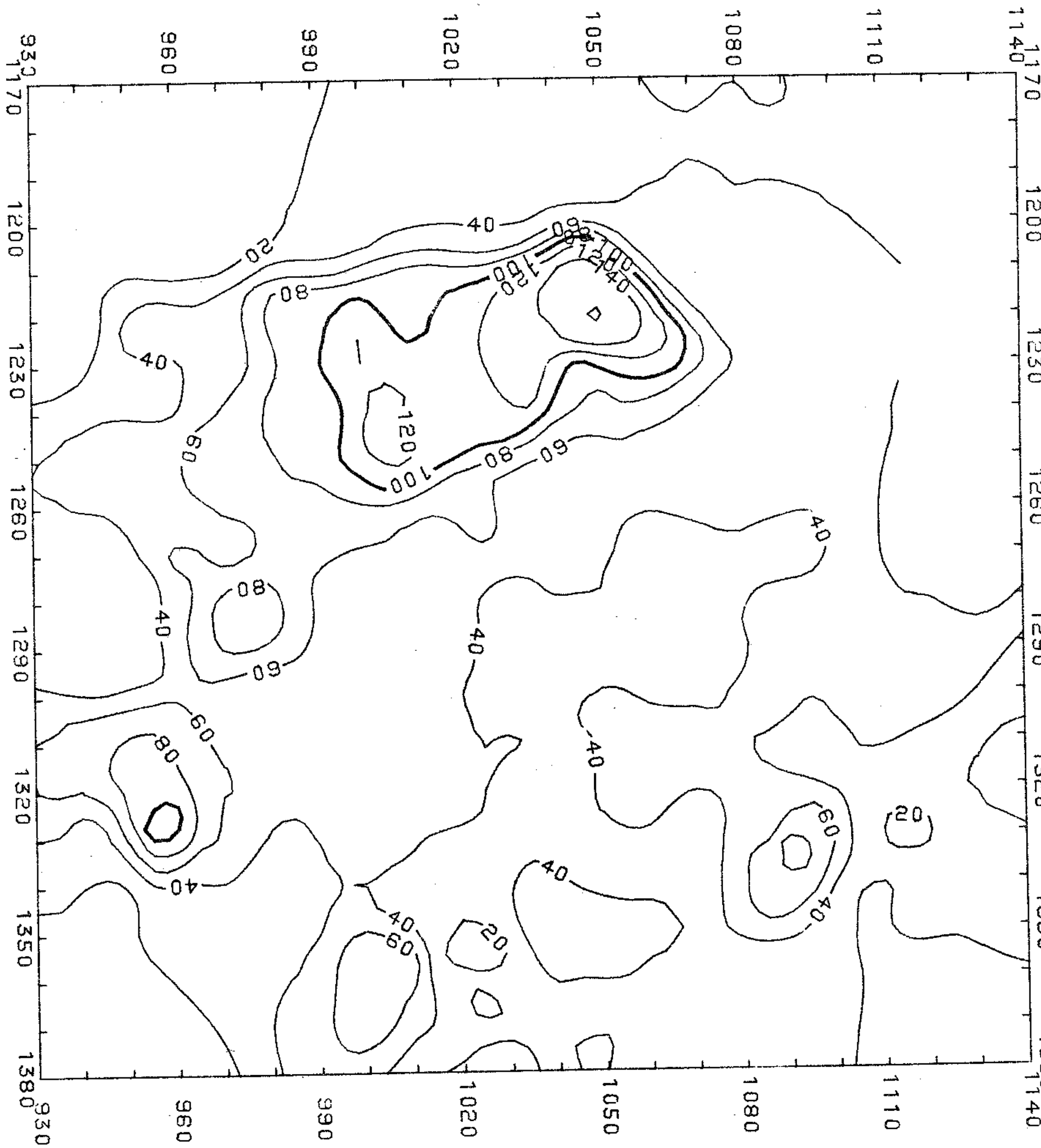
SWA ONE - DAY STORM DATE 53/02/05

PLOT NO. 1 DATE 2/05/80 TIME 12:46:35



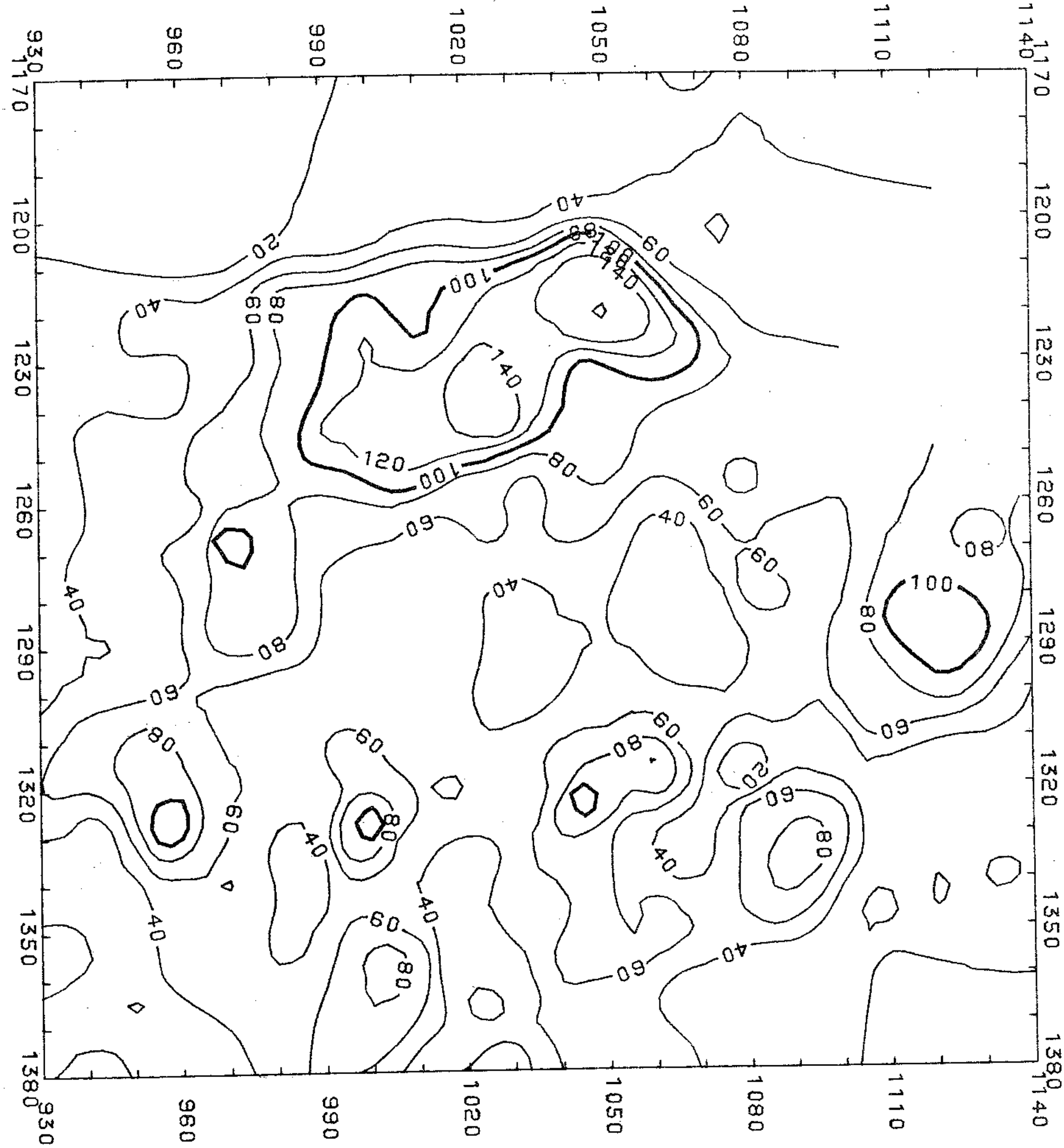
SWA THREE - DAY STORM DATE 53/02/05

PLOT NO. 1 DATE 2/05/80 TIME 12:48:03

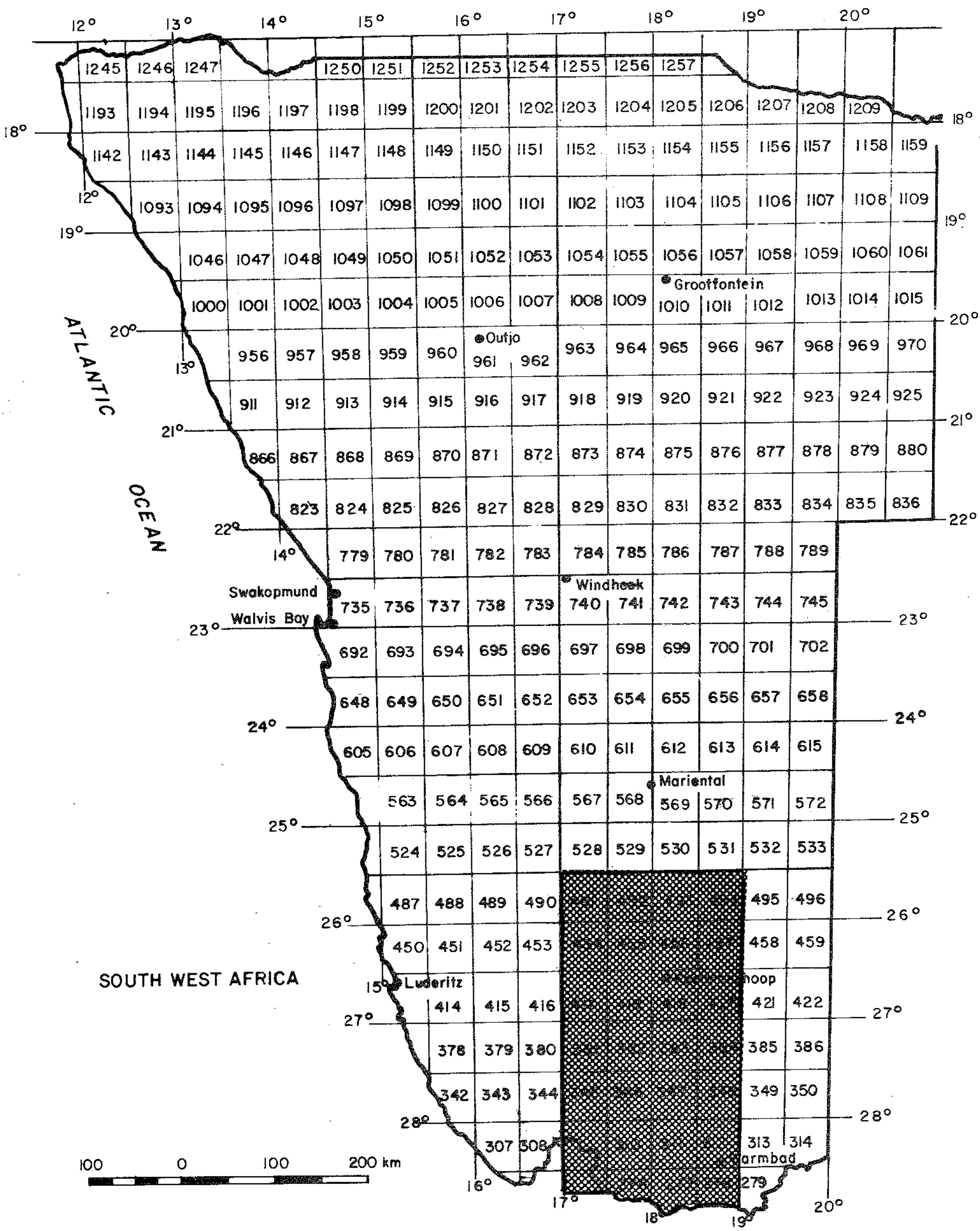


SWA FIVE - DAY STORM DATE 53/02/05

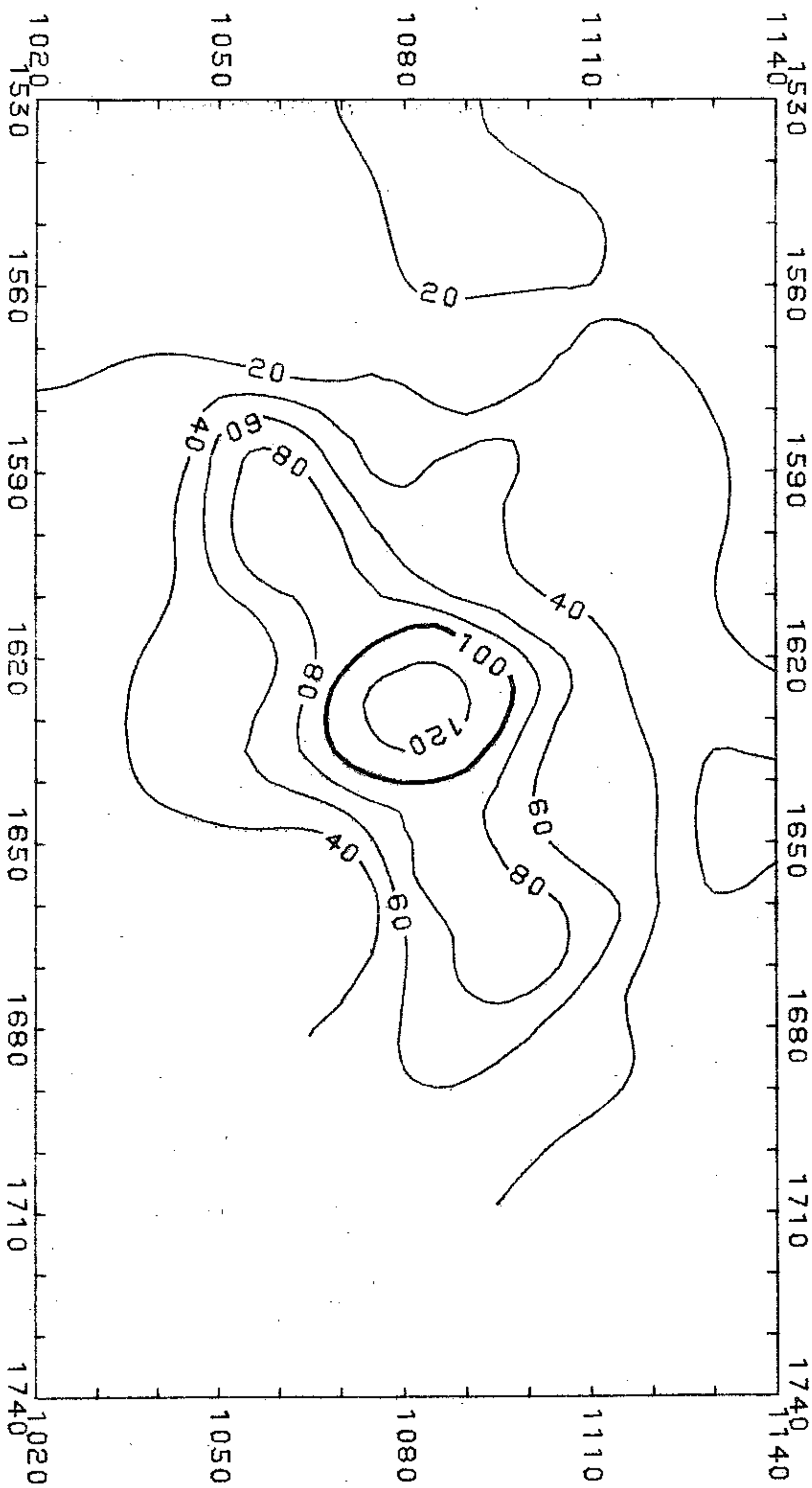
PLOT NO. 1 DATE 2/05/80 TIME 12:50:39



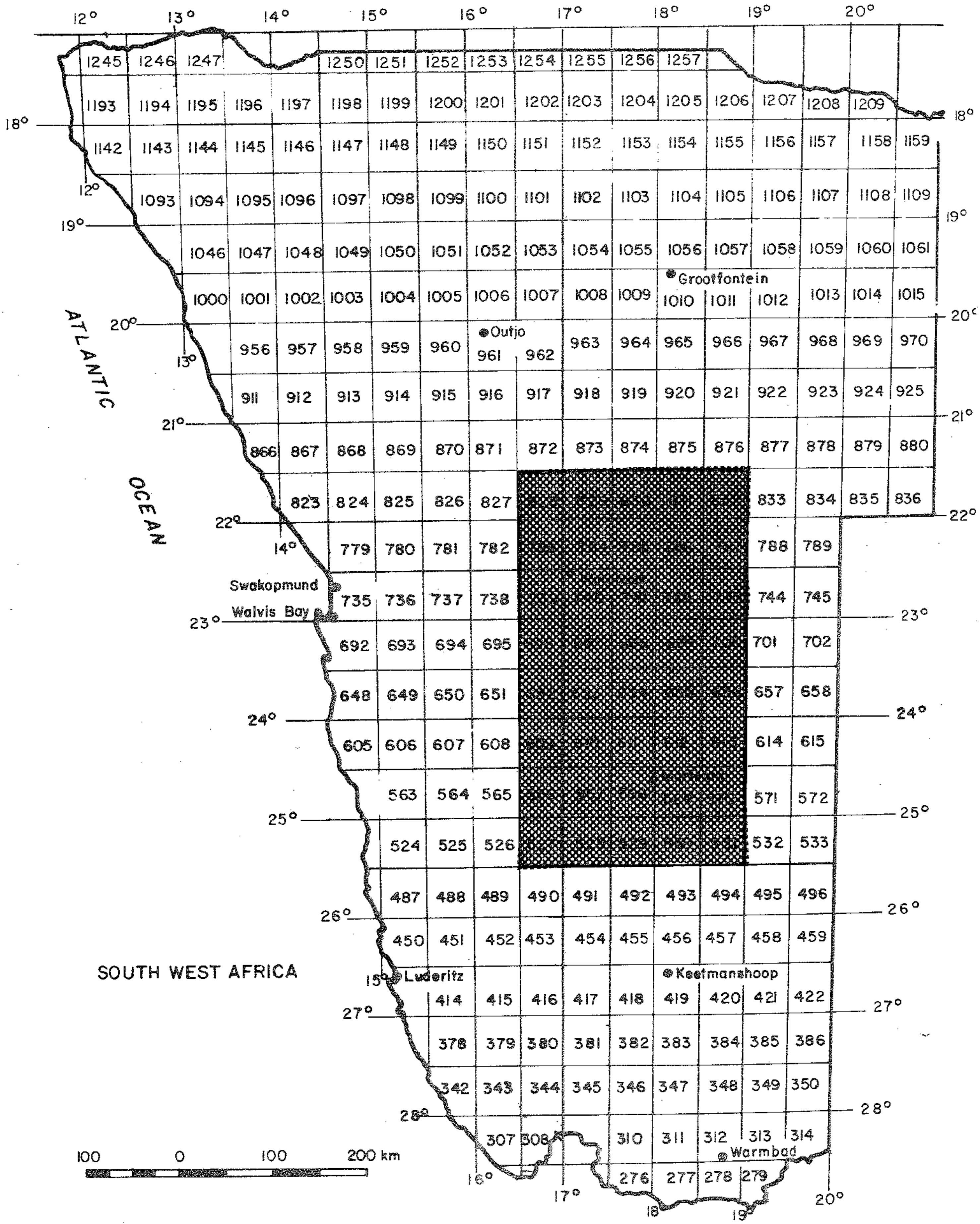
