WATER RESEARCH COMMISSION

POTENTIAL IMPACTS OF RAINFALL STIMULATION IN SOUTH AFRICA: A RESEARCH PLANNING STUDY

by

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EXECUTIVE SUMMARY

Goals of the planning study

The two South African rainfall stimulation projects at Bethlehem (BPRP) and Nelspruit/Carolina (PAWS) were initiated in 1983 and have hitherto primarily had an exploratory character. At present there appears to be consensus in the cloud-seeding community that an on-going need for vastly improved understanding of local cloud microphysical and meso-scale processes dictates that the two South African projects will need to be integrated and continued in an exploratory mode as a national research programme for a number of years to come. This implies that catchment-scale rainfall stimulation experiments *or operational programmes will not be feasible in the short- to medium-term.* Given this need for a longer-term perspective of rainfall stimulation research, the Water Research Commission (WRC) initiated this planning study at the end of 1988 to

* define needs of end-users of the technology, such as agriculture, forestry and water resources, and the potential impacts in end-user and other impact fields

* identify timeously the requirements for and the existence of expertise for research into potential impacts

* integrate these requirements in proposals for a multi-disciplinary, multi-objective research programme

* define a suitable target area

* ascertain the feasibility of developing credible modified rainfall scenarios on the basis of South African cloud-seeding project findings.

Modus operandi

The modus operandi followed in this study was dependent on the consultative collaboration of a large number of people in a variety of disciplines related to rainfall stimulation or to its end-users and other impact fields. Apart from the conventional steps of literature survey and theoretical orientation, the modus operandi was structured around

- in-depth interviews with some 43 knowledgeable persons in the relevant scientific and administrative fields

- a scientific Workshop attended by 21 persons

- formulation of a feasible multi-objective impact research programme

- soliciting of preliminary research proposals from specific interviewees

- study of selected storm track data from the Nelspruit experiment to investigate the feasibility of deriving credibly modified daily rainfall time series

- compilation of this report, both as a handy reference work for prospective researchers in impact disciplines and to motivate and detail the proposed research plan.

Structure of this report

The report was conceived in four main sections:

* State-of-the-art of rainfall stimulation research - including overseas and local projects: Chapters 2, 3 and 4.

* Situation analysis of research and research needs in end-user and impact fields:

    Chapter 5 - modified rainfall
    Chapter 6 - water resources, agriculture, forestry
    Chapter 7 - social and socio-economic
    Chapter 8 - legal considerations.

* Proposed research programme: Chapter 9.
* Relevant data and other information: Appendices

Findings and Conclusions

The findings and conclusions that we arrived at are very much integrated with the text of the report. These are here summarised per chapter.

Chapter 2:

- Glaciogenic seeding of convective clouds has a solid scientific basis but has not yet been exhaustively researched anywhere in the world.

Chapter 3:

- Steady scientific progress was made during a number of famous cloud-seeding experiments in various parts of the world during the sixties, seventies and early eighties. However, only one project reported in the English-language literature produced a positive seeding effect during both the exploratory and the confirmatory phases and which survived scientific peer scrutiny: the Israeli I and II projects between 1961 and 1975.

Chapter 4:

- Statistically significant positive seed/no-seed differences in radar-derived mean values for rainflux, storm volume and storm area have been determined in PAWS for the time window 30-40 min after seeding decision time. For the 20-30 min window only rainflux and storm volume were found to be statistically significant.

- Sizeable initial biases in the above variables marred interpretation of PAWS results, despite proof that the biases were not statistically significant.

- Microphysical differences between seeded and non-seeded clouds were shown to be statistically significant in BPRP. However, no results of radar-derived seed/no-seed differences have so far been made available for this project.

Chapter 5:

Using processed PAWS storm track data we

- Quantified "true" positive seeding effects, i.e. after discounting the initial bias, during each of four ten-minute time windows spanning cloud lifetimes 20 to 60 minutes after decision time.

- Demonstrated that the PAWS "true" seeding effects represent a large-scale average seasonal seeding effect that is unlikely to exceed 10% on average.

- Found that "outlier" storms do not dictate the finding of a positive mean seeding effect.

- Shown that inter-storm seeding effects seem extremely variable.

- Found indications that incremental rainflux growth in seeded storms remain dominant until 40 minutes after decision time, whereas, for no-seed cases, decay becomes dominant 10 minutes earlier.

- Shown that the variability of rainflux growth of seeded storms is very similar to that of unseeded storms beyond 40 minutes after decision time, but is substantially different before that point.

- Concluded that it would be feasible to derive, within one year, plausible modified areal rainfall time series by utilising PAWS seeding experiment data, the full set of PAWS radar-derived storm tracks and time histories for the period October 1982 to the present, all available rainfall time series in selected target areas, satellite cloud data and synoptic weather data from the national network.

- Concluded that the expertise for such a task, as well as suitable supporting milieus are available in South Africa.

Chapter 6:

- Three routes are defined by which impact studies in the end-user fields could occur: desk-top assessments via yield/growth modelling, field experiments under simulated cloud-seeding (by irrigation) conditions and field experiments under operational cloud-seeding.

- Of the three end-users - water resources, agriculture and forestry - the potential impact on forestry is expected to be the most beneficial.

- Of the three end-users the potential impact on water resources is the most contentious issue and is regarded as the most difficult to quantify with reasonable confidence by desk-study, given that the magnitude of the areally distributed enhancement of rainfall achievable by seeding is suspected to be smaller than the accuracy attainable with rainfall-runoff models.

- Despite the preceding observation, the local state-of- the-art of numerical modelling in all three end-user fields is perceived to be suitably advanced to justify a decision to launch desk-studies of impacts. Dynamic timber growth simulation is at present less systematised than modelling in the other end-user fields and some development work to this end is required.

- The common ultimate goal of desk-studies is to enable calculation of the total net economic benefit of rainfall stimulation for the whole of the target area for a representative set of primary end-users.

- An extended corridor about 500 km long, running through Nelspruit and Bethlehem and beyond, would be a rational choice for a plausible target area for operational rainfall stimulation. This choice requires recognition of fifteen individual considerations, detailed in section 6.9.

Chapter 7:

- Positive social attitudes to and public perceptions of rainfall stimulation are as important to the possible future success of research in this field as overcoming technical hurdles might be.

- Impact research should include public opinion surveys and research on suitable forms of public education about rainfall stimulation and its benefits.

- There is a need for a socio-economic research programme which would, inter alia, see to the conversion of individual end-user benefits to monetary values, to the appropriate costing of operational cloud-seeding programmes and to effecting an integrated cost-benefit assessment for the whole target zone, including all secondary, multiplier, market, demographic, infrastructural, and administrative impacts.

Chapter 8:

- A substantial number of legal considerations in the areas of water rights, liability, administrative and statutory control and litigation deserve attention during the planning of operational cloud-seeding programmes. These are detailed in Appendix C.

Proposed research programme

A proposal for an integrated, multi-disciplinary research programme concludes our report as Chapter 9. The abbreviated goals of the research are:

* to obtain results in the short- to medium-term which can be used to inform decision-makers/planners as well as the general public of the potential benefits and drawbacks of rainfall stimulation

* to obtain results in the medium-term which can be used to set rainfall stimulation programmes in an optimal economic framework

* to develop an experimental framework for the effective field monitoring of the consequences of possible future operational rainfall stimulation programmes.

A three-stage programme is proposed:

Stage 1: End-user desk-studies and social/socio-economic impact studies.

Stage 2: Optimisation stage to derive a range of rainfall stimulation programmes that are cost-effective and socially acceptable.

Stage 3: Confirmatory field experimentation and monitoring.

We propose six guidelines for the choice of pilot target areas on which Stage 1 studies would focus and then proceed to name and describe three pilot areas that are suitable, namely the Wilge, Usutu/Upper Vaal, and Upper Crocodile River Areas. Details of eight preliminary proposals for Stage 1 research that have been solicited from centres of expertise in the various end-user/impact fields are provided.

The report is concluded with preliminary proposals regarding Stage 2 and Stage 3 research aims and approaches.

ACKNOWLEDGEMENTS

In this report we attempt to integrate the views, opinions and understandings conveyed by a large number of knowledgeable persons interviewed by us. Their names and affiliations are listed in Chapter 1. We are truely grateful for their frank advice and friendly contributions. Special thanks are due to the following persons who smoothed our path at crucial points in the study:

Graeme Mather	-	Cloud Quest
Roelof Bruintjes	-	Weather Bureau
Ron Grosh	-	CSIR
George Green	-	WRC
Hugo Maaren	-	WRC

Finally, in the course of this study our path strayed into the domain of many individual scientific disciplines. We would like to use this opportunity to salute the quality of the scientists and the scientific endeavours that we were privilege to have access to.

1. THE PLANNING STUDY: BACKGROUND AND MODUS OPERANDI

1.1 Background

The two current South African artificial rainfall stimulation (cloud-seeding) research projects at Bethlehem and at Nelspruit/Carolina, respectively, were initiated in 1983 and have hitherto primarily had an exploratory character. The randomised cloud-seeding experiments which form part of these projects have not produced overwhelming proof of rainfall increases in response to cloud-seeding, although various levels of proof have been attained that seeded clouds differ in various "promising" ways from unseeded clouds. At present there appears to be general consensus in the cloud-seeding community that the ongoing need for vastly improved understanding of local cloud microphysical and meso-scale processes dictates that the two South African projects will need to continue in an exploratory mode for many years to come. This implies that catchment-scale rainfall stimulation experiments will not be feasible in the short- to medium-term.