Storm 6 53/12/18



SWA ONE - DAY STORM DATE 53/12/18
PLOT NO. 1 DATE 2/05/80 TIME 12:50:51



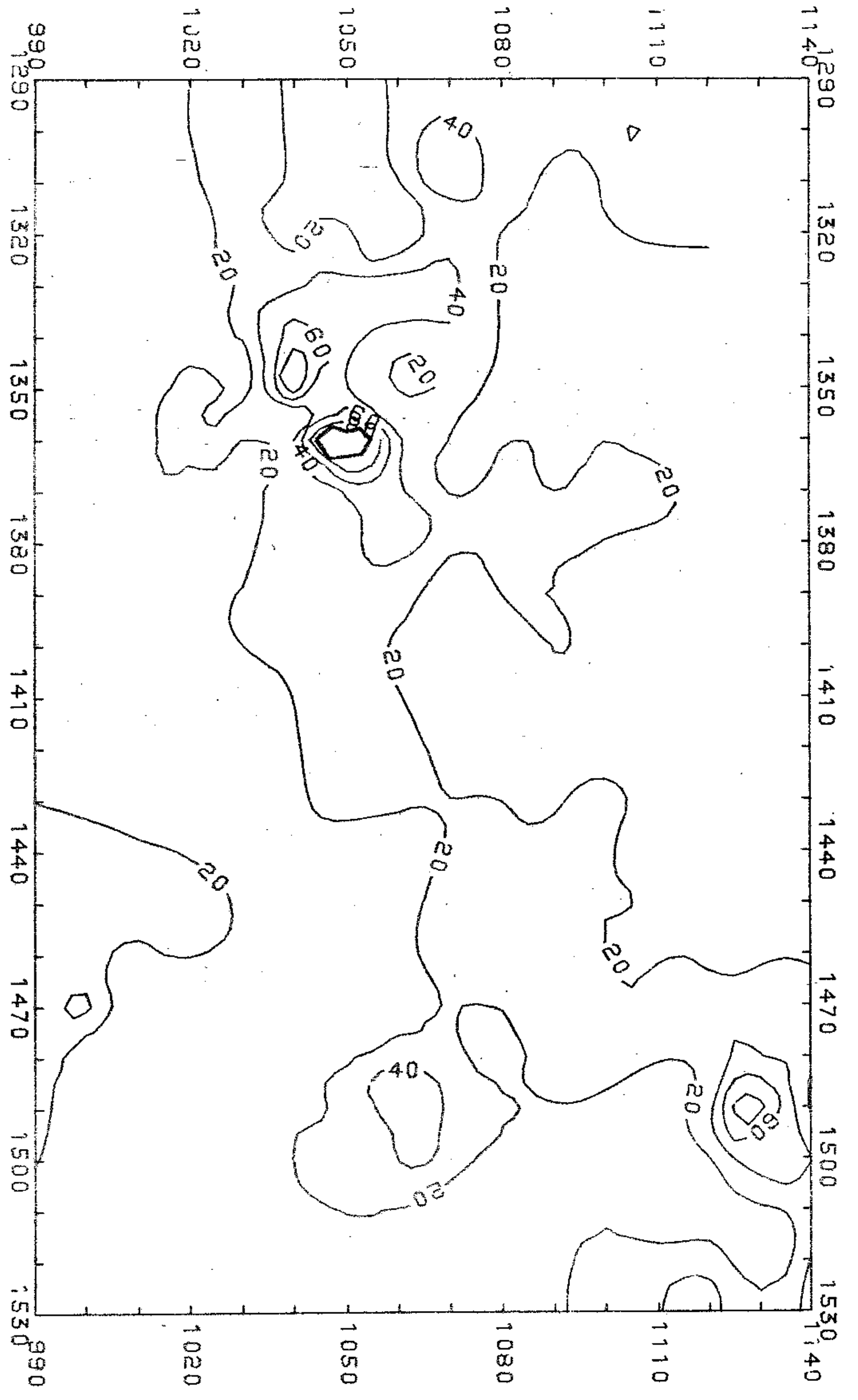
Storm 7 56/02/08



B24

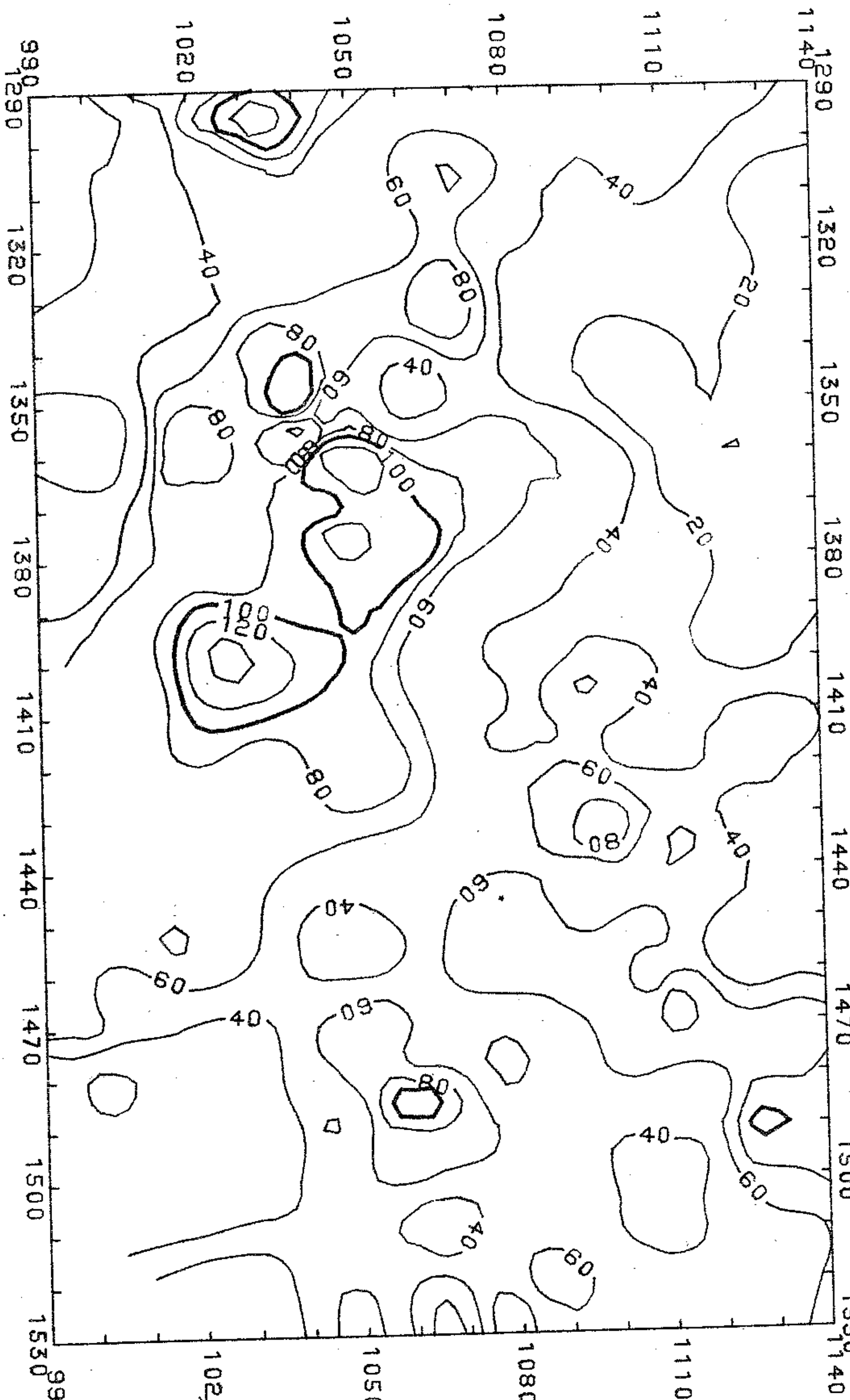
SWA ONE - DAY STORM DATE 56/02/08

PLOT NO. 1 DATE 2/11/80 TIME 14:36:38

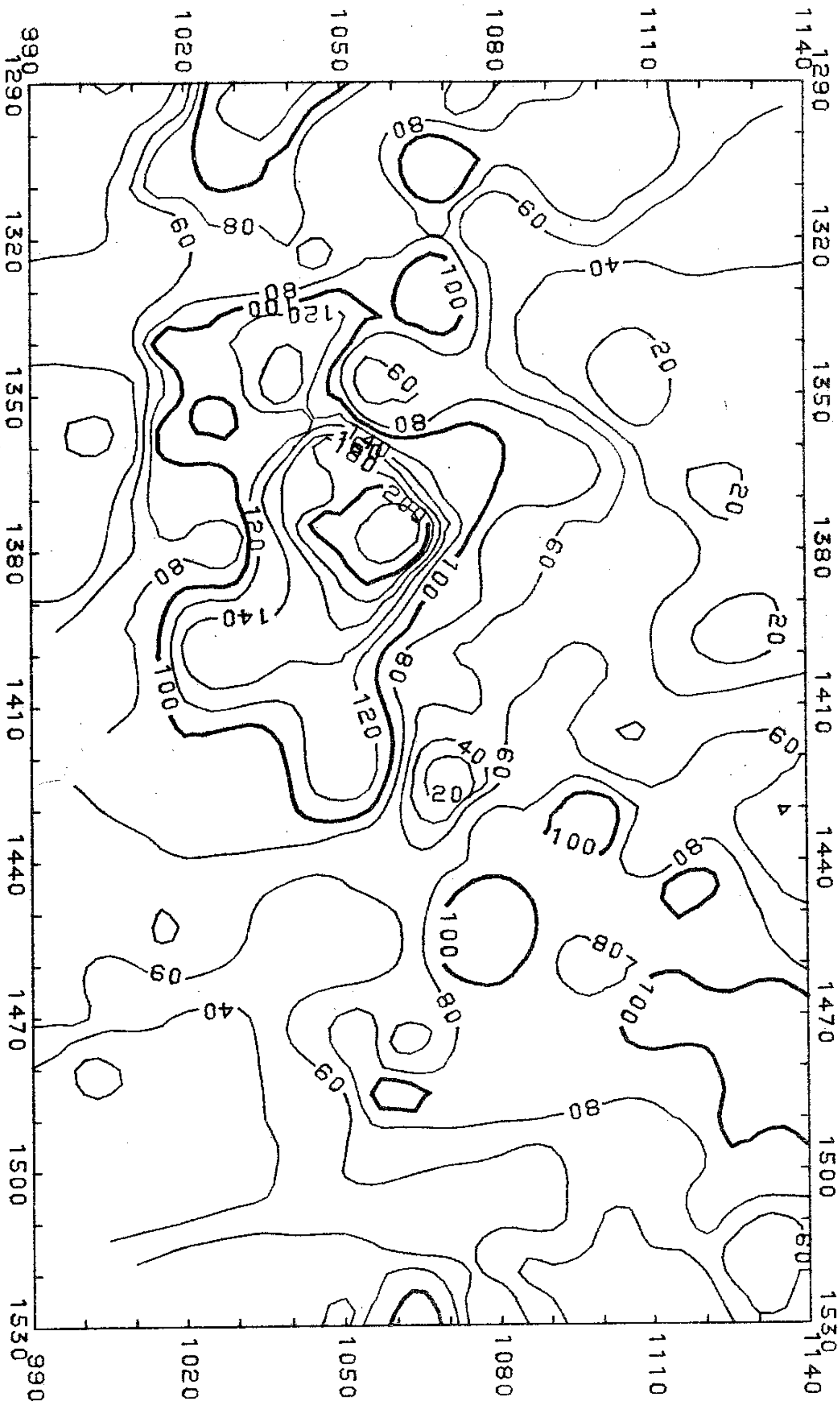


SWA THREE - DAY STORM DATE 56/02/08

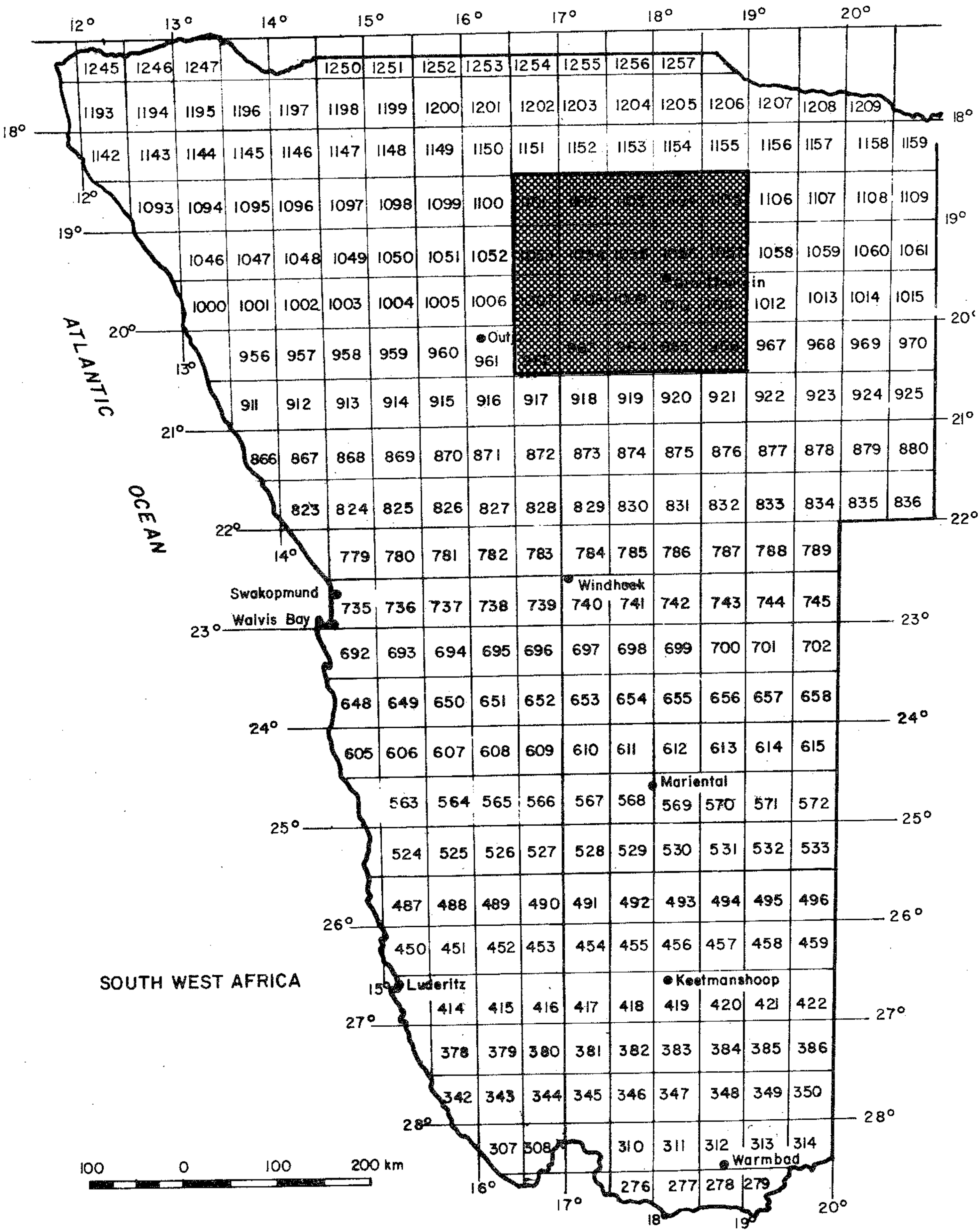
PLOT NO. 1 DATE 2/11/80 TIME 11.08:50