Despite many problems experienced in the South African projects, there exists a large measure of consensus that the potential of successful implementation of rainfall stimulation as an additional water source is so great that research should be continued. So far, the planning of rainfall stimulation research has not included explicit consideration of the needs of "end-users" such as agriculture, forestry and water resources and of the potential impacts in end-user and other fields. Given the need, mentioned above, for a medium- to long-term perspective of rainfall stimulation research, the Water Research Commission (WRC) initiated a planning study at the end of 1988

* to define end-user needs

* to identify timeously the requirements for research and the existence of expertise for research into potential impacts

* to integrate these requirements appropriately in proposals for a multi-disciplinary, multi-objective research programme

* to define a suitable target area

* to ascertain the feasibility of developing credible modified rainfall scenarios on the basis of the South African cloud-seeding project findings.

Ninham Shand Inc. was appointed to undertake the study, with Dr A. Görgens and Dr A. Rooseboom - the authors of this report - as project leader and advisor respectively.

1.2 Modus operandi

Apart from the conventional steps of literature survey and theoretical orientation, the modus operandi that we followed in this planning study was heavily dependent on the **consultative collaboration** of a large number of people in a variety of disciplines related to rainfall stimulation or to its end-users and other impact fields. As novices in the cloud-seeding discipline we accepted that we could not aspire to an in-depth knowledge of the discipline in the time available. We therefore accepted that our most useful course of action would be that of **neutral synthesis** of views, perceptions, understanding and expectations of the broadest possible cross-section of knowledgeable persons in the relevant scientific and administrative fields. Our modus operandi was structured around eight discrete activities:

- orientating interviews with representatives of the two South African cloud-seeding projects,

- consultative interviews with representatives of the interested state departments such as the Weather Bureau, and the Departments of Water Affairs (DWA), of Agriculture (DA), and of Environment Affairs (DEA) (Forestry) to identify priorities, as well as experts and "target" persons in all relevant fields for further interviews,

- in-depth interviews with researchers, research coordinators, managers and planners at universities, state departments and research institutions,

- planning, organisation and facilitating of the "Workshop to guide planning of rainfall stimulation end-user research", held during September, 1989, in Pretoria,

- broad formulation of a feasible multi-objective impact research programme,

- soliciting of preliminary research proposals from specific interviewees to meet the requirements of the aforementioned research programme,

- study of selected storm track data from the randomised seeding "PAWS" experiment at Nelspruit to investigate the feasibility of deriving a credibly modified daily rainfall time series,

- compilation of this planning report.

It was our hope that the consultative process embodied by our modus operandi would lead to a multi-disciplinary research plan that would represent a rational integration of available South African expertise and be in harmony with the state-of-the-art in science and technology in all the relevant disciplines.

1.2.1 Interviews

Personal interviews were conducted with some 39 persons while telephonic discussions were held with a further four persons. The following list provides the details:

(1) Mr P du Toit - Weather Bureau
(2) Mr R Bruintjes - Weather Bureau
(3) Mr P Steyn - Weather Bureau
(4) Mr K Estie - Weather Bureau

(5) Mr G Mather	- Cloudquest, Nelspruit
(6) Mr R Grosh	- Ematek, CSIR
(7) Mr E Braune	- HRI, DWA
(8) Mr A Conley	- Strategic Planning, DWA
(9) Dr A Seed	- HRI, DWA
(10) Dr D Scotney	- SIRI, DA
(11) Dr T Dohse	- SIRI, DA
(12) Dr A van der Merwe	- SIRI, DA
(13) Dr J Dreyer	- GCRI, DA, Potchefstroom
(14) Mr P van Rooyen	- GCRI, DA, Potchefstroom
(15) Mr J van den Berg	- GCRI, DA, Potchefstroom
(16) Dr J Mallett	- GCRI, DA, Cedara
(17) Ms S Fleischer	- GCRI, DA, Cedara
(18) Dr M Hensley	- DA, Glen
(19) Dr D van der Zel	- Forestry, DEA
(20) Prof P Roberts	- ICFR, Univ. Natal
(21) Prof R Schulze	- Agric. Eng., Univ. Natal
(22) Prof G Pegram	- Civ. Eng., Univ. Natal
(23) Prof W Alexander	- Civ. Eng., Univ. Pretoria
(24) Prof N Rethman	- Past. Sci.,Univ. Pretoria
(25) Prof J van Heerden	- Met. Sci., Univ. Pretoria
(26) Prof J de Jager	- Agromet., U.O.F.S.
(27) Prof A Bennie	- Soil Sci., U.O.F.S.
(28) Prof M Viljoen	- Agric. Econ., U.O.F.S.
(29) Prof O Bosch	- Plant Sci., Potch. Univ.
(30) Dr J Booysen	- Plant Sci., Potch. Univ.
(31) Prof F Steffens	- Statistics, UNISA
(32) Prof D Hughes	- HRU, Rhodes University
(33) Dr J Lindesay	- CRG, Wits University
(34) Prof K von Gadow	- Forestry, Univ. Stellenb.
(35) Prof A Rabie	- Law, Univ. Stellenb.
(36) Mr W Labuschagne	- Legal Services, DWA
(37) Dr J Bosch	- Foresttek, CSIR
(38) Dr G Green	- WRC
(39) Mr H Maaren	- WRC
(40) Dr D Herbst	- HSRC
(41) Dr J Schnetler	- HSRC

(42) Dr J Kriel - Retired Chairman, WRC

(43) Mr A Raubenheimer - Chairman, WRC

In many instances more than one round of discussions ensued while a certain amount of written consultation also took place.

1.2.2 Workshop

The "Workshop to guide planning of rainfall stimulation end-user research programmes" was held on 21 September 1989 at the Water Research Commission offices in Pretoria. The purpose of the Workshop was to bring together active researchers and research managers/coordinators in both the rainfall stimulation research field and the fields that can be regarded as end-users of such research, i.e. water resources, agriculture and forestry, to meet the following needs:

(i) information-transfer:

(a) to bring the end-user participants up to date regarding rainfall stimulation research,

(b) to inform rainfall stimulation researchers on the perceptions and data needs of end-user researchers;

(ii) key-issue formulation:

to define, after discussion of the principal areas of uncertainty in the rainfall stimulation research fields, those issues that affect impact-related research in the end-user fields;

(iii) consensus-seeking: to seek agreement

(a) on the priorities of end-user research directions and

(b) the information needs of the end-user researchers.

The Workshop was attended on invitation by 21 participants and took place as a one-day event consisting of a Plenary Session lasting about 4 hours and a Work Session of about 2.5 hours duration. The Chairman was Dr A Görgens. During the Plenary Session six addresses were made, summaries of which had been circulated in pre-Workshop documentation. A report on the Workshop (Görgens, 1989), its procedures and its achievements was subsequently distributed to all participants.

The Workshop created an opportunity for issue-formulation and consensus-seeking which played an essential part in ordering the many and diverse results of our earlier interviews with individuals. For this reason we do see a need to relate at this somewhat premature point the major items of consensus and the unresolved issues that surfaced at the Workshop, despite the risk of pre-empting much of the material we present in later chapters:

Consensus:

* that "overwhelming" proof of rainfall increases due to cloud-seeding need not be a prerequisite for impact research in the end-user fields to take off. "Promising results", which is the state-of-the-art in South Africa as conveyed to the Workshop, was accepted as an adequate spur for complementary research in other fields.

* that the state-of-the-art of numerical modelling of crop/timber growth and production, as well as of catchment runoff generation, holds great promise for desk-studies of rainfall stimulation impacts.

* that a daily rainfall time series, on which cloud-seeding effects are superimposed, would be adequate for yield modelling in the agricultural and forestry fields. In the hydrological field there appeared to be some support for the requirement of a finer time resolution than daily rainfall values.

* that the two most severe constraints on attainment of proof of rainfall increases due to cloud-seeding seem to be

  (a) the accurate definition of the experimental control-volumes (i.e. the seeded clouds) and their in- and outputs so that accurate mass balances are possible, and

  (b) the accurate measurements of areal rainfall on the ground. As radar measurements, both aerial and ground-based, are crucial components of both (a) and (b), there was strong consensus that research into all relevant aspects of radar observations of clouds and rainfall deserve an urgent, high priority status in the context of rainfall stimulation research planning.

* that future impact assessments should include benefit-cost analyses. The yield benefits that artificial increases of rainfall would offer grain and timber production seem readily quantifiable through numerical modelling. However, the Rand cost of an operational cloud-seeding programme that would have high probability of certain minimum levels of benefit, would have to be discounted in the process.

Key issues:

* **Point versus areal yield modelling:**

  In the forestry and agricultural fields crop yield modelling at a point location seems to be the norm and participants from these fields did not regard extrapolation to large-area yields as a serious problem; possibly because only the vertical dimension, and then only the rootzone depth of the soil, is of importance. Runoff generation, on the other hand, is a spatially continuous process in three dimensions and the hydrological modellers present were not confident that runoff generation modelling could claim the same accuracy as the modellers in the other fields seem to achieve. South African catchments exhibit severe spatial variability of runoff controlling characteristics and there appears to still be a lack of confidence in distributed forms of modelling aimed at handling this.

* **Areal cloud-seeding effects:**

  Spatially distributed end-user yield modelling presupposes spatially distributed cloud-seeding effects. This step in the quantification of the South African cloud-seeding projects is still in abeyance.