SWA FIVE - DAY STORM DATE 56/02/08
PLOT NO. 1 DATE 2/11/80 TIME 11:09:49

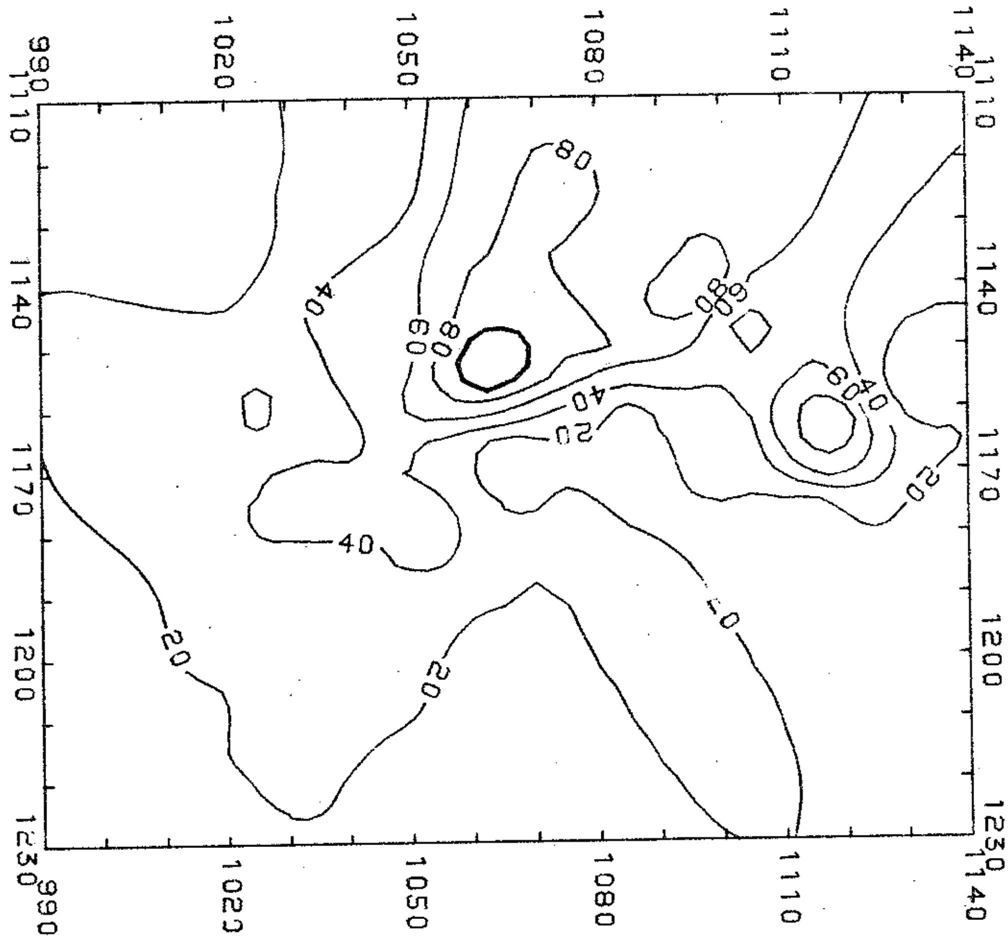


Storm 8 56/02/22

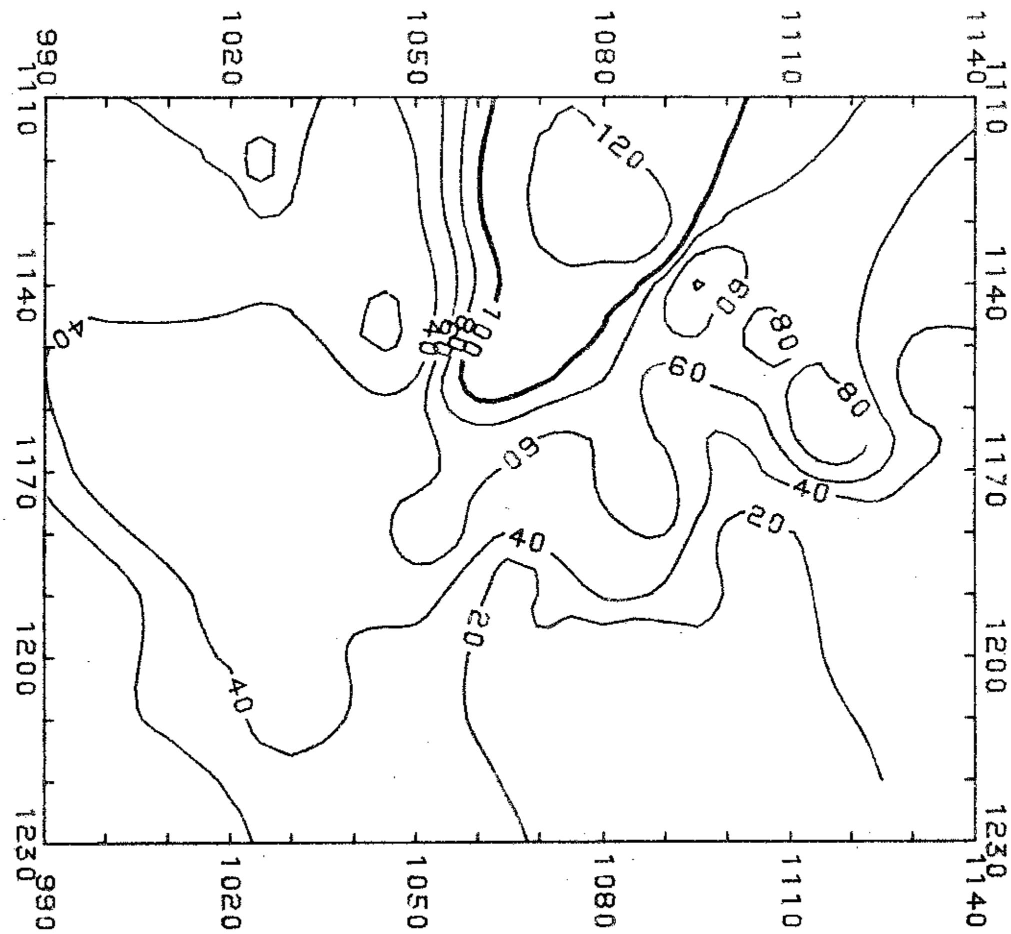


SWA ONE - DAY STORM DATE 56/02/22

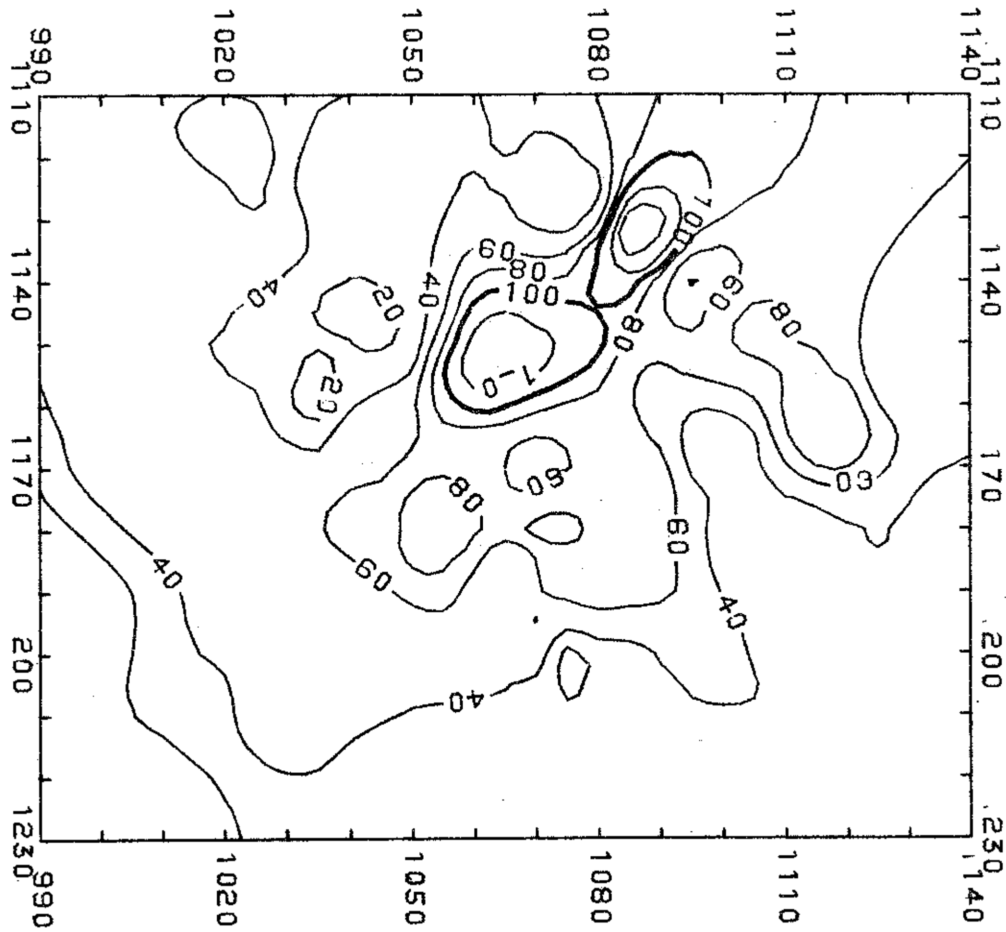
PLOT NO. 1 DATE 2/06/80 TIME 9:48:38



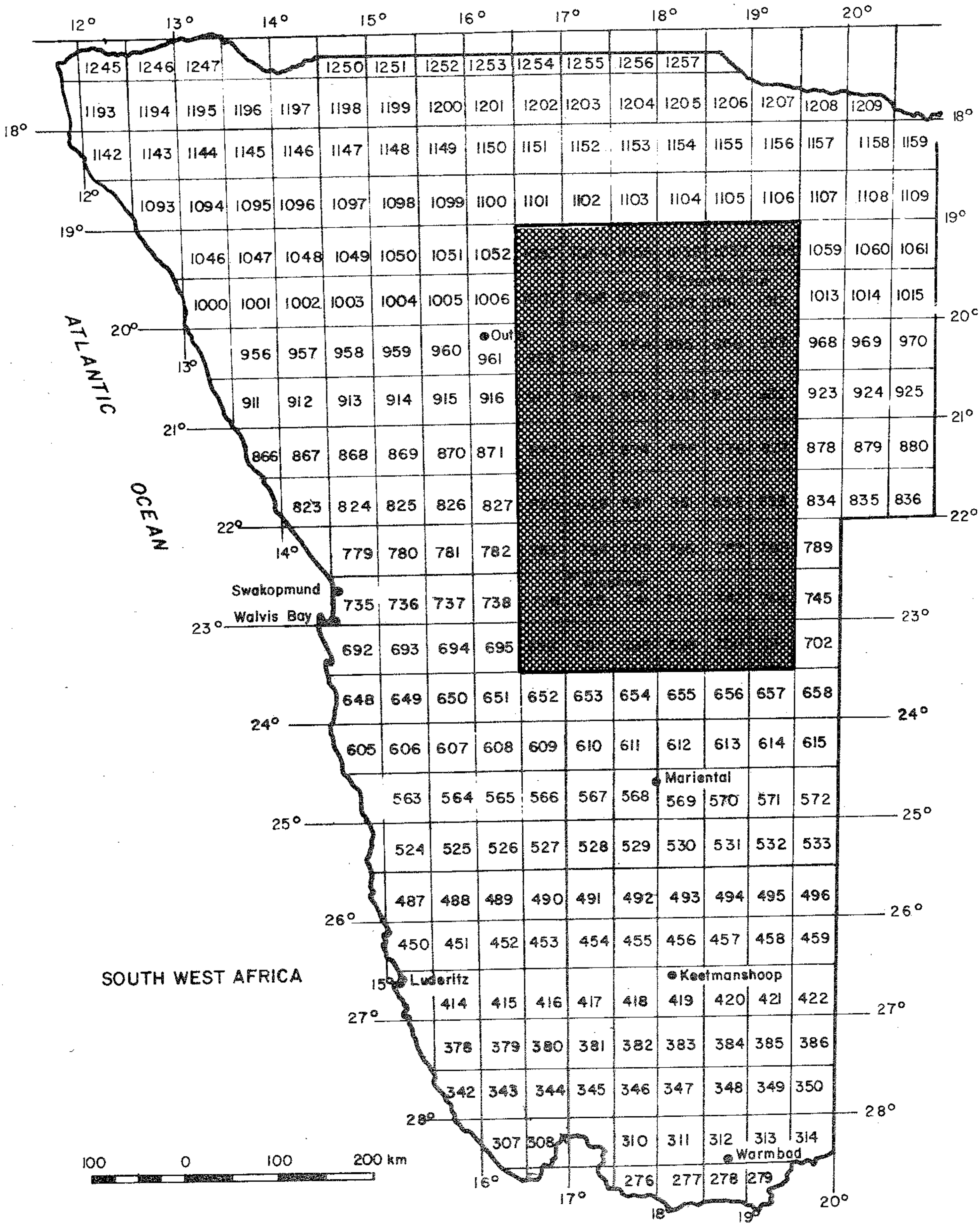
SWA THREE - DAY STORM DATE 56/02/22
PLOT NO. 1 DATE 2/06/80 TIME 9:54:07