1.2.3 PAWS randomised seeding storm track data

The last-mentioned key issue identified by the Workshop, as well as a general impression we gained during our interviews and the literature study of the South African projects that the findings of the randomised seeding experiments were not transparent, convinced us that we should make ourselves more au fait with the primary data produced by these projects. We also surmised that any prospective researchers in the end-user/impact fields would experience a similar need to orient themselves via a relatively simplistic perusal of the experimental seeding response data - apart from the previously stated modelling requirement for modified daily rainfall time-series. For these reasons we decided to devote a chapter to a presentation and analysis of such data. It soon became clear that it was too early in the life of the Bethlehem project to attempt this and therefore our efforts concentrated on the PAWS storm track data only. These endeavours resulted in Chapter 5 below.

1.3 Philosophy and structure of this report

The purpose of a report on a multi-disciplinary research planning study such as this might be regarded as two-fold:

- to motivate and detail the research plan for the benefit of the research administrators/managers, and
- to provide a handy reference work for the individual prospective researchers in the different disciplines, most of whom might be laymen in the complementary disciplines.

To fulfil this purpose the report was conceived in five main sections:

(i) State-of-the-art of rainfall stimulation research - including overseas and local projects: Chapters 2, 3, 4.

(ii) Derivation of plausible modified rainfall scenarios for South Africa: Chapter 5

(iii) Situation analysis of research and research needs in end-user and impact fields: Chapters 6, 7 and 8.

(iv) Proposed research programme: Chapter 9.

(v) Appendices presenting relevant data and the detailed legal discussion.

Although focussed on specific areas, the first four sections of the report are not free-standing and present much that is inter-related with material in other sections.

2. THE SCIENTIFIC BASIS OF RAINFALL STIMULATION

The information presented in this chapter has been summarised or, in many instances, paraphrased from the following sources : WMAB (1978), ASCE (1983) and American Meteorological Society (1986).

2.1 Introduction

The scientific basis for rainfall stimulation in the form of cloud seeding rests on two assumptions:

(i) natural cloud precipitation efficiency can be increased (the basis for the "static" seeding approach);

(ii) cloud development can be enhanced (the basis for the "dynamic" seeding approach) to produce bigger clouds that "process" more water vapour.

Increasing the precipitation efficiency of existing clouds presupposes that at least some clouds are inefficient natural processors of cloud moisture for the formation of precipitation. The assumption that cloud development might be enhanced implies that critical amounts of latent heat can be released artificially to substantially promote cloud growth in certain "suitable" clouds.

2.2 Natural precipitation efficiency

Precipitation efficiency can be defined as the percentage of condensed water within a cloud system that reaches the ground as precipitation. The remainder of the condensed water in the cloud is returned to vapour form, either through evaporation at the cloud boundary, or through horizontal or vertical transport out of the cloud as precipitation particles or ice crystals to be evaporated later.

The amount of water that can be held in the atmosphere in vapour form is temperature-dependent and at surface temperatures and pressures the actual vapour content of air is typically less than that required for saturation. Sufficient lifting and consequent adiabatic cooling of an air parcel results in temperatures at which the vapour-holding capacity of the air is exceeded and the excess water is condensed out, generally in the form of cloud droplets (diameter $<$ 10 micron) but, on occasion, directly as ice crystals. As cloud temperatures may well be below freezing (0°C), the cloud droplets actually exist in a supercooled state. The competition for the water vapour excess among the droplets is severe and further growth by condensation is severely restricted. Since the fall velocity of these droplets is low ($<$ 3 mm/s), they essentially move with the air currents either horizontally or vertically within the visible cloud. Such clouds are typically referred to as microphysically (or cloud-colloidally) stable. The presence of supercooled water and concomitant low concentrations of ice particles at temperatures well below 0°C are generally taken as evidence of the inefficiency of the precipitation process in a cloud.

Two different mechanisms can disrupt the microphysical stability of a cloud and lead to larger cloud particles or precipitation embryos which, in turn, have greater fall velocities and can fall out as precipitation:

(i) Collisions and coalescence among the drops so that successively large water drops form. This process is facilitated by the presence of hygroscopic salt particles upon which large cloud droplets can condense. It follows that the pure collision/coalescence mechanism is associated with maritime clouds whose tops are below freezing elevations and can be expected to be sub-dominant in interior, continental areas where large hygroscopic particles for large drop formation are less commonly available. The formation of rain by this mechanism required droplets with diameters $>$ 40 micron.

(ii) Interaction between supercooled cloud droplets and ice crystals. An ice crystal in the presence of supercooled droplets will grow by vapour deposition, while nearby droplets evaporate, because the saturated vapour pressure over ice is less than that over supercooled liquid at the same temperature. In this way a crystal can gradually acquire the mass of many cloud droplets. This allows it to fall through the cloud, perhaps growing by collision with some of the droplets, and to exit the cloud as a precipitation particle in the form of a granular pellet of snow or soft hail, known as graupel. Results of cloud physics research have shown that all important convective rain from mixed-phase clouds involves graupel as a dominant precipitation type.

Graupel development in convective clouds is related to a varying degree of interdependence between collision/coalescence and ice growth processes and is the result of four primary chains of events. Riming, i.e. the freezing of droplets onto existing ice crystals in shell-like layers, plays a role in all four of these event-chains:

(a) primary ice crystal growth by vapour diffusion of smallest droplets followed by riming growth after collision/coalescence with "larger" droplets during descent [the so-called ice-riming-graupel (IRG) process],

(b) collision/coalescence growth of droplets followed by freezing followed by riming growth as for (a) above [the so-called coalescence-riming-graupel (CRG) process],

(c) secondary ice crystal production by splintering of newly-rimed ice during either (a) or (b) above, leading to new riming growth as for (a) above.

(d) secondary ice crystal production by splinter ejection during the freezing of large droplets, leading to riming growth as for (a) above.

It should be noted that secondary ice crystal production can occur in other ways as well, such as fragmentation due to collision of various ice particle types, but rime-splintering and freeze-splintering [(c) and (d) above] represent the best documented mechanisms.

The aggregation of ice crystals as a result of seeding appears to be a common occurrence. Aggregation is more likely to occur when the IRG mechanism is dominant and is primarily the result of high ice concentrations following seeding, but may also be related to low liquid water contents and weak updrafts. There is some evidence that aggregates tend to grow slowly because they are inefficient embryos for accretion. If this is the case, it would mean that such a seeding effect is driving the cloud into a less efficient precipitation process than the natural one, leading to rainfall decreases.

Natural precipitation efficiency is ultimately also a function of the cloud condensate source-rate which, as indicated earlier, is dependent on updraft speed - an entity that is very different in different classes of clouds. In large-scale synoptic systems, upward motions are about 1-4 cm/sec and are driven mainly by large-scale dynamic forcing. Updrafts in convective clouds are largely driven by thermal buoyancy and range up to tens of meters per second. In orographic clouds, wind-driven upslope motions may reach a few meters per second. It follows that precipitation characteristics differ markedly in these different cloud systems.

2.3 Glaciogenic cloud seeding

2.3.1 Scientific foundation

The scientific foundation of glaciogenic (ice-phase) cloud seeding rests upon two postulates related to the two assumptions mentioned in

2.1 above.

(i) The natural precipitation efficiency of some clouds is limited by a shortage of natural ice nuclei effective at the extant cloud temperatures. Adding artificial nucleants to these clouds should enhance the precipitation process.

(ii) Increased buoyancy, resulting from seeding-induced conversion of supercooled drops into ice particles, will invigorate cloud updrafts. This will enable clouds to grow larger, process more water vapour and yield more precipitation.

Production of significant precipitation involves synergistic interactions of physical systems of three different scales; large-scale atmospheric motion systems, clouds and meso-scale systems and cloud microphysical particle systems. The direct effect of glaciogenic seeding is to alter the cloud at the microphysical scale by creating ice crystals and releasing latent heat of fusion.

The two most common types of artificial ice nucleants are dry ice and a variety of silver iodide agents.

2.3.2 Dry ice

Pellets of dry ice produce ice crystals from water droplets nearly instantaneously at temperatures of -2°C and colder. Despite its extensive use as a seeding agent, several issues concerning the activity and effectiveness of dry ice remain undecided:

(i) Mode of nucleation: it is generally agreed that the number of ice crystals produced by dry ice cannot be explained solely by the freezing of pre-existing cloud droplets and that direct deposition of water vapour into ice nuclei seems also to play a role.

(ii) Effectiveness: the potential ice crystal production rate of dry ice is still relatively uncertain. Theoretical, laboratory and model studies have produced estimates of dry ice effectiveness spanning a range from 10^8 to 10^{16} crystals per gram. An important finding in this context is the fact that dry ice effectiveness seems to be two orders of magnitude larger at -20°C than at -2°C.

(iii) Appropriate seeding rate or dosage: a wide range of seeding rates have been in use with no clear indication that a specific seeding rate is most effective in initiating precipitation. Rates ranging from 0,1 kg/km to 13 kg/km have been reported in the literature; the more recent experiments have tended to favour relatively low rates.

2.3.3 Silver iodide

In spite of its extensive use as a cloud seeding agent, the state of knowledge of the various processes associated with its activity and effectiveness is still somewhat in flux:

(i) Mode of nucleation: Most of what is known on the nucleation characteristics of silver iodide agents has been learned from theoretical and isothermal cloud chamber studies, but the applicability of these results to real cloud conditions is still unclear. A major difficulty in making this transfer is the fact that ice nucleation on silver iodide particles can occur by four different mechanisms: deposition, condensation-freezing, contact-freezing and immersion-freezing.

(ii) Effectiveness: the cloud chamber ice nucleating activity of silver iodide aerosols begins at about -5°C to -8°C, increases by four to five orders of magnitude with decreasing temperature to about -16°C, and increases very slowly thereafter, spanning a range of about 10^9 - 10^{15} crystals/gm silver iodide in the process. However, the real effectiveness of silver iodide is of course measured by the number of ice crystals it produces at the prevailing temperatures of real clouds. This ice crystal yield is mainly determined by the seeding agent's nucleation rate and residence time in the portion of the cloud of interest. Silver iodide used in airborne generators is usually dissolved in acetone, for which a catalyst is required. Ammonium iodide is now regarded as the catalyst that promotes maximal effectiveness of the seeding complex's nucleating ability. Experimental work on a variety of silver iodide complexes indicates that at temperatures warmer than -16°C it takes from about 15 min. to one hour for 90% of the silver iodide complex to be used up as ice nuclei, the exact times being dependent on the specific chemical compositions and the cloud conditions.

2.3.4 Aerial transport and dispersion

This section concerns itself with the only form of seeding agent dispensing relevant to South African cloud-seeding research, i.e. aerial dispensing.

Both dry ice and silver iodide are initially dispensed in highly concentrated dosages, either as vertical lines produced by airborne drops of dry ice pellets or free-falling silver iodide flares, or as horizontal lines produced by airborne silver iodide-acetone generators and end-burning silver iodide wing-mounted flares. Transport and dispersion by natural air motions of the seeding agents and/or the ice crystals they produce are then relied on to achieve the proper concentration of ice crystals in the targeted cloud volume at the appropriate time.

Cloud-top or in-cloud seeding provides the greatest assurance that the seeding agent/ice crystals will be introduced at the appropriate levels in the cloud in a timely manner, but the time and vertical distance available for dispersion throughout the target volume may be quite limited. Due to the nearly instantaneous nucleation rate of dry ice, its seeding "signature" is very dramatic, but rapid dispersion of growing ice crystals is required. Fortunately, dry ice seeding often results in enhanced convection and turbulence in the cloud resulting from the greater heat released more rapidly by the induced phase change. Silver iodide seeding, on the other hand, produces ice crystals over a period of time [see 2.3.3(ii)]. Provided that the required seeding concentration can be maintained by in-cloud transport, the timed release feature of silver iodide may be beneficial since it can have a lingering effect on clouds where the liquid water continues to be replenished. Dry ice seeding under such conditions may entail several additional doses of seeding if nucleation during the full life-span of the cloud is to be effective.

2.4 Static and dynamic seeding modes

The literature abounds with references to the so-called "static-mode" and "dynamic-mode" seeding concepts. In the foregoing sub-sections, numerous distinctions have already been made between the processes underlying the physical hypothesis of each of these two cloud seeding approaches. For the sake of completeness these two seeding modes are redefined at this point.

The static-mode seeding concept relates to increasing precipitation efficiency and amounts to the addition of small concentrations of ice nuclei to clouds in which precipitation efficiency is limited by a shortage of natural ones. The dynamic-mode seeding concept relates to the enhancement of cloud development and aims at maximising the effect of latent heat release by glaciating cloud updraft earlier in time, at warmer temperatures, and more completely than can be accomplished by the less efficient natural nuclei. The additional heat release should invigorate the updraft, resulting in taller clouds and more precipitation.

In the past, the static/dynamic distinction served as more than a mere descriptive "tag" - it signified the underlying physical hypothesis of a cloud seeding experiment. Of the well-known overseas experiments mentioned in section 3.1 below, the static seeding concept underlay Whitetop, Israeli I and II and HIPLEX-I, while FACE I and II were based on the dynamic seeding hypothesis. It is clear that in existing cloud seeding experiments the static/dynamic distinction is losing its significance in the light of requirements for more complex physical hypotheses that consider microphysical - dynamical interactions associated with multicell convective cloud systems.

2.5 The basics of cloud-seeding experiments

Since the initiation of cloud-seeding experiments in the 1940's there has been a progressive improvement (albeit haphazardly so) in understanding the requirements for an adequate cloud-seeding experiment. Early attempts were essentially "black-box" experiments. Currently there seems to be general consensus that substantiation of the underlying physical hypotheses of cloud-seeding experiments requires one of two general approaches:

(i) That which requires each step in the chain of events leading to precipitation formation, in both the treated and non-treated clouds, to be specified in advance within the framework of a detailed conceptual model and later to be verified by quantitative observations.

(ii) That which defines the conditions that are conducive to positive seeding effects on the basis of a general conceptual model, resting on previous studies of cloud microphysics and dynamics of the clouds and cloud systems involved, and analyses the results for their physical plausibility within stratifications of the experimental data.

The first of these two approaches is used to establish the physical basis for rainfall enhancement techniques and hence is very basic, expensive and time consuming. The second is obviously more risky. It requires, however, less in the way of facilities and highly skilled human resources and, under favourable conditions, may provide quicker answers at a reduced cost. The crucial factor in the latter approach is the complexity of making sound physical hypotheses on the basis of circumstantial scientific evidence only. It would be appropriate to point out that the second approach cannot be a substitute for the first, but, rather, it could be used to facilitate the transfer of knowledge gained in the conduct of the basic studies by the first approach to similar rainfall regimes.

Of the overseas projects listed in 3.1 below, HIPLEX-I was the only experiment to be designed and conducted according to the first of these two approaches. Table 3.1, below, is an example of a general conceptual model used in the FACE experiments, which corresponds with the second of the above two approaches.

Recent literature indicates that it is likely that current and future experimental cloud-seeding programmes will not achieve scientific credibility without conforming to certain basic principles and procedures:

(a) The requirement for a four-stage experiment: observational phase, cloud-scale exploratory treatment, cloud-scale confirmatory treatment and meso-scale confirmatory treatment (the observational and exploratory phases might overlap).

(b) The three treatment phases should be underlain by a chain-of-events physical hypothesis of cloud-seeding effects [as opposed to a mere conceptual model, see (i) and (ii) above], which is rooted in the initial observational phase.

(c) The acceptance of a pervasive role for statistics in the design, execution and analysis of the experiment. The treatment design should address the following topics:

- the populations and experimental units of interest
- the design configuration
- the methods for reducing variability
- statistical handling of bias
- physical importance of bias
- allocation of treatments to the units
- the total number of experimental units.

(d) Proof of increases in rainfall at ground level at the meso-scale should be the ultimate aim of the experimental programme.

2.6 Cumulus cloud systems

Most of the world depends on cumulus clouds for water, food and fibre production. Cumulus clouds supply as much as 75% of the precipitation in middle-latitude crop-growing areas. Also in South Africa most of the rainfall over the main grain-and timber-producing regions is from cumulus clouds. For this reason, and because they appear to be the cloud systems with the highest seedability potential, the focus in this report falls strongly on those aspects of rainfall stimulation that relate to cumulus clouds.

Cumulus clouds form in bubbles of bouyant air rising from heated land or ocean surfaces. They exist in a spectrum from small fair-weather cumuli that last a few minutes to giant cumulonimbus thunderstorms which last for hours. Such large convective cloud complexes are often sustained by the continual merging of smaller storm cells. Cumulus clouds are characterised by their shape in that they appear like a pile of clouds, they often form an "anvil" on top and, when clustered, tend to grow "turrets" on their flanks.

3. REVIEW OF MAJOR OVERSEAS RAINFALL STIMULATION RESEARCH PROJECTS

3.1 Introduction

The modern origin of the science of rainfall stimulation research is rooted in the classic work of Bergeron (1933) on the role of ice in the initiation of precipitation in supercooled clouds. Findeisen (1938) expanded on Bergeron's precipitation initiation concepts and recognised the potential for rainfall stimulation in these findings. However, it was not until the next decade when Schaefer (1946) scattered a little dry ice into the top of a supercooled stratified cloud and confirmed that the seeded portion of the cloud was transformed within minutes into a mass of snow crystals, that a practical method became available for the scientific exploration of rainfall stimulation possibilities. Vonnegut (1947) repeated Schaefer's experiment with silver iodide, and field experiments on artificially stimulating rain from convective clouds based on the "Bergeron process" began in the same year. The "cloud seeding rush" had taken off.

In the 40 years since this historic period, well over 500 operational cloud-seeding projects and over 40 precipitation augmentation research experiments have been conducted in over 70 countries under a variety of meteorological conditions, geographical settings and experimental expertise (Todd and Howell, 1985). From the available literature on these research experiments, five specific projects which have had a major influence on the development of the science have been selected for review in the sections below.

3.2 Whitetop (1960-1964)

After a decade of exploratory experiments in a variety of meteorological settings and a rush of commercial projects in the USA (coinciding with the severe drought of the fifties), Project Whitetop was conducted in Missouri from 1960 to 1964 by the University of Chicago. This project represented one of the best planned randomised experiments in the seeding of convective clouds during this early period (Braham, 1966). Whitetop was a "blackbox" type statistical experiment based on the static seeding concept, with parallel observational studies to provide physical information about raindrop nucleation processes and cloud characteristics. Seeding was implemented by non-selective broadcasting of silver iodide at cloud-base level.