SWA FIVE - DAY STORM DATE 56/02/22
PLOT NO. 1 DATE 2/07/80 TIME 8:56:58

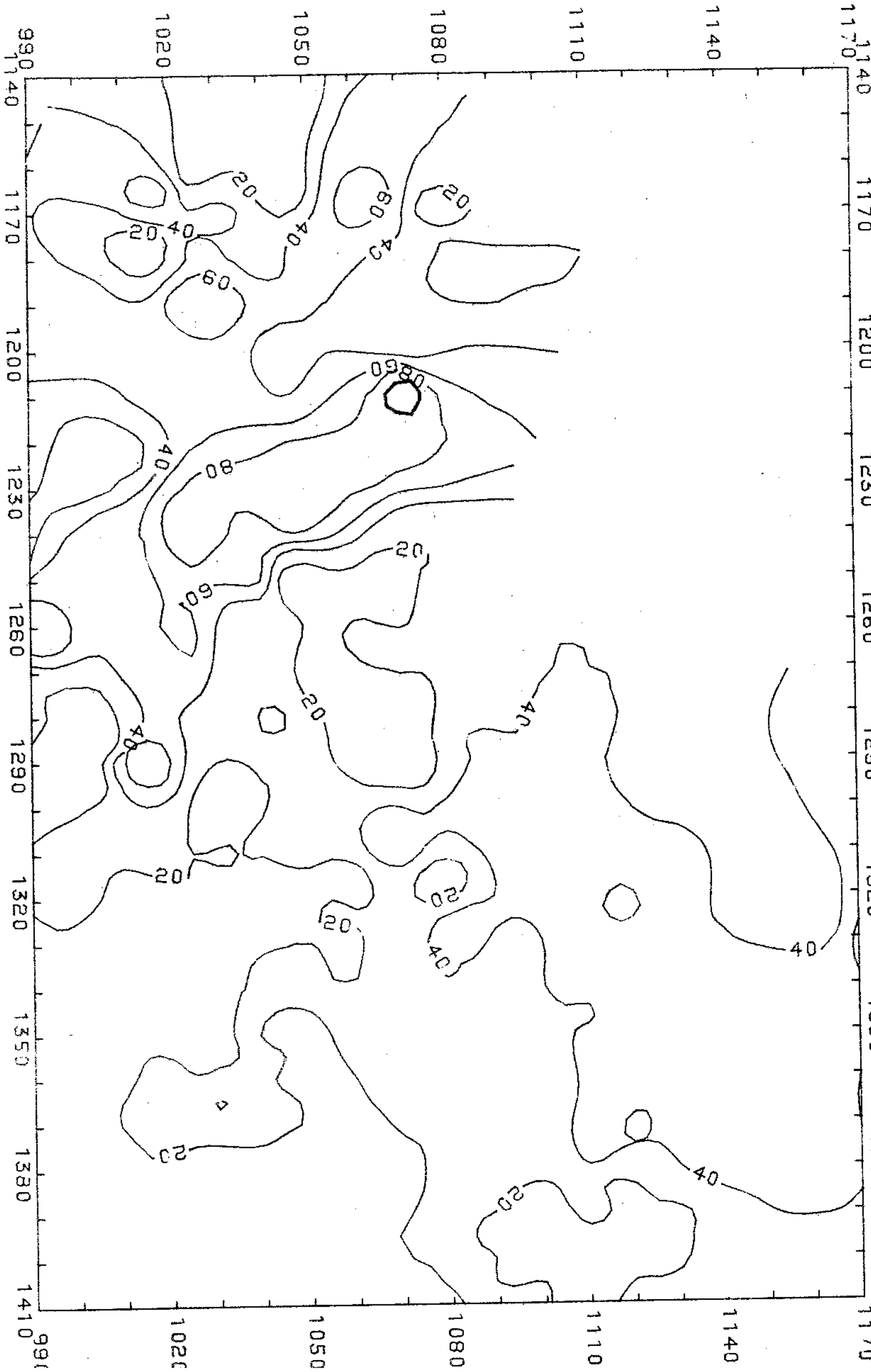


Storm 9 60/02/23



SWA ONE - DAY STORM DATE 60/02/23

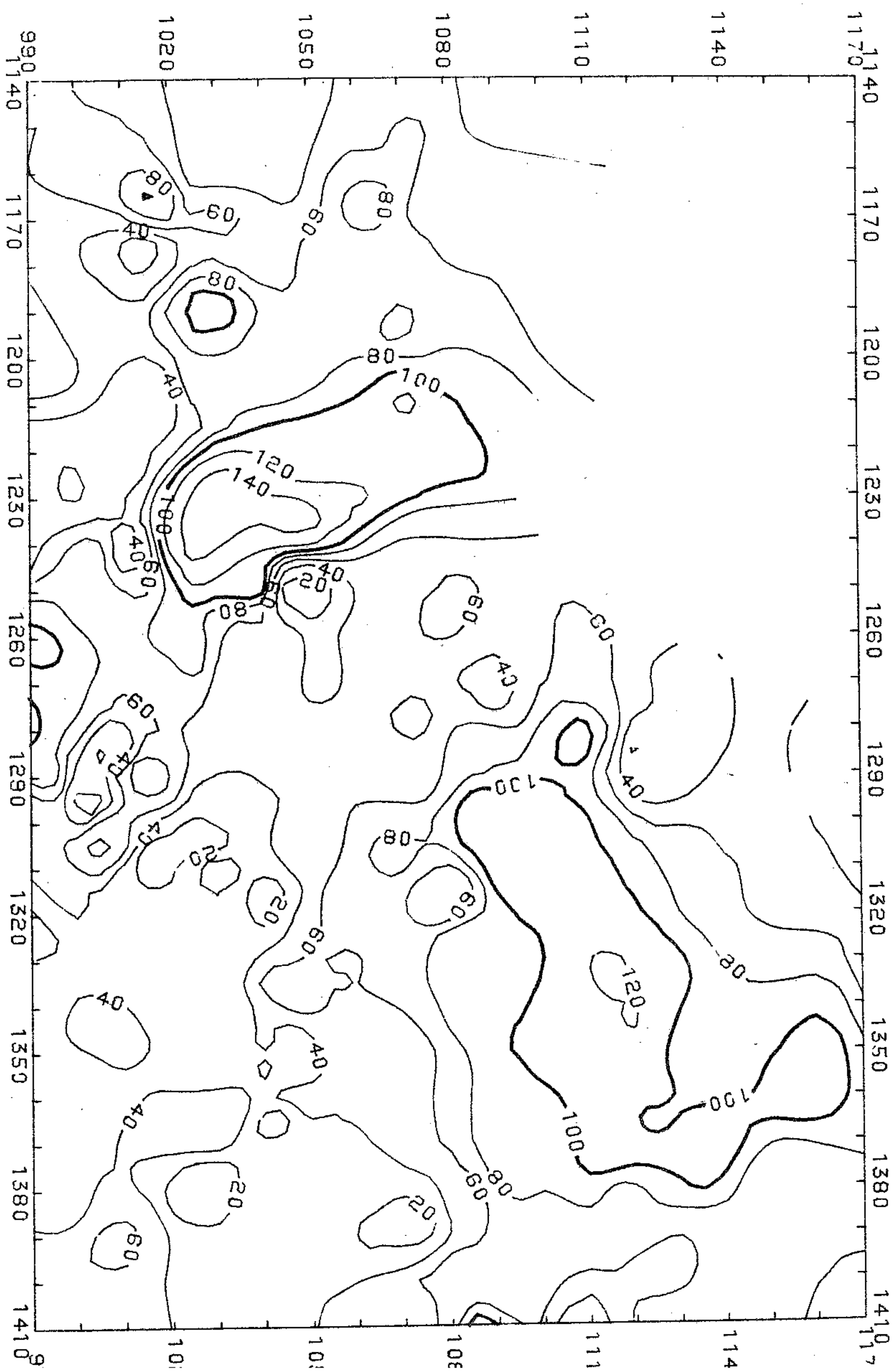
PLOT NO. 1 DATE 2/06/80 TIME 3:27:21



B33

SWA THREE - DAY STORM DATE 60/02/23

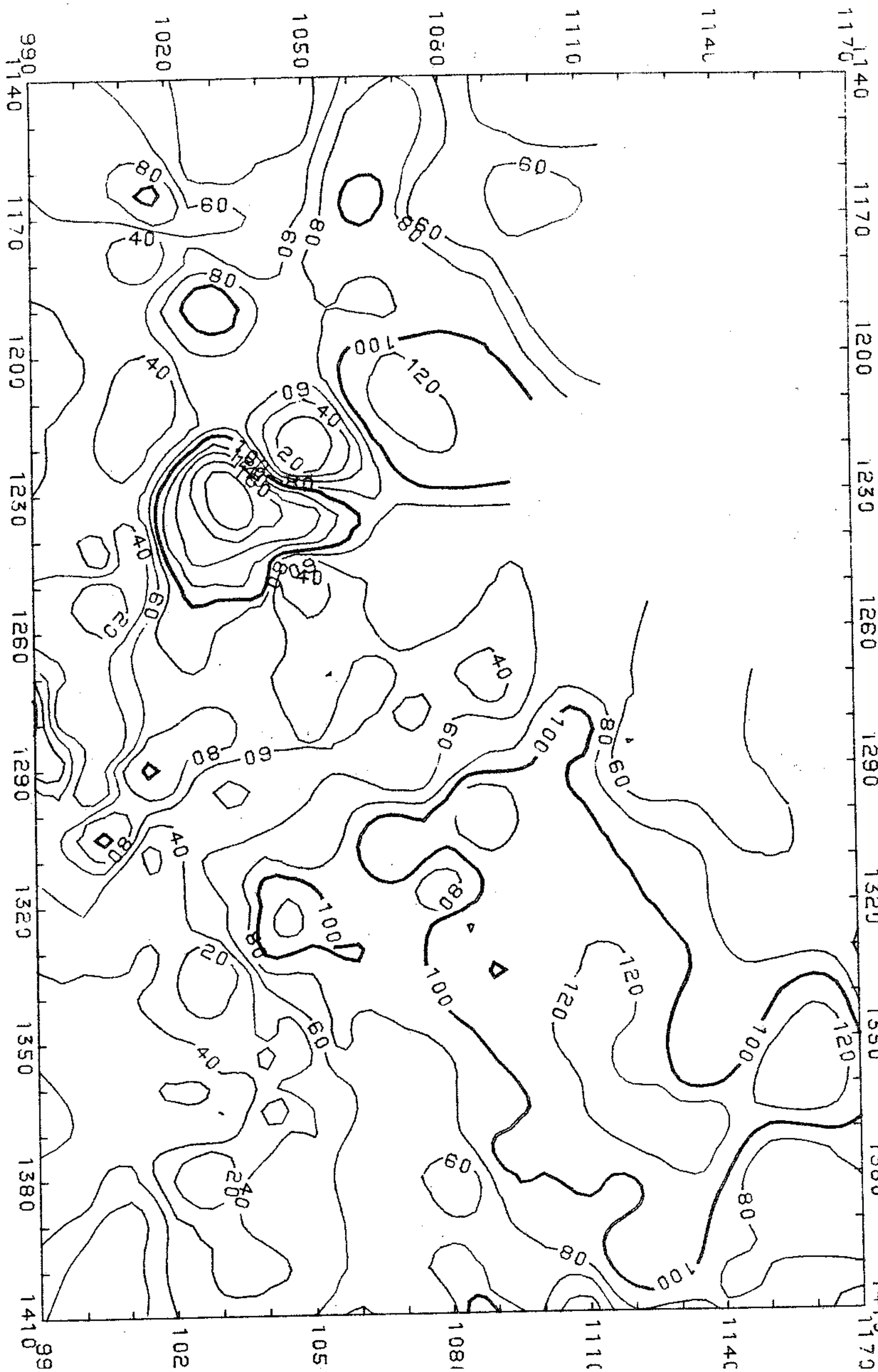
PLOT NO. 1 DATE 2/06/80 TIME 9:30:27



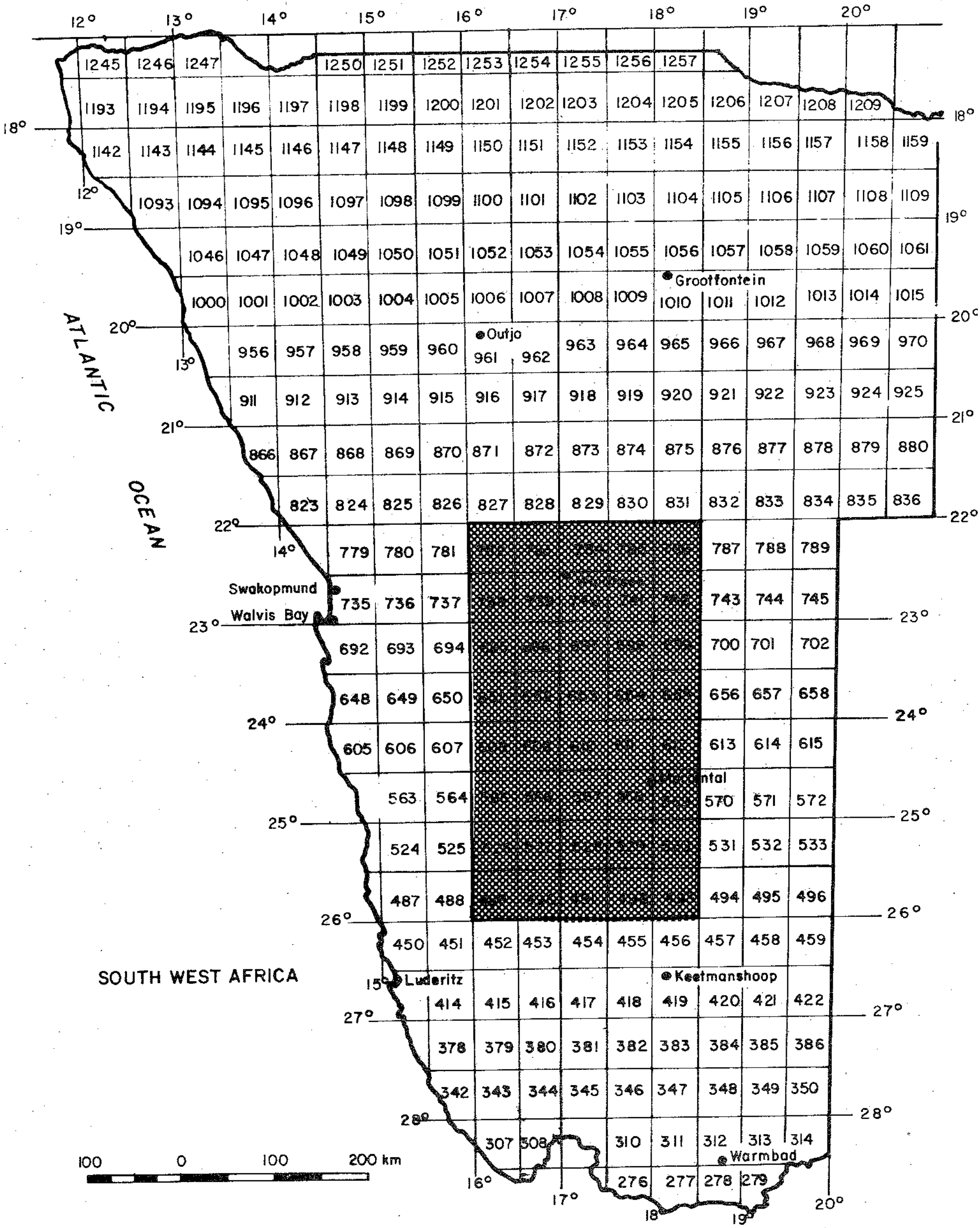
B34

SWA FIVE - DAY STORM DATE 60/02/23

PLOT NO. 1 DATE 2/06/80 TIME 9:48:24

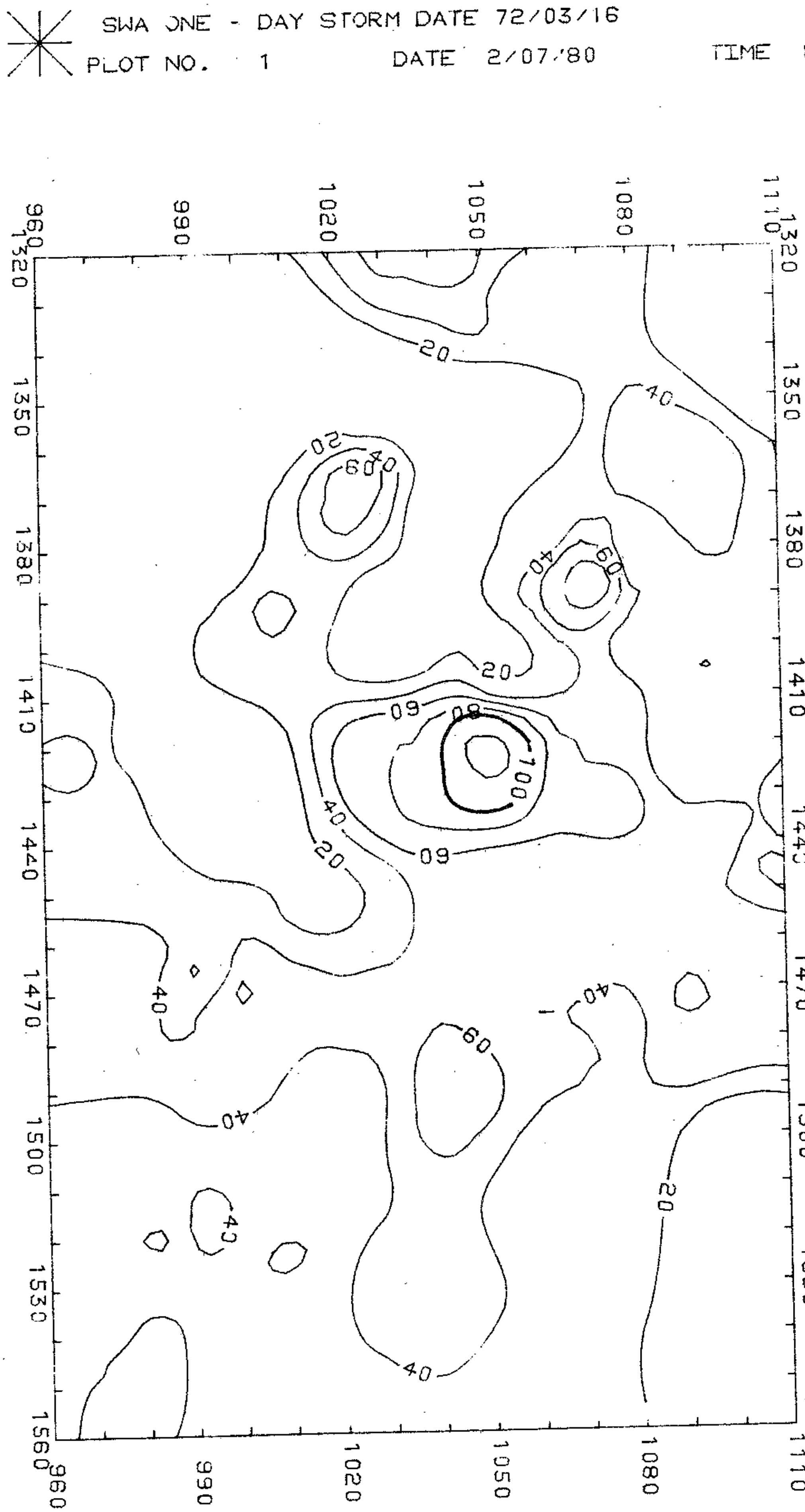


Storm 10 72/03/16



SWA ONE - DAY STORM DATE 72/03/16

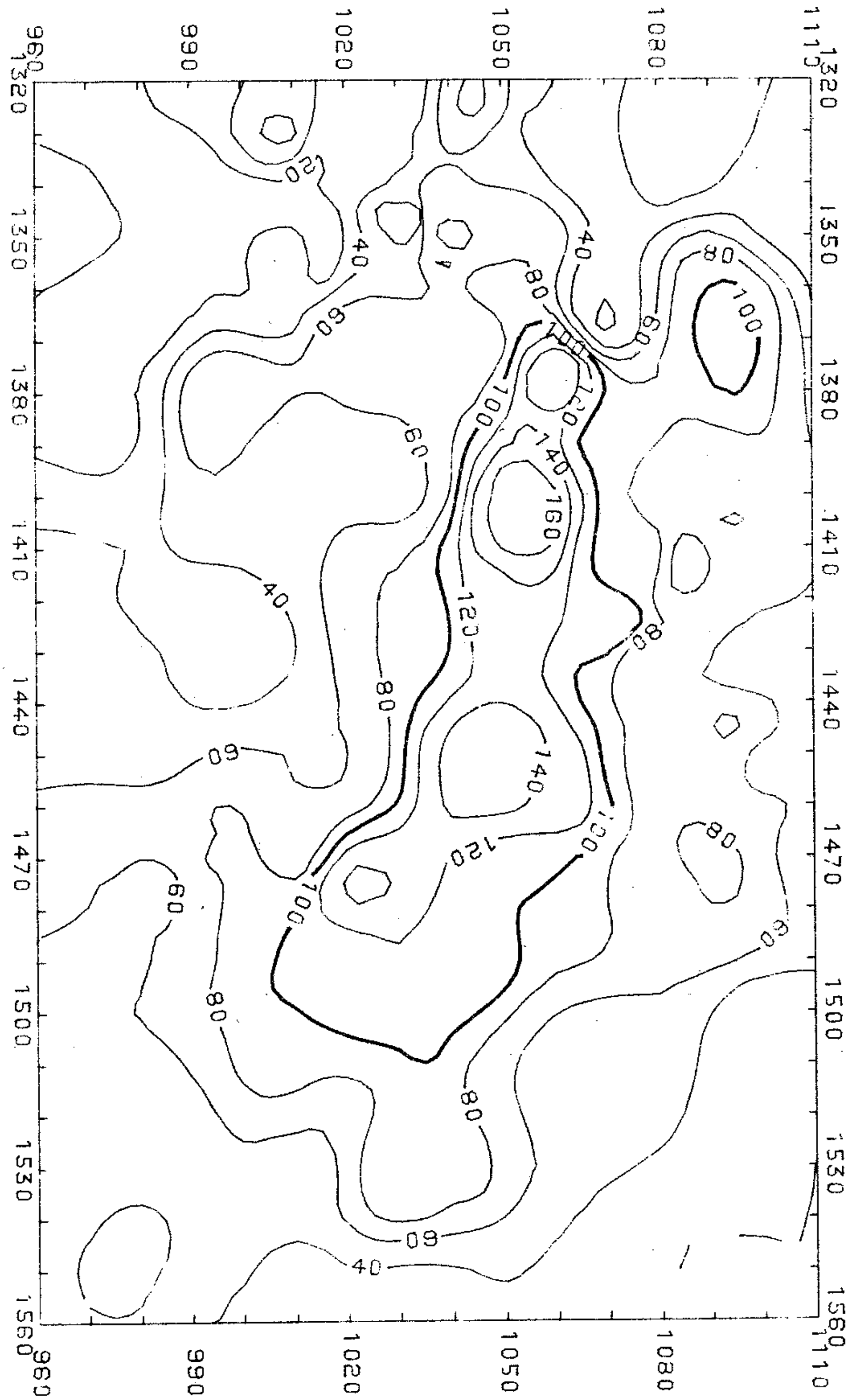
PLOT NO. 1 DATE 2/07/80 TIME 8:59:58



B37

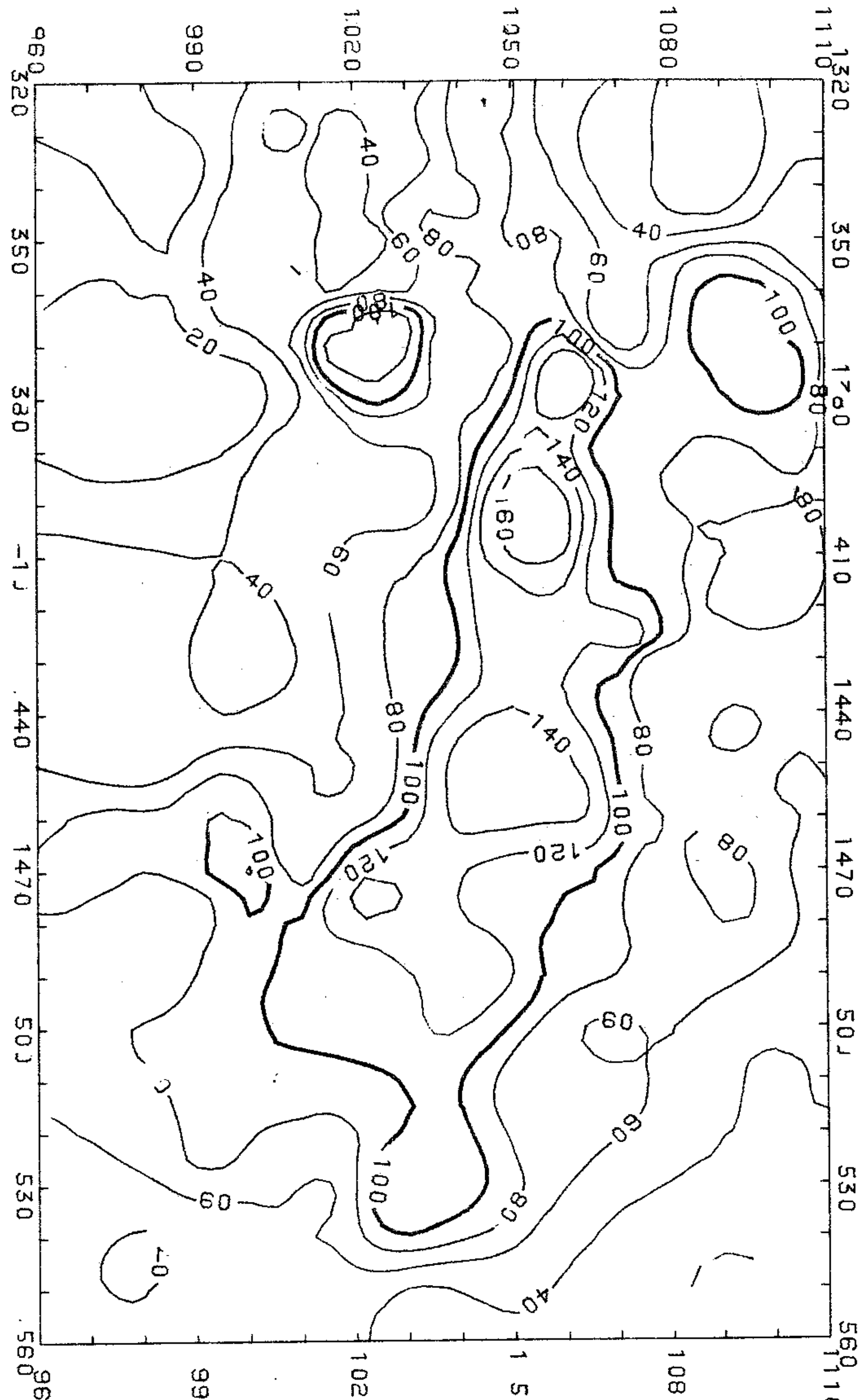
SWA THREE - DAY STORM DATE 72/03/16

PLOT NO. 1 DATE 2/07/80 TIME 9:06:26