The design in Whitetop included procedures for determining a floating target and control area based upon measured winds between the surface and 14 000 ft, and the location of the seeding line. As summarised by Braham (1979), the overall effect of seeding in Whitetop was a decrease in both rainfall and radar echo cover. Braham noted that the apparent seeding effect varied with the maximum depth of clouds on any given day. If the maximum echo tops were warmer than -10°C (6 km) or colder than -40°C (12 km), the inferred seeding effects were negative. On days when the maximum echoes were between -10° and -40°C, the target control differences suggested 68% to 100% increases in rainfall. The days with deep convective clouds (known as cumulonimbus), however, dominated the overall rainfall during the experiment, leading to a net decrease in rainfall due to seeding. Thus the overall statistical results of Whitetop did not support the original static seeding concept, although a possible "window" where the seeding concept may be applicable was elucidated.

Parallel observational studies during Whitetop also raised serious doubt about the validity of the "static seeding" concept. Observations were made of high concentrations of ice crystals that appeared to be adequate for natural precipitation formation and were in excess of those expected at warmer temperatures by silver iodide seeding. The rapidity of glaciation of the cloud was correlated with the presence of supercooled raindrops. The high concentrations of ice crystals were hypothesized to be the result of the operation of a secondary ice multiplication process, which, with the addition of seeding material to the cloud, produced an "overseeding" phenomenon.

Braham (1979) speculates that some of the tall clouds (over 12 km) in Whitetop may have been caused by the seeding and were essentially overseeded, sweeping up all of the seeding material in the sub-cloud layer. Clouds of intermediate size were able to use the seeding material beneficially and were given moderate to low dosage rates, the clouds being isolated to some degree from the seeding material. Finally, because the area seeded was very large, clouds of all types and in all stages of "seedability" were seeded, leading to counter-productive results.

Braham concluded that Project Whitetop should be regarded more as an exploratory experiment, raising more questions than it answered. It should probably be repeated, he stated, from a cloud physics viewpoint, but ethically it is difficult to justify, in his opinion, rerunning an experiment that gave evidence of rainfall decrease in a rain sensitive area.

Apart from the lessons implicit in the "overseeding" phenomenon, in the negative results of the non-selective broadcasting seeding method and in the illustration of the need to predict "seedability", Whitetop scored two firsts in the search for understanding of rain-producing mechanisms. If offered the first documentation of a field experiment in which the CRG mechanism [see point 2.2(b) above] was dominant in cold-top summer cumuli. Furthermore, it offered the first indirect evidence of the importance of secondary ice crystal production [see 2.2(c) and (d) above] in precipitation formation.

3.3 Florida Area Cumulus Experiment (FACE-1: 1970-76 and FACE-2: 1978-80)

The Florida Area Cumulus Experiment (FACE) was a two-stage programme to investigate the potential of dynamic-mode seeding for enhancing convective rainfall in a fixed target area in South Florida. It represents the only summertime, areal, convective cloud seeding experiment ever conducted in the USA whose stated objective was to increase areal precipitation by altering cloud dynamics. Table 3.1

presents the dynamic seeding hypothesis chain which underlays FACE. The first, or exploratory phase (FACE-1, 1970-76), produced indications of increased rainfall in the target area (Woodley, et al, 1982). The second, or confirmatory phase (FACE-2, 1978-80), did not confirm the results of FACE-1 statistically, although it did produce indications of a possible seeding effect in initial analyses (Woodley, et al, 1983), as well as in later ex post facto analyses (Gagin, 1986).

In both phases seeding occurred by ejection of silver iodide flares from aircraft which penetrated convective cloud towers (turrets) that, during pre-seeding observations, had met all seedability criteria. The primary response variables during both phases were rain volumes in the "total target" area and in the "floating target" area, the most intensely treated portion of the target. The total target area was a 13 000 km^2 trapezoid with a regular rain gauge network of density 1 gauge/130 km^2. Area-wide radar-measured rainfall within this target from the time of the first seeding until six hours later was known as the target rainfall. The floating target rainfall was defined as the rainfall directly associated with treated clouds and neighbouring clouds with which the treated clouds merged. Groundlevel rainfall was estimated using radar observations after adjustment by rain gauges. The rainfall equivalents (R) of the radar reflectivities (Z) were computed through the relation $Z = 300\ R^{1,4}$, which had been predetermined for the FACE project. Each radar rainfall value was "corrected" by a corresponding gauge-to-radar rainfall ratio for a 400 km^2 block containing a dense gauge network (one gauge per 10 km^2) within the target area.

During both phases of FACE, treatment (seed/no-seed) decisions were randomised by day and, during, FACE-2 also by one of four (blocked) wind indices. A no-seed treatment consisted of flares filled with sand instead of silver iodide. An important difference between FACE-2 and FACE-1, however, was that in the latter there was a possibility of subjective influences of seeding knowledge among the participating scientists and pilots, whereas FACE-2 treatment decisions were withheld from all FACE scientists until the field

TABLE 3.1 : SUMMARY OF HYPOTHESIZED DYNAMIC SEEDING CHAIN OF EVENTS*

Stage I: Initial vertical tower growth

1. Rapid glaciation of the updraft regions of supercooled convective tower(s) by silver iodide pyrotechnic seeding.

2. Invigoration of the updrafts through buoyancy increase produced by the release of latent heats of fusion and perhaps deposition; the latter may or may not contribute as the cloud air approaches saturation relative to ice.

3. Pressure falls beneath the actively growing tower due to upward acceleration and upper level warming followed by increased inflow at mid to low levels (surface to 6 km) which fuels the initial stage of cloud growth.

   Stage I may last 10-20 min, sometimes longer.

Stage II: Horizontal cloud expansion, secondary growth

4. Enhanced downdrafts below the invigorated seeded tower as the precipitation and evaporatively cooled air moves downward.

5. Convergence at the interface between the downdraft and the ambient low-level flow, instigating tower ascent fed by the warm, moist inflow.

6. Growth of secondary towers (which, in turn, might be seeded).

7. Horizontal enlargement of the cloud by joining of the feeder towers, leading to wider protected updraft(s), augmented condensation, water content, rainfall.

   Stage II may last 30-50 min.

Stage III: Interaction with neighboring clouds

8. Seeding of secondary towers in the parent cloud results in their growth, followed by expansion and intensification of the downdraft area which then moves outward to interact with outflows from neighboring clouds (which might also have been seeded). This increases the convergence on a larger scale, deepens the moist layer and results in new cloud growth and merger in the convergent regions between the cloud systems. These new towers are normally seeded as well.

9. The increased seeding-induced growth and merger of clouds on the mesoscale coupled with sinking in their near environments results in a mesoscale region of warming (50 km on a side). The resulting thermally direct mesoscale circulation provides additional low-level mass and moisture convergence to fuel new cloud development and perhaps to prolong the lives of the older cloud systems. Further, under certain conditions, the upward branch of the mesoscale circulations may become saturated and produce a period of stable (non-convective) rainfall.

Stage IV: Increased area rainfall

10. Seeding increases rainfall over the floating target by:
    a. enhancing the growth of the directly treated cloud towers.

    b. inducing additional cloud growth and larger cloud systems through the mechanism of downdraft interactions.

    c. indirectly increasing the efficiency of cloud elements as they grow in the more moist environment provided by the larger cloud systems; and

    d. augmenting the supply of available moisture through the enhancement of the thermally-direct mesoscale circulation.

11. Seeding increases rainfall over the total target by:
    a. obtaining more rain from the available moisture than would have occurred naturally, and/or by

    b. enhancing the moisture supply to the target.

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*From Woodley _et al._ (1982b).

experiment was completed and all of the data fully reduced and verified. This "lack of blindness" as to treatment decisions was an important reason why FACE-1 results could not be regarded as conclusive, and why a confirmatory experiment was required.

The summarised results of the two experiments are as follows:

FACE-1 results had indicated small differences in seed (S) and no-seed(NS) rainfalls in the 0-2 h period after seeding, substantial differences in the 2-5 h period after treatment with the S rainfall peaking 1,5 h after the NS rainfall, and small differences again after 5-6 h. Point estimates of effects were 1,30 and 1,43 in the floating target and total target areas. These and other rainfall data led the investigators to set up three levels of confirmation involving various combinations of seed, no-seed rainfall ratios in the 0-6 h period after treatment and double ratios of seed, no-seed rain in the 2-5 h period and 0-2 h period after treatment. Unfortunately, none of these ratios or double ratios achieved statistical significance, so the weakest level of confirmation has not been realised in FACE-2.

Replication of the FACE-1 rainfall analyses was accomplished in FACE-2. A clear difference in the FACE-2 data when compared with the FACE-1 results was earlier rainfall in the seeded versus the unseeded cases. In addition, the linear analysis of FACE-2 using the FACE-1 predictor variables (pre-wetness, model predicted rainfall, mean vector wind speed, and large square rainfall) yielded much smaller point estimates of treatment effects (1,06 and 1,09 in the floating target and the total target) and 95% confidence limits that bracketed 1,00, the no-effect value.

A single, large rainfall event on a no-seed day (29 July 1978) is blamed for much of the failure to verify the FACE-1 results, although the timing effect would still fail even if that one day were excluded from the sample.

After-the-fact analyses by scientists such as Gagin (1986) of FACE-2 data shed valuable light on the reasons for the inconclusive overall results of FACE-2, which relate to suppression of control clouds by invigorated seeded clouds, timing of seeding, and a bias towards wetter days for sand (no-seed) treatment. In corresponding criticisms of the FACE project design Orville (1986) and Cotton (1986) indicate that, in spite of monumental efforts, FACE did not make enough provision for the complexity of the physical hypothesis it set out to prove (see Table 3.1). Such hypotheses are "inherently unstable, as the failure of any one link will cause the succeeding links to fail or be suspect" (Orville). "Herein lies the problem with a 'blackbox experiment'. Had we observed and tested the various links in the chain, we might have been able to detect the problem and alter our strategies and experimental design to overcome this weakness" (Cotton).

3.4 Israeli experiment (Israeli I: 1961-1967 and Israeli II: 1969-1975)

Cloud seeding, aimed at rainfall enhancement through the production of static effects on cloud microstructure, was carried out in two consecutive, long-term, randomised experiments referred to as Israeli I and II. Daily rainfall, averaged over the entire target area was found to be increased, under seeding, by about 15% in Israeli I (Gabriel, 1970; Gagin and Neumann, 1974) and by about 13% in Israeli II (Gagin and Neumann, 1981). These results were significant at less than 5%. In primary sub-areas of the target, roughly the same distance from the seeding line, positive effects of 24% and 18% were found. In these latter cases the statistical significance levels were less than 3%. Thus the results of the second experiment constitute a confirmation of the findings of the first experiment.

At the outset of each of these experiments, the following two assumptions were made:

- ° The so-called ice-crystal mechanism is the most efficient precipitation-forming process for the given regional meteorological conditions. It is assumed that there are periods when a deficiency of natural ice nuclei results in a delay, or even failure, of precipitation initiation.

- ° Silver iodide was selected as the seeding agent. This implied a hope for achieving rain stimulation by ice-crystal formation, either through making the existing process of rain formation more effective or through inducing precipitation formation in clouds that otherwise would not have precipitated naturally.

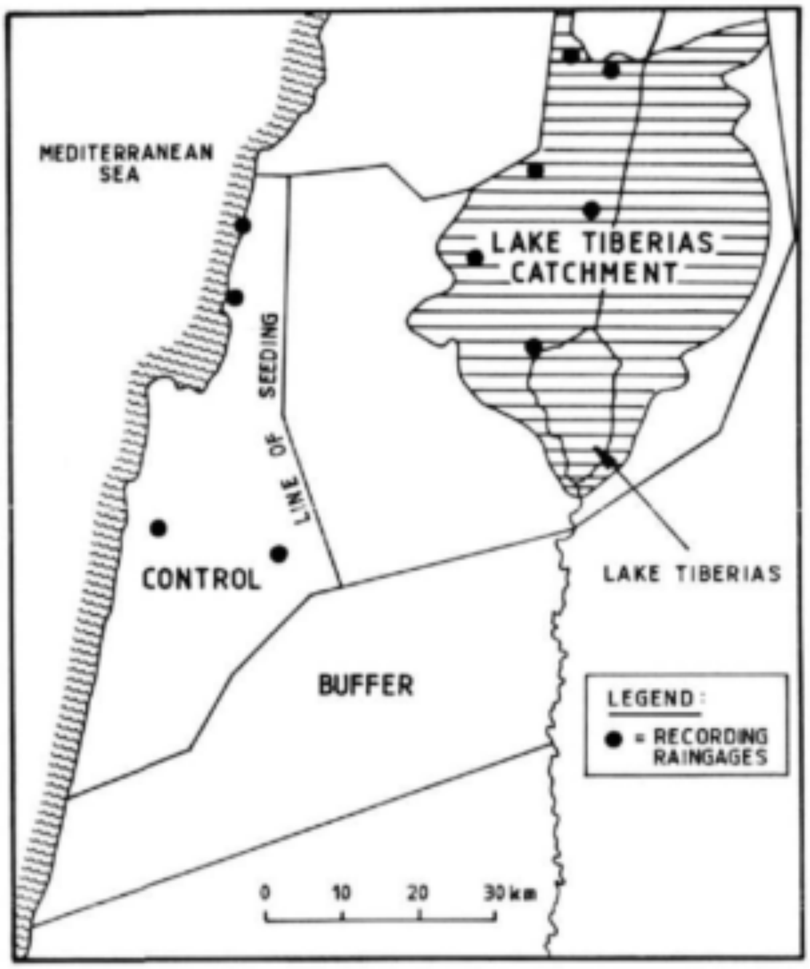
The winter cumulus clouds treated in the Israeli experiments were organised along cold fronts or in postfrontal bands moving in from the Mediterranean Sea. Physical studies accompanying the Israeli experiments showed that winter Eastern Mediterranean clouds seemed significantly continental in nature. These clouds are deficient of large drops (>100 micron) at all altitudes, a fact indicating the absence of an efficient collision-coalescence process. Furthermore, it was found that in all probability precipitation elements in these clouds form by the combined processes of ice-crystal nucleation and growth by vapour deposition.

In both phases broadcast seeding occurred at cloud-base level by aircraft patrolling along a north-south "seeding line" upwind of the target areas. The primary target was northern Israel, including the catchment of Lake Tiberias, a major surface water source. A second target, separated from the primary by a buffer zone, was to the south in Israel. Seeding of either the north or the south target was randomised by day. Thus one target became the control area whenever the other was seeded, the so-called "cross-over" seeding design. Most analyses have focused on the northern target experiment. The primary response variable during both phases was daily rainfall observed at rain gauges organised in an irregular network.

For Israeli I the seeding line was chosen offshore to allow for the dispersion and transport time required by the silver iodide to reach cloud levels where its nucleation activity commences ($\angle$ -5°C). The area of maximum effect occurred 20 to 50 km downwind from the seeding line, but still to the west of the Lake Tiberias catchment. The seeding line for Israeli II was shifted eastwards (inland) to target the Lake Tiberias catchment better. This resulted in a corresponding shift of the area of maximum effect eastward by a distance comparable to the shift of the line of seeding.

One of the salient results of initial analyses of Israeli II (Gagin and Neumann, 1981) is that the treated clouds responded to seeding in a manner that depended systematically on cloud-top temperature. On days when the modal values of the cloud-top temperature distributions were -15°C to -21°C, maximum positive effects of about 46% were observed, a result statistically significant at less than 1%. On the other days, when the modal values of cloud-top temperatures were either warmer than -10°C or colder than -21°C, the effects of seeding were found to be either nil or insignificant. These experimental results were anticipated by theoretical studies that actually predicted these effects (Gagin and Neumann, 1974). Both the direct results of the parallel physical studies (Gagin, 1975) and the results of the initial statistical analyses of the seeding experiments as summarised above provide a reasonably acceptable corroboration of the above-stated assumptions. A recent Israeli II analysis by Gagin (1986) offers findings in further strong support of these assumptions.

It uses recording rain gauge data to study seeding effects on the daily values of duration, intensity and number of rain periods. The data set used in this case can be regarded as completely independent of that used in the initial analysis. Also, instead of the "cross-over" control areas, this study used the Mediterranean coastal area west of the target as a control area. In Israel, on all days of rain, the winds at cloud-base levels and above always have a westerly component. Figure 3.1 presents a simple map of the northern experimental area, the location of the recording rain



LOCATION OF THE ISRAELI II CLOUD SEEDING EXPERIMENT (AFTER GAGIN, 1986)

FIGURE 3.1

gauges, the seeding line, the control area, the Lake Tiberias catchment (LTC, the primary target) and the buffer zone.

This analysis shows positive seeding effects in LTC of 25% and 18% on daily recorded rainfall and mean daily duration of rain, with significance levels of 0,6% and 1,8% respectively, for an unstratified sample of 209 seeded and 179 unseeded experimental days. The analysis suggests further that rainfall intensity was not affected by seeding. Stratification of the data by daily modal cloud-top temperatures produced overall positive effects on daily rainfall in LTC, under seeding, of 45% on days when the modal values of daily cloud-top temperatures are in the range of -11°C to -21°C (significance level of 1,0%). The equivalent positive effect on daily rainfall duration is 47% at 0,2% significance. On days when the cloud-top modal values are either warmer than -11°C or colder than -21°C, the effects on the above two parameters are either not significant or nil.

The following retrospective explanation of why the Israeli experiments were so successful (while others were not) has been given by Silverman (1986):

"Benefiting from clever research, insight and design, and a large measure of luck, it appears that the Israeli scientists were blessed with the following unique combination of favourable meteorological and operational conditions:

"(i) The target clouds are post-cold-front, continental convective bands and clusters that develop precipitation exclusively through the IRG mechanism. The cloud-base temperatures occur in a fairly narrow range from 5°C to 8°C. Gagin (1975) states that there is no evidence that the coalescence process is active or that secondary ice-crystal production occurs in the Israeli clouds.

"(ii) A substantial fraction of the total daily cloud population on rain days, especially light rain days, have cloud-top temperatures that are within the cloud-seeding temperature window.

"(iii) As the cloud systems move into Israel from the west, they are invigorated by convergence at the coastline and a moderate rise in topography, thereby providing for continued release of condensate and a fairly persistent supply of liquid water in the clouds.

"(iv) Airborne cloud-base patrol seeding allowed time for dispersion of the nuclei before activation and produced ice-crystals in moderate concentrations at the appropriate time and place in the invigorated clouds. A particularly convincing result is the eastward shift in the maximum effect of seeding in Israeli II (as opposed to Israeli I) by a distance comparable to the shift in the line of seeding.

"(v) The use of a silver iodide-sodium iodide seeding material may have produced an unexpectedly high ice-crystal yield at the targeted temperature levels.

"(vi) Despite the lack of cloud selectivity by the mode of seeding, it does not appear that there were any negative effects of seeding clouds outside the cloud seeding temperature window.