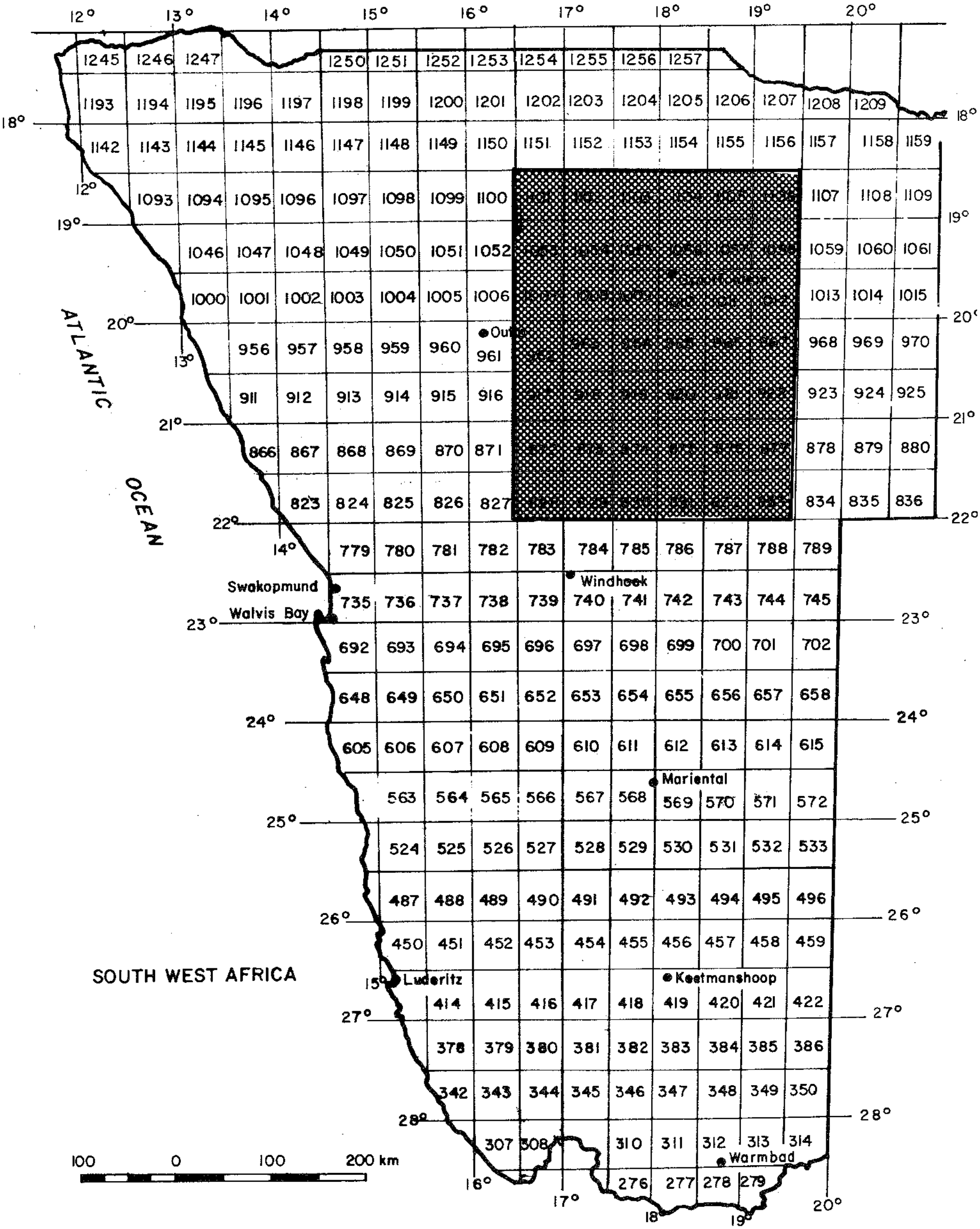


SWA FIVE - DAY STORM DATE 72/03/16

PLOT NO. 1 DATE 2/07/80 TIME 9:07:52

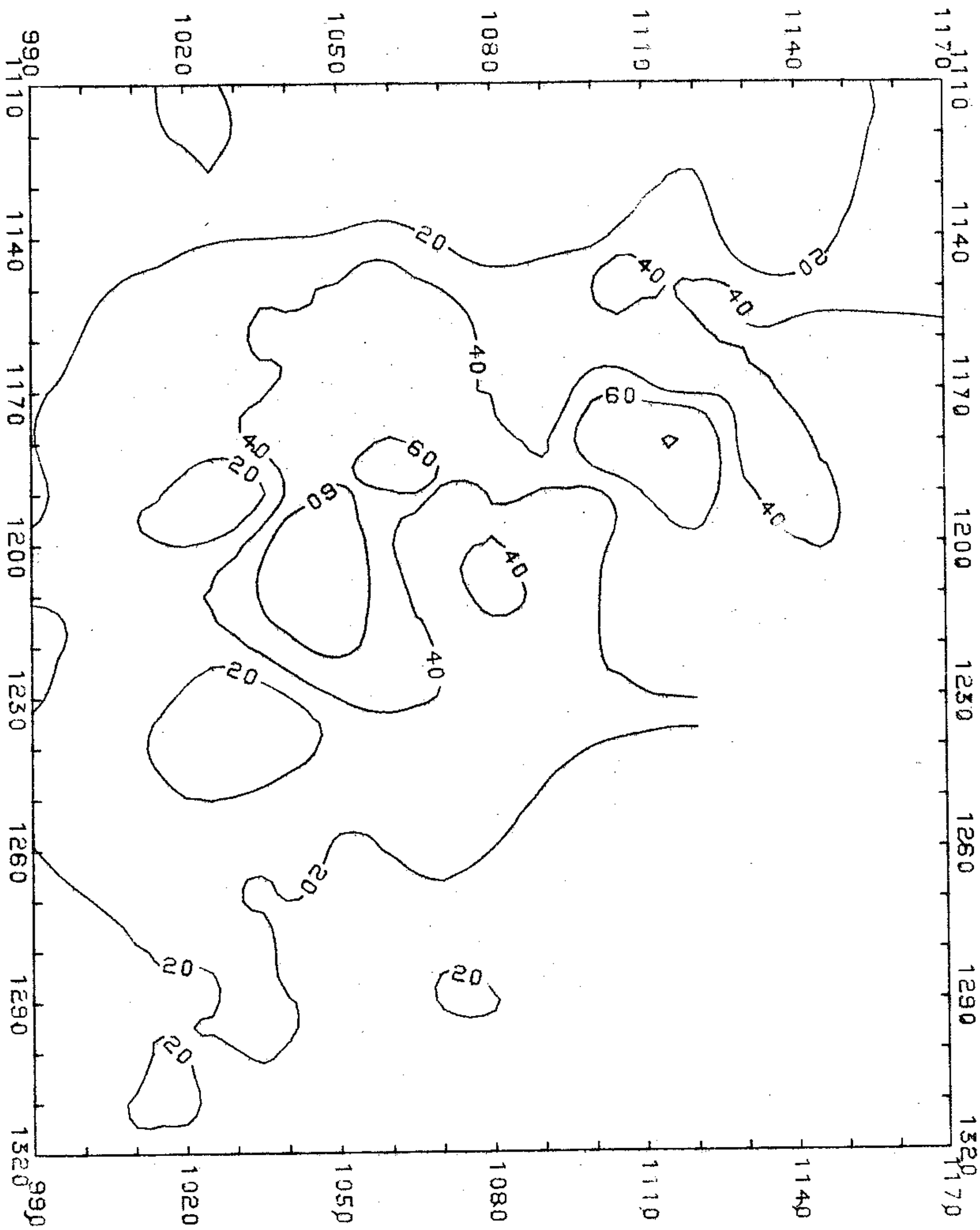


Storm 11 74/01/12



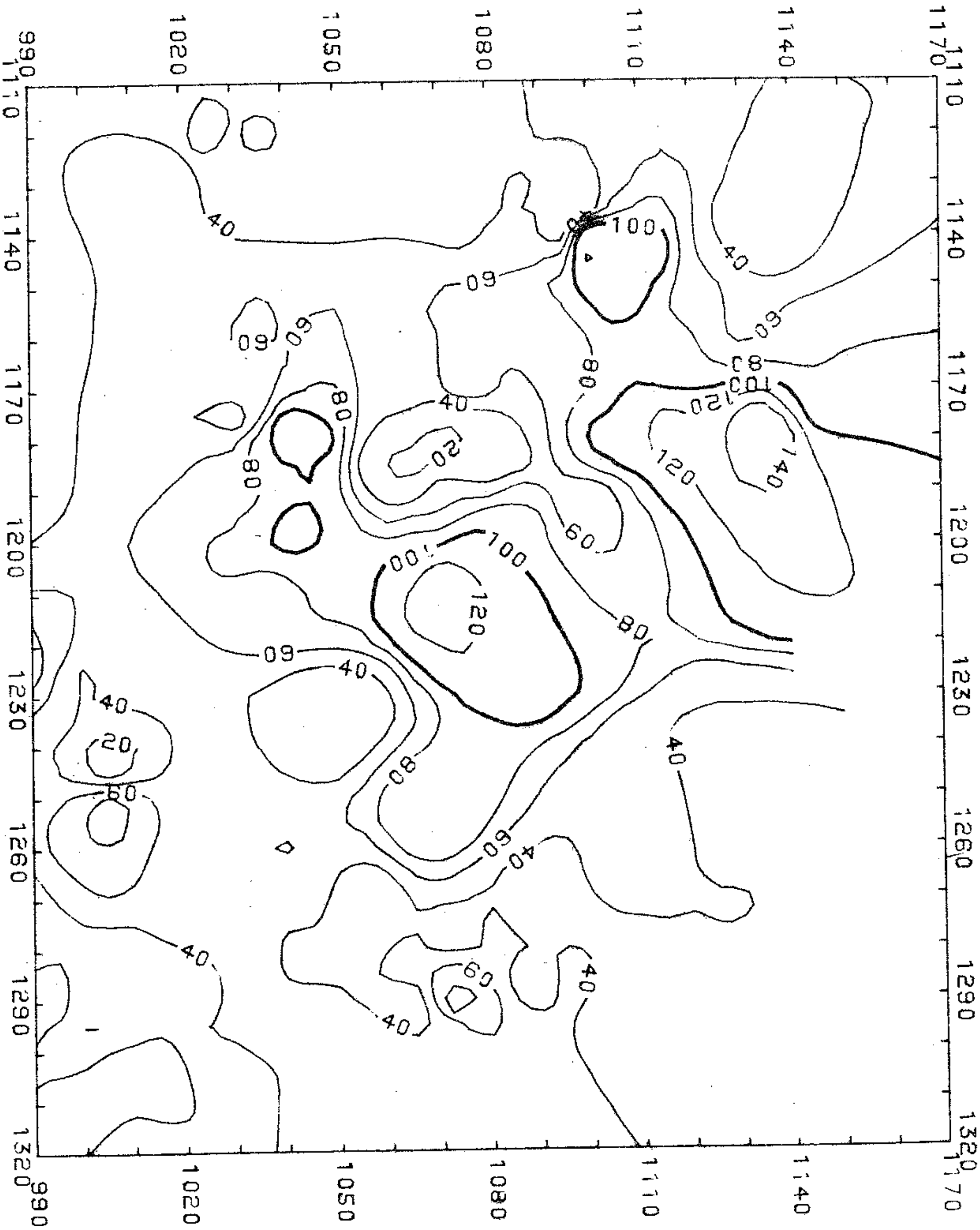
SWA ONE - DAY STORM DATE 74/01/12

PLOT NO. 1 DATE 2/08/80 TIME 11:56:16



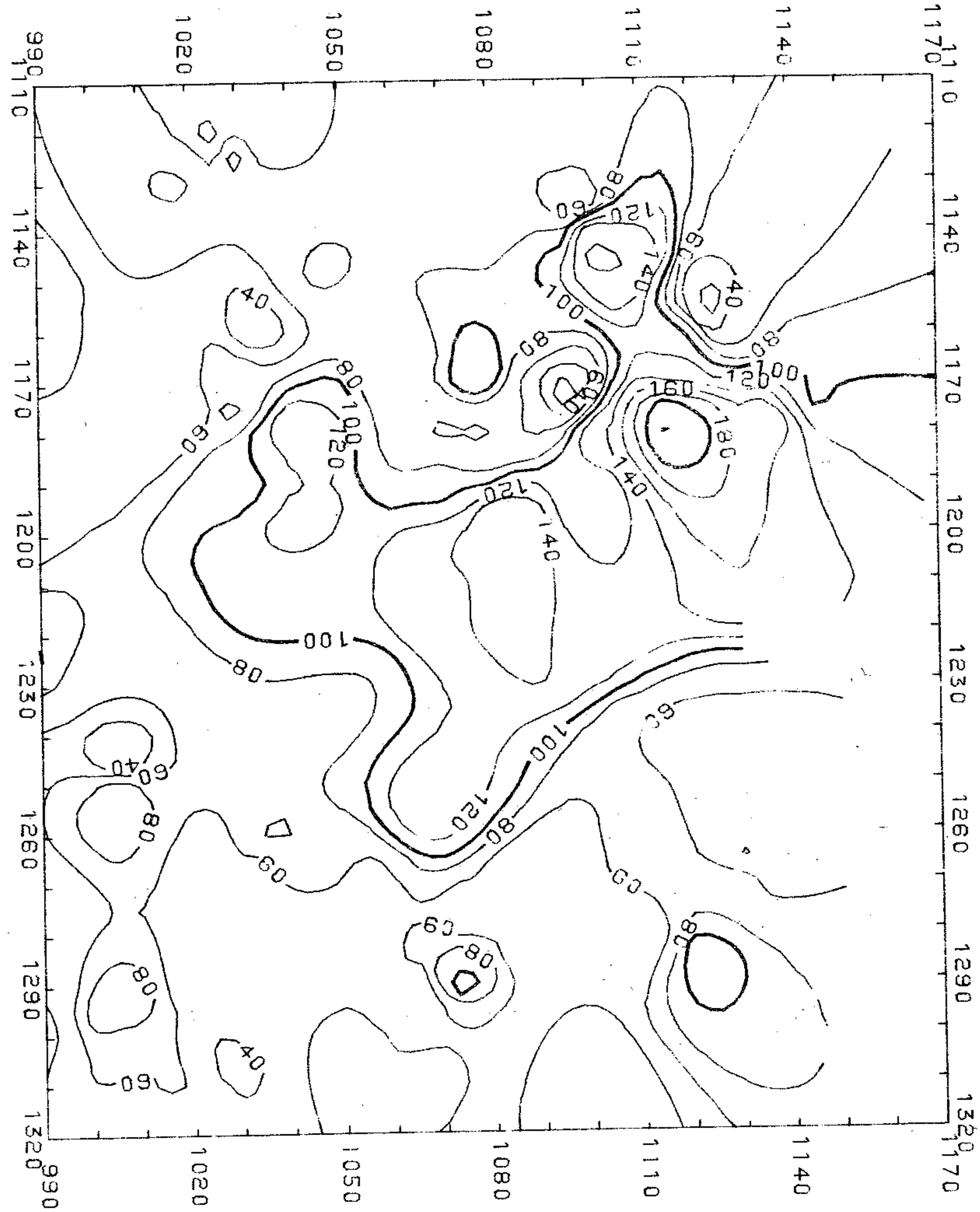
B41

SWA THREE - DAY STORM DATE 74/01/12