"The physical picture that has been presented for the Israeli experiments should be subjected to confirmation by making some critical chain-of-physical-events measurements in a sample of seeded and non-seeded clouds. One wonders, for example, how clouds with top temperatures as warm as -12°C can precipitate unless secondary ice-crystal production is occurring. The Israeli experiments must, of course, also be duplicated in another area before the inferential support for the physical results can be considered as hard data."

The remarkable success of the Israeli experiments is concurrently under renewed scrutiny both in terms of physical plausibility and in terms of statistical problems with the "cross-over" control area definition. Gagin's (1986) paper using data from a separate control area partially refutes criticism based on the latter, but the problem of physical plausibility was illustrated quite well in a recent paper by Rangno (1988). This study, based on rawinsonde data, surface synoptic reports and satellite data, indicates that at least 20% of clouds that produce rain in Israel have top temperatures $\geqslant$ -10°C. Such precipitation must form either by the collision-coalescence process or by the ice crystal mechanism (see 2.2(i) and (ii) above). Clouds containing droplets large enough for the collision-coalescence mechanism should exhibit secondary ice-crystal production (see 2.2(c) and (d) above), and therefore contain high concentrations of ice particles, if their top temperatures are $<$ -5°C. These findings on cloud microstructure in Israel differ from those by Gagin and Neumann (1974; 1981) and Gagin (1975) on which much of the physical plausibility of Israeli I and II has been based. Rangno's (1988) findings imply that, if precipitating clouds with top temperatures $\geqslant$ -10°C can be expected to have reasonable ice particle concentrations, then natural clouds with cloud top temperatures from -15°C to -21°C will have far higher ice particle concentrations, i.e. they would be far more efficient. Therefore, the physical plausibility of Gagin and Neumann's report (1981) of a significant rainfall increase of 46% due to seeding for such clouds appears to be under siege.

3.5 High Plains experiment (HIPLEX-1:1979-1981)

The High Plains Co-operative Experiment (HIPLEX-1) was a randomised, double-blind experiment to test the static mode seeding concept for convective clouds in Montana (Bureau of Reclamation, 1979). It specified in advance and attempted to verify by observations during the course of the experiment each step leading to additional precipitation at cloud-base. The experimental units of HIPLEX-1 were semi-isolated cumulus congestus clouds. Such clouds usually develop precipitation naturally through the IRG mechanism. HIPLEX-1 represents the first attempt to move from "black-box" statistical tests of a hypothesis to a multiresponse statistical experiment. Table 3.2 presents the static seeding hypothesis for this experiment.

TABLE 3.2: PHYSICAL-CHAIN-OF-EVENTS SEEDING HYPOTHESIS USED IN HIPLEX-1

1) Production of an average ice crystal concentration of about 10 L^{-1} in the supercooled water cloud at temperatures higher than -10°C. The initial ice crystal concentration in the unmixed seeding plume will be considerably higher to allow for the effects of diffusion. The average ice crystal concentration produced by seeding at these warm temperatures is higher than that found in untreated clouds at comparable times after treatment.

2) Diffusion growth of the ice crystals to a size at which riming occurs, so that higher concentrations of rimed crystals appear in seeded clouds at comparable times after treatment. The seeding-produced crystals tend to develop as columns. Crystals found at these temperatures in unseeded clouds at comparable times after treatment tend to have habits characteristic of growth at lower temperatures.

3) Accretional growth of the rimed ice crystals in the liquid portions of the cloud to graupel on the order of 1 mm in diameter and concentrations of about 0,1 L^{-1}, which then fall through the cloud. Accretional crystals growth is accompanied by a decrease in liquid water content relative to the untreated cloud at comparable times after treatment. The ice crystals produced by seeding have a significant advantage over those that occur in unseeded clouds because they originate earlier in the lifetime of the cloud. This leads to the earlier appearance of precipitating ice particles in the seeded clouds, so greater concentrations and larger sizes of such particles are present at comparable times after treatment.

4) Earlier development of first echoes in seeded clouds as opposed to untreated clouds.

5) Fall of precipitation from the cloud base in the form of graupel and/or rain (melted graupel) earlier in the lifetime of the cloud and in greater volumes than occur in unseeded clouds. In addition, a larger proportion of seeded clouds than unseeded clouds will produce rain.

Based on preliminary exploratory studies (which included cloud modelling studies), the cloud selection criteria that are shown in Table 3.3 were expected to result in a sample of clouds that would be amenable to seeding according to the static mode and last at least 30 minutes after treatment for the seeding to be effective. The qualifying variables were measured during a pre-treatment pass by a cloud physics aircraft flying through a visually promising cloud at the -8°C level and immediately evaluated by an onboard computer to determine whether or not the selection criteria for any of the specified cloud types were met.

The seeding was conducted by dropping a line of dry ice pellets from a jet aircraft at a rate of 0,1 kg/km near the -10°C level within 2 min. after a suitable cloud was selected. Following the treatment, dry ice or placebo, both the seeding and cloud physics aircraft made repeated passes at specified times and specified levels in and below the cloud to document the subsequent chain of physical events as represented by the response variables shown in Table 3.4.

During the course of the two-year experiment, 55 clouds were tested for acceptance as experimental units, but only 20 met all the selection criteria. Of the 20 test cases, only 12 were seeded. The statistical results (Mielke, et al, 1984) showed that seeding had no significant effect on precipitation, but that the postulated increases in cloud ice concentrations associated with the seeding and the subsequent onset of riming were unequivocally established despite the limited sample size. However, it was clear that many of the clouds were not behaving as expected.

The parallel physical evaluation (Cooper and Lawson, 1984) revealed that, in 4 of the 12 clouds that were seeded, precipitation developed in the hypothesised manner, but physically significant departures occurred in the remainder:

TABLE 3.3 : CLOUD SELECTION CRITERIA FOR HIPLEX-1 (SILVERMAN, 1986)

Class A-1 Cloud Criteria

1. Average cloud liquid water concentration greater than 0.5 g m^{-3} over approximately a 1-km-long cloud region determined by 10 s of flight at approximately 100 m s^{-1}
2. Average ice crystal concentrations less than 1.0 L^{-1} in the 1-km-long (10 s of flight) cloud region of maximum average liquid water concentration
3. Maximum ice crystal concentration less than 5.0 L^{-1} for any 1-km-long (10 s of flight) cloud region (defined by FSSP liquid water concentration greater than 0.01 g m^{-3}) during the test pass
4. Vertical air velocity greater than −1.0 m s^{-1} in the region defined by item 1, but if the vertical velocity is greater than 10.0 m s^{-1} and the buoyancy is greater than 1°C, reject the candidate
5. Length of the test penetration more than 2 km and less than 8 km as defined by an FSSP liquid water concentration greater than 0.01 g m^{-3}
6. *No radar echo detectable on the aircraft weather radar*
7. Cloud-top temperature lower than −6°C but higher than −12°C
8. Cloud-base temperature higher than 0°C
9. Minimum separation between the current test cloud and previous test clouds greater than 15 km to insure the meteorological independence of the clouds

Class A-2 Cloud Criteria

1. Items 1 through 9 of Class A-1 Cloud Criteria
2. An average wind direction between the surface and 800 kPa from 250° to 040° true
3. A 30-kPa-thick stable layer present with its base between 0° and −10°C and its top temperature at least 1.5°C higher than the temperature extrapolated from the base of the layer to the top using pseudoadiabatic ascent
4. A 10°C dewpoint depression present somewhere within the 30-kPa layer of B.3 above

Class B Cloud Criteria

1. Items 1, 2, 3, 5, 6, 8 and 9 of Class A-1 Cloud Criteria
2. Cloud-top temperature lower than −6°C but higher than −20°C
3. Vertical air velocity greater than −1.0 m s^{-1} in the region defined by Item A.1, but no other vertical velocity or buoyancy restrictions

TABLE 3.4 : HIPLEX-1 PRIMARY RESPONSE VARIABLES (SILVERMAN, 1986)

1.	CIC2	Cloud ice concentration, 2 min after treatment
2.	CIC5	Cloud ice concentration, 5 min after treatment
3.	CCR5	Concentration of crystals rimed, 5 min after treatment
4.	PIC8	Precipitating ice number concentration, 8 min after treatment
5.	MVD8	Mean volume diameter of precipitating ice particles, 8 min after treatment
6.	AWC8	*Average liquid water concentration, 8 min after treatment*
7.	TFPI	Time to first precipitating ice (particles with diameters >0.6 mm in concentrations >0.1 L^{-1})
8.	TFE	Time to first SWR-75 radar echo (15 dBZ)
9a.	TIPA	Time to initial precipitation at +10°C level, aircraft measurement
b.	TIPR	Time to initial precipitation at +10°C level, SWR-75 radar (15 dBZ)
10a.	RERC	Radar-estimated rainfall at +10°C level, using a constant *Z–R* relationship
b.	AER	Aircraft-estimated rainfall at +10°C level

(a) The liquid water content depleted faster by entrainment than seeding could exploit it to develop precipitation, and the clouds did not last the required 30 minutes after seeding.

(b) Precipitation development did not proceed via the graupel process as hypothesised. Seeding produced such high ice concentrations that a combination of aggregation and accretion onto the loose aggregates was the dominant precipitation process, leading to small raindrops.

(c) The main precipitation growth occurred at temperatures colder than -10°C, i.e. above the seeding level - leading to the conclusion that the seeding level was, perhaps, too low since it failed in most cases to take advantage of the region of rapid development of graupel from ice crystals.