PLOT NO. 1 DATE 2/08/80 TIME 12:01:40

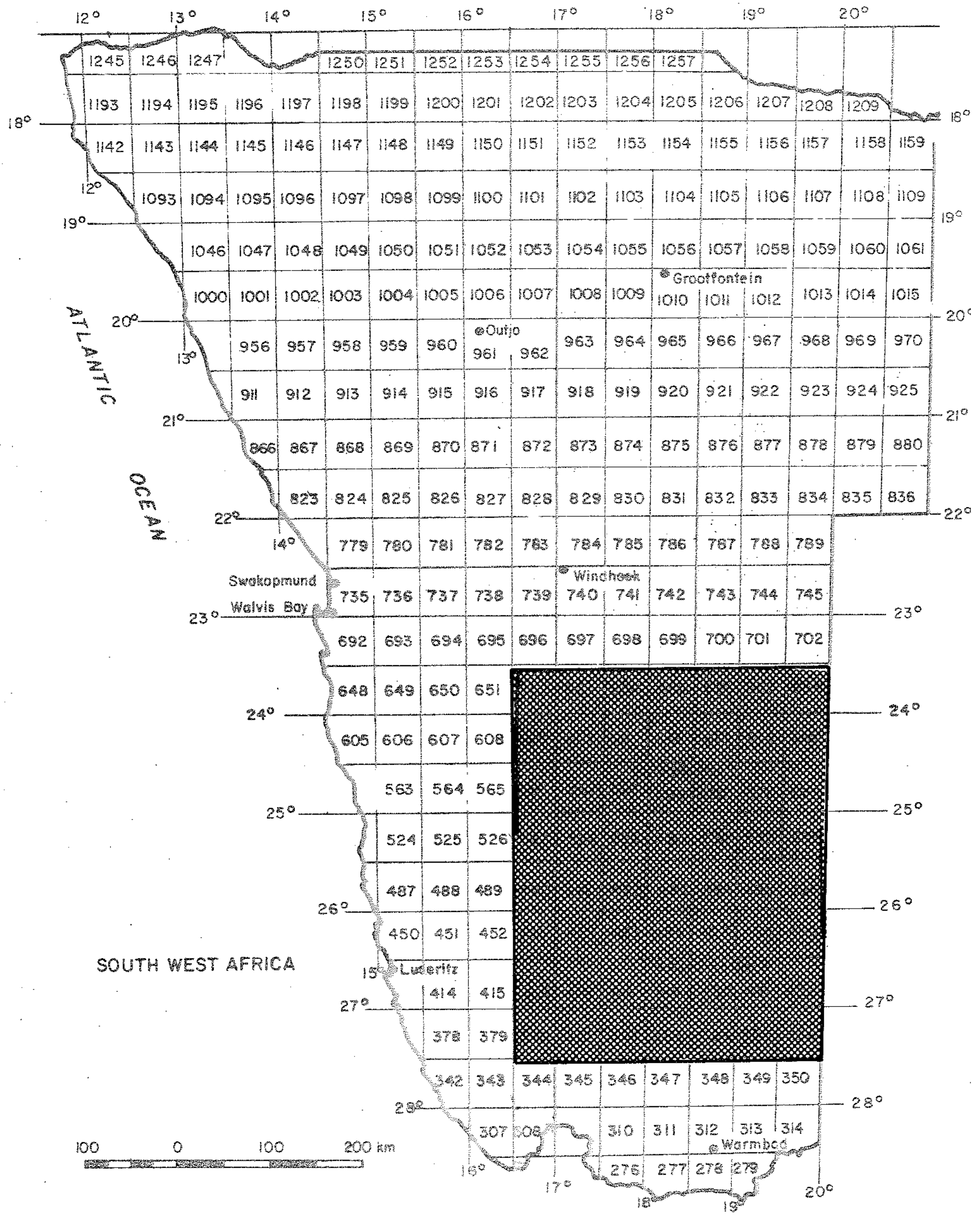


SWA FIVE - DAY STORM DATE 74/01/12

PLOT NO. 1 DATE 2/11/80 TIME 14:33:20

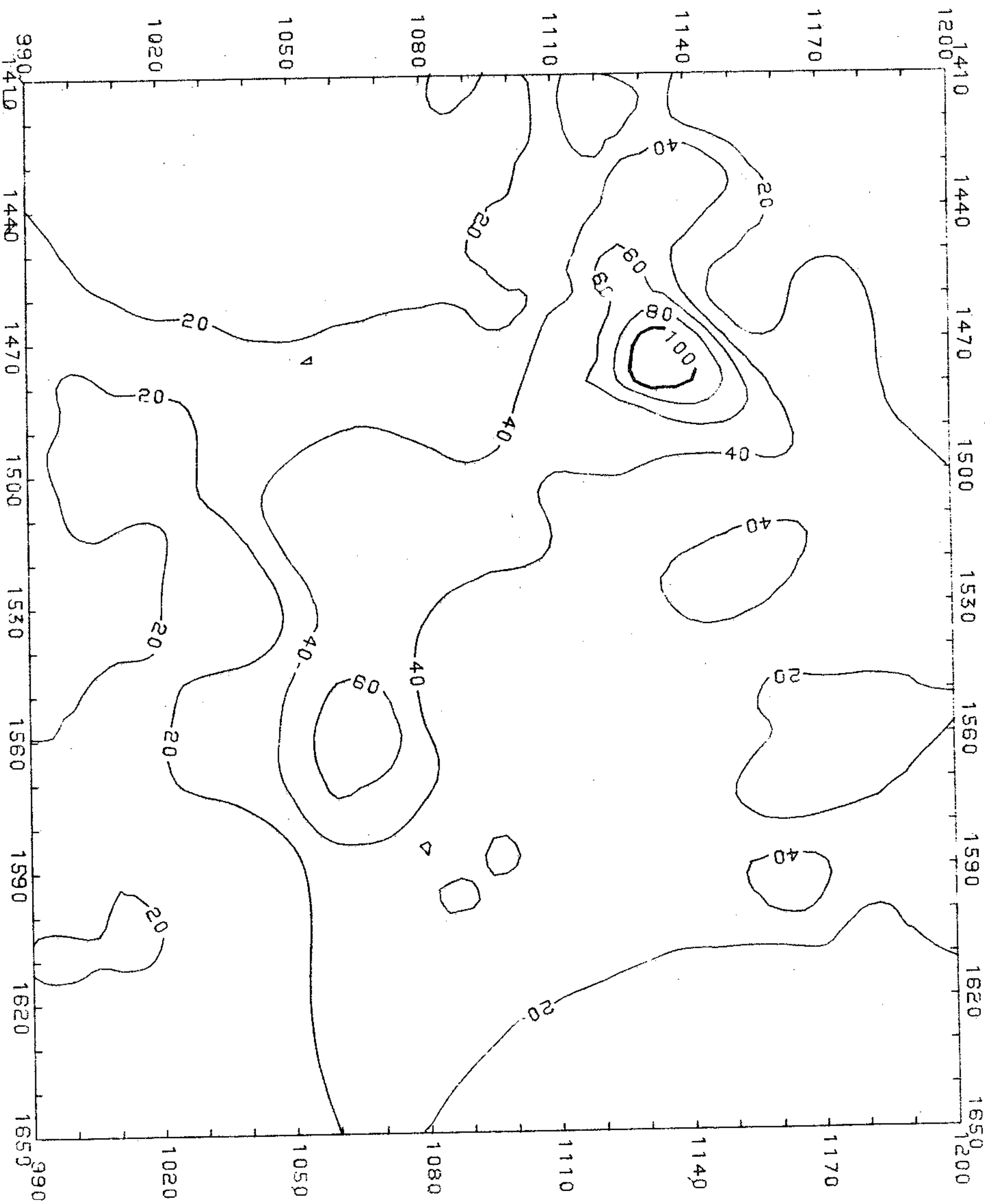


Storm 12 74/02/01



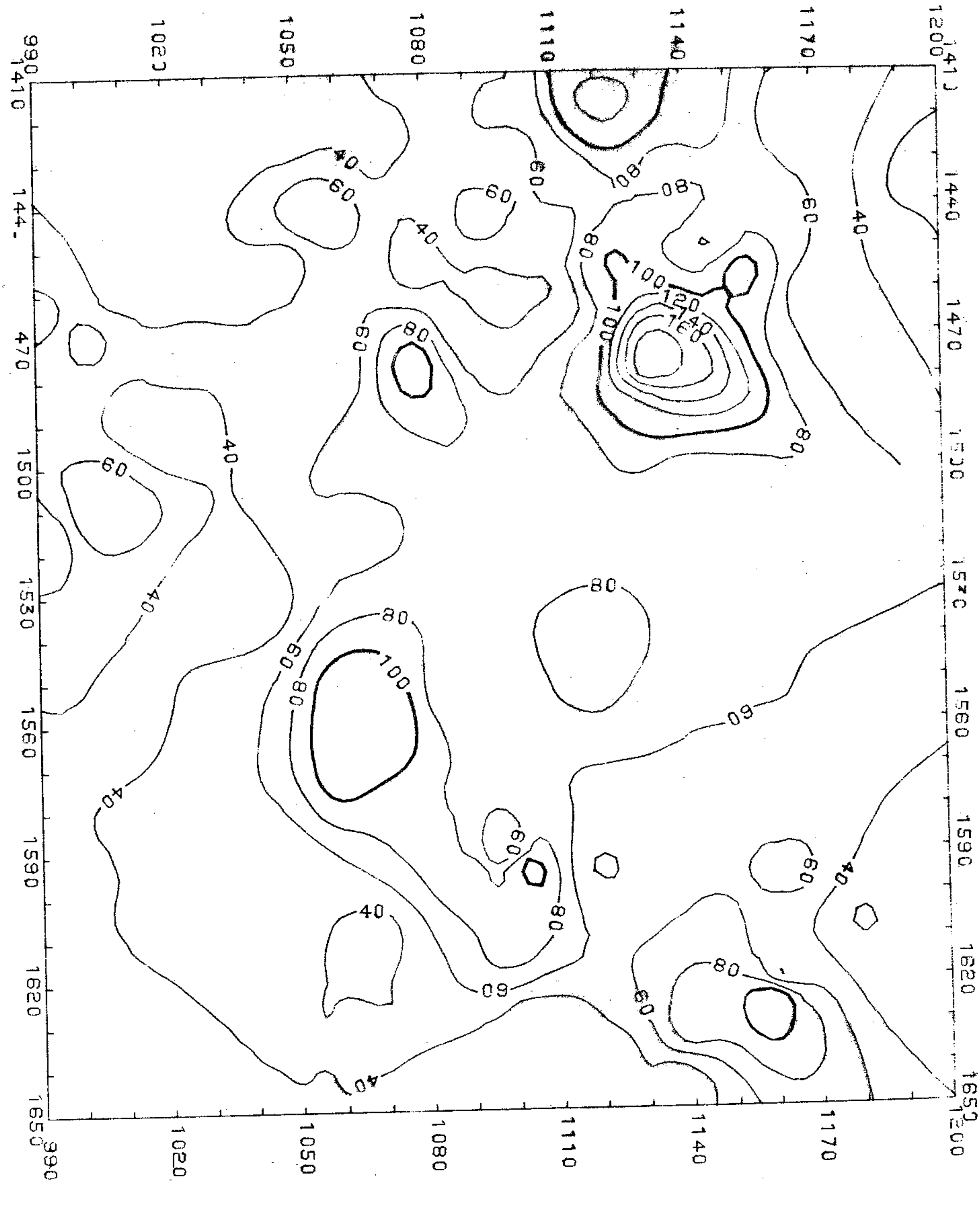
B44

SWA ONE - DAY STORM DATE 74/02/01
PLOT NO. 1 DATE 2/11/80 TIME 10:40:19



SWA THREE - DAY STORM DATE 74/02/01

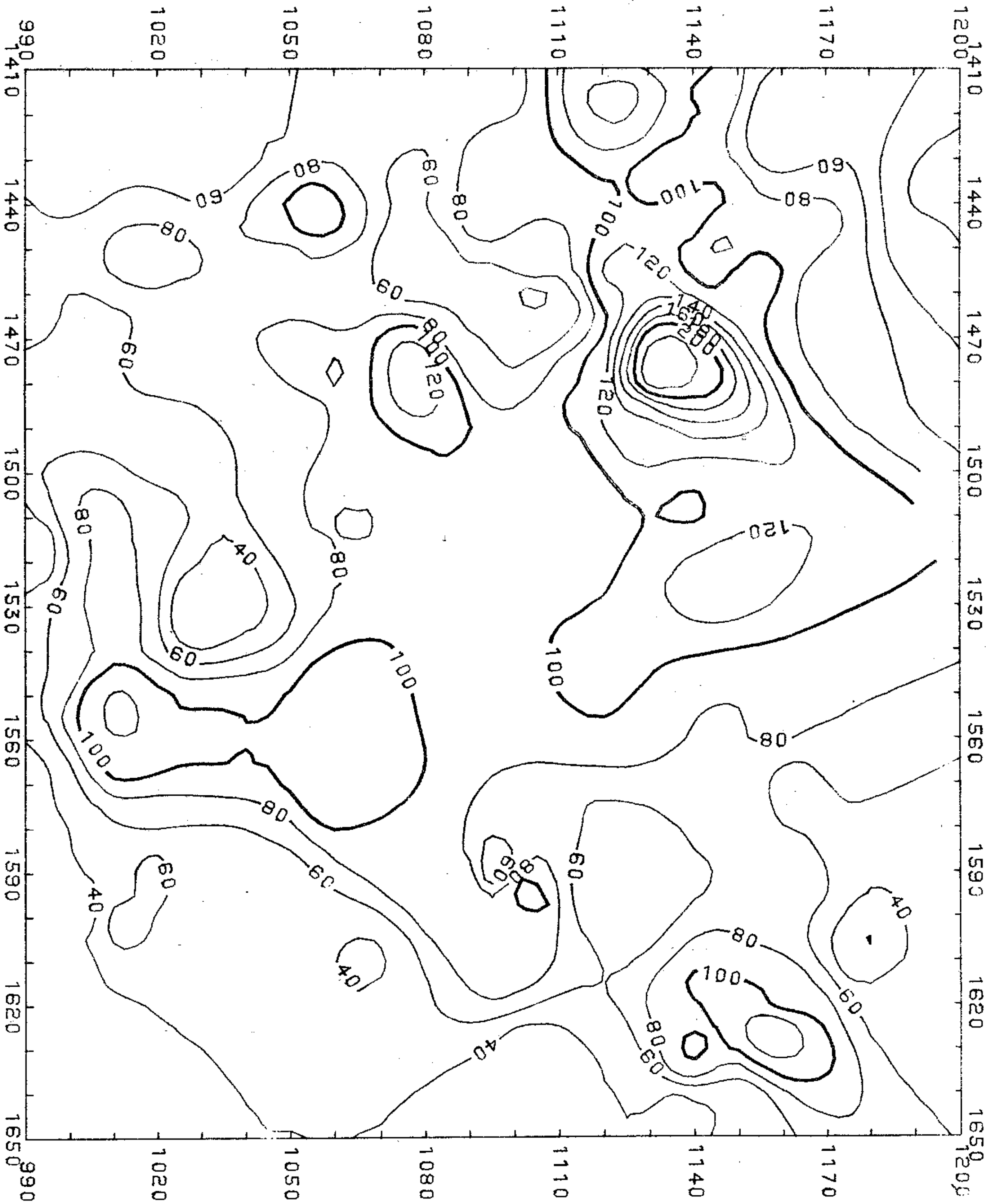
PLOT NO. 1 DATE 2/11/80 TIME 10:49:15



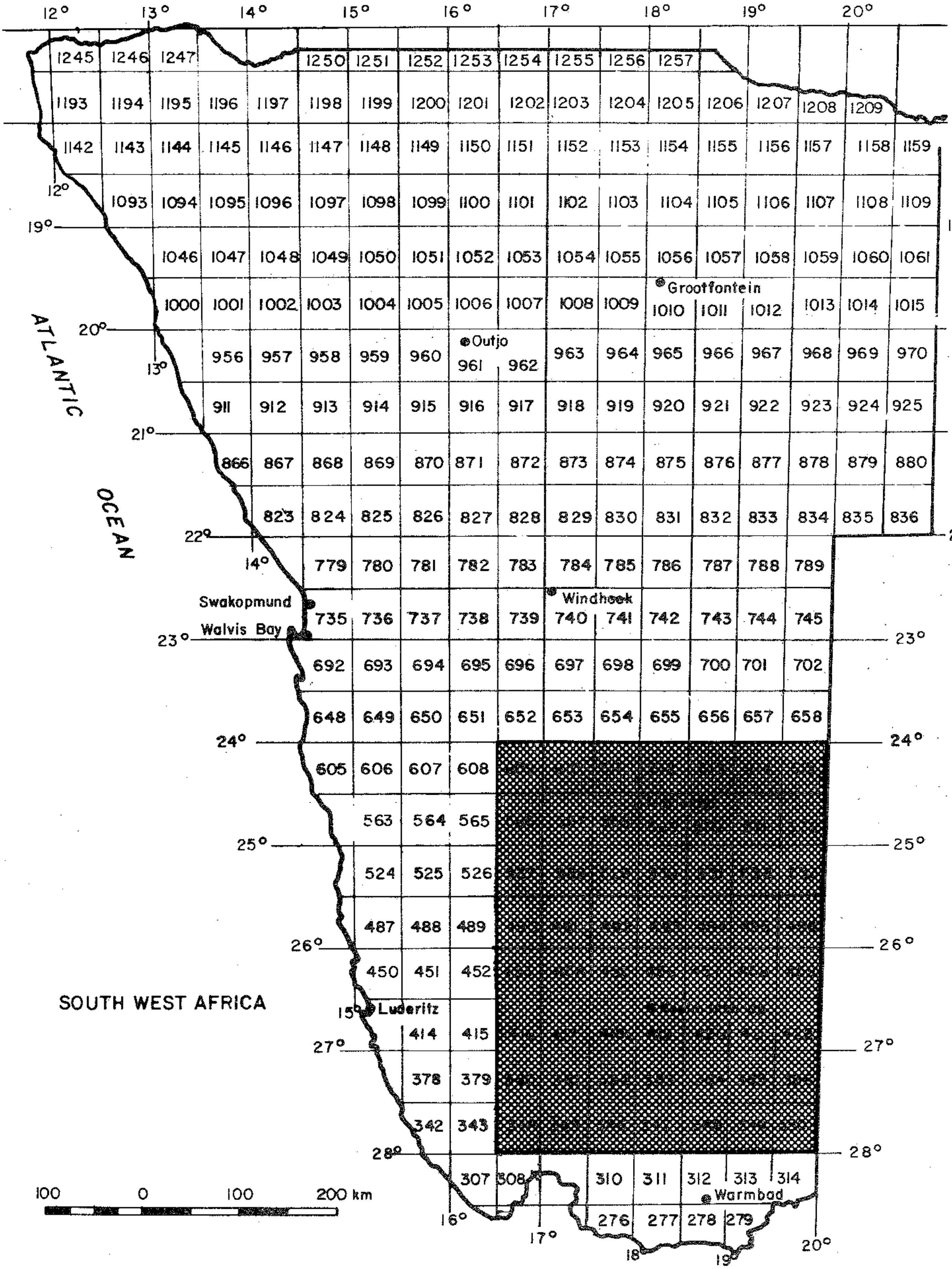
B46

SWA FIVE - DAY STORM DATE 74/02/01

PLOT NO. 1 DATE 2/11/80 TIME 10:57:52

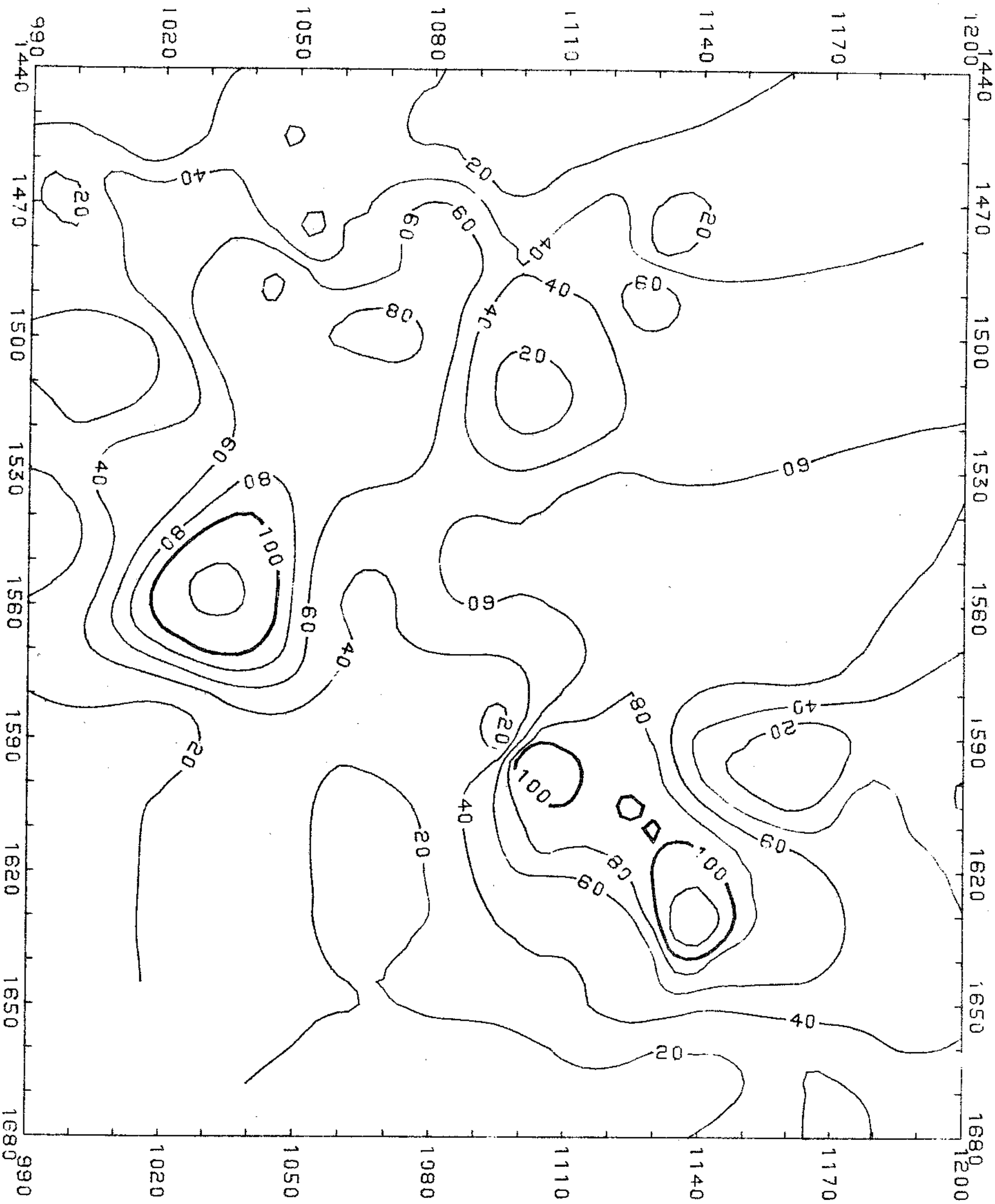


Storm 13 74/02/20



SWA ONE - DAY STORM DATE 74/02/20

PLOT NO. 1 DATE 2/06/80 TIME 9:17:57



B49

SWA THREE - DAY STORM DATE 74/02/20

PLOT NO. 1 DATE 2/06/80 TIME 9:23:19