HIPLEX-1 was essentially a failure in terms of achievement of an increase in rainfall due to seeding. Nevertheless, in many respects the clouds seeded during HIPLEX-1 were similar to the wintertime cumuli seeded in the successful Israeli experiments. Cooper (1987) analyses this apparent anomaly as follows:

"The HIPLEX-1 clouds were generally (but not always) cold-cloud-based, continental cumuli such that warm-rain precipitation broadening was unlikely. Moreover, the HIPLEX-1 design excluded the deep towering cumuli and cumulonimbi that overwhelmed the precipitation statistics in Whitetop. Thus, HIPLEX-1 could be thought of as a more sophisticated statistical/physical experiment that involved the transfer of technology from the Israeli experiment. There was one important difference, however. In order to facilitate the detection of a clear seeding signal in the hypothesised sequence of events, clouds were individually seeded with dry ice from an aircraft. This should be distinguished from both Whitetop and the Israeli experiments, where seeding was implemented by airborne broadcast seeding of AgI. In HIPLEX, however, an observer first sighted a suitable cloud, then an instrumented aircraft penetrated the cloud, and then a second aircraft commenced seeding the cloud near the -10°C level. These manoeuvres led to a 3-5 minute delay at the start of the study. During this period, the cloud had typically achieved its maximum liquid water content, the liquid water being eroded by the effects of entrainment. The short lifetimes of the natural clouds provided an important limitation to the precipitation efficiency of the clouds.

"One might ask, therefore, why entrainment did not limit the opportunity for precipitation enhancement in the Israeli clouds. One possibility is that the difference between the two experiments was not the dynamic character of the cloud systems, but the method of implementing seeding. The Israeli broadcast seeding strategy allowed some cumuli to be affected by seeding early in the lifetime of cloud before entrainment significantly eroded the liquid water content.

"Another possibility is that the clouds over the Israeli target area received sustained topographic lifting as the air masses moved inland from the Mediterranean Sea. As a result of this favourable dynamic forcing, it is possible that the Israeli clouds were longer-lived and, therefore, exhibited a larger "seeding window". In contrast, the clouds seeded over the HIPLEX target were generally over irregular terrain, which does not provide a coherent, sustained subcloud forcing."

4. RAINFALL STIMULATION RESEARCH IN SOUTH AFRICA

4.1 The first decade

The year 1971 saw the initiation of the first two large-scale precipitation modification projects in South Africa:

(i) Bethlehem Weather Modification Experiment (BEWMEX), a scientific cloud seeding experiment aimed at increasing the rainfall over and, therefore, the runoff from the south-easterly headwaters of the Vaal Dam catchment - conducted under the auspices of the Weather Bureau.

(ii) Nelspruit hail-suppression programme, a commercial undertaking in the eastern Transvaal, east of the Escarpment - conducted under the auspices of the Lowveld Tobacco Corporation.

For a variety of reasons, both these projects were terminated after a decade, but in each case a new long-term project with substantially modified objectives was started in 1983.

These are:

(a) Bethlehem Precipitation Research Project (BPRP), and

(b) Programme for Atmospheric Water Supply (PAWS) (Nelspruit).

The following review will focus only on these two "new" projects and not on their predecessors, because the varied results of the latter, though valid, have been "overtaken" by progress made since 1983.

4.2 Bethlehem Precipitation Research Project

(BPRP: 1983 - 1989)

4.2.1 General Description

The BPRP is a long-term, multiphase, randomised, convective cloud-seeding experiment supported by parallel physical observations, executed under the auspices of the Weather Bureau. The experimental area represents a circle of approximately 100 km radius centred on Bethlehem, but excluding areas in Lesotho and Natal that fall inside the circle. (Recently an area between 210 and 300 degrees magnetic was also excluded from aircraft operations.) Thus, the experimental area is focused on what is generally known as the south-eastern Highveld.

Following on from the BEWMEX approach the initial experimental unit was the summertime isolated or semi-isolated cumulus congestus type cloud. However, a study by Steyn (1985) showed that these clouds are responsible for less than 10% of the BPRP area's rainfall. Consequently, the experimental unit definition was broadened to include multicellular convective clusters. The latter cloud type was shown by Steyn to produce about 45% of the BPRP area rainfall. Turrets on the upshear sides of convective complexes are the specific targets identified for seeding. More recently (1987-1988), isolated convective clouds were excluded from the experimental unit.

4.2.2 Physical hypothesis and experimental procedure

The physical hypothesis of the chain-of-events leading to seeding induced changes in the clouds makes provision for both the static and dynamic modes of seeding effects and is summarised in Table 4.1. Table 4.2 presents the primary response variables which are monitored to test the key features of the hypothesis. Notable is the distinction between aircraft and radar response variables and the fact that rainfall measurements are radar-based. Radar-based rainfall observations are supplemented by more than 200 daily-observed raingauges, more than 80 recording raingauges and more

TABLE 4.1: **PHYSICAL CHAIN-OF-EVENTS SEEDING HYPOTHESIS USED IN BPRP**
(Weather Bureau, 1988)

- The ice concentrations in seeded clouds will be greater than in the unseeded clouds early in their lifetimes.
- The diffusional growth of ice crystals is followed by the onset and dominance of accretional growth. Higher concentrations of rimed ice crystals appear in the seeded clouds. The formation of precipitation sized particles appear earlier and in higher concentrations in the seeded clouds because more ice crystals originate earlier and at lower levels.
- If clouds are invigorated as a result of seeding, clouds should be able to maintain higher concentrations of supercooled water longer, radar echoes will form, grow to greater sizes and persist longer.
- The earlier and higher concentrations of precipitation sized particles in seeded clouds should result in radar detectable echoes earlier in their lifetime with a higher intensity than in unseeded clouds.
- Consequently, the amount of rain at cloud base should be greater in the seeded clouds than in the unseeded clouds. The duration of a radar echo together with the duration of rain at cloud base should also be longer and over a larger area in the seeded cases.

TABLE 4.2: **PRIMARY AIRCRAFT AND RADAR RESPONSE VARIABLES USED IN BPRP** (Weather Bureau, 1988)

Primary aircraft response variables:

- liquid water mass concentrations.
- concentration of rimed particles as well as the size and concentration of precipitation sized particles.

Primary radar response variables:

- the presence or absence of a radar echo.
- echo size and duration.
- maximum echo top.
- maximum echo reflectivity and the rate of change of the reflectivity.
- rain volume at cloud base.
- first echo height and temperature.

than 40 automatic weather stations distributed in an irregular network, throughout the BPRP area.

Both silver iodide and dry ice are being used as seeding agents. Seeding rates of 0,6 kg/km and 0,14 kg/7 minute flare-burn are used for dry ice and silver iodide respectively. Currently, seeding is done according to the following experimental procedure (Weather Bureau, 1988):

* only cumulus turrets growing on the flanks of existing multicellular convective complexes and line storms are selected;

* the main storm has to meet the following visual criteria to justify selection:

  (i) cloud base: wider than cloud top, firm and continuous, not ragged and evaporating;

  (ii) cloud top: indicative of active convection, no visual signs of widespread evaporation or glaciation;

  (iii) cloud top temperature: between -10° and -20°C;

  (iv) storm position between 20 and 90 km from Bethlehem inside the experimental area boundary;

* the primary research aircraft makes an inspection penetration 200-300 m below cloud top, with the seeder aircraft following 2-5 km behind at about -8°C level if the cloud meets the in-cloud selection criteria;

* in-cloud selection criteria (measured by primary aircraft) that determine final seeding decisions, are:

(a) liquid water content greater than 0,5 gm/m^3 and ice crystal concentration smaller than $10/\ell$ for five continuous seconds of flight,

(b) vertical velocity greater than 2 m/s,

(c) cloud diameter greater than one km;

* subsequent to seeding, the primary aircraft makes repeated observational penetrations between the -10 and -15°C levels, while the seeding aircraft carries out further penetrations to gather data between the -5 and -10°C levels; these physical observations continue until the cloud either dissipates or becomes too large to safely enter;

* seeding treatment is applied to any new turrets growing through the -10°C level - a process that continues until no newly emerging turrets are available;

* once a storm has been treated, no further treatment is allowed on that particular complex at a later stage;

* a cloud-base aircraft keeps continuous check on the cloud base during the abovementioned data-gathering penetrations - this aircraft penetrates the rainshafts 200-300 m below cloud bases to determine variations in raindrop size distributions.

4.2.3 Test cloud summary

At the time of writing, results are available only up to the end of the 1987-88 field season. During the four seasons 1984-88 a total of 380 clouds passed the visual criteria for the randomised seeding experiment. However, only 186 of these satisfied both the visual and in-cloud criteria, leading to the following sample sizes: silver iodide - 60; dry ice - 61; placebo - 65. Of the treated clouds, 80 were classified according to the radar criteria to be complex clouds and 100 isolated, while six clouds could not be classified owing to missing radar data (Weather Bureau, 1988).

4.2.4 Results: statistical

Statistical analyses of primary research aircraft data gathered for the three operational seasons 1984-1987 (103 isolated clouds; 66 complexes) were available at the time of writing (Kahn and Fletcher, 1988). These analyses focused on response variable values observed during the inspection pass and during six "time windows" after seeding - with midpoints 3, 6, 9, 12, 15 and 18 minutes after seeding respectively. The first time window (inspection) data is used to indicate bias prior to seeding.

Analysis by re-randomisation of the isolated as well as the complex cloud data supports the hypothesis that seeding with both dry ice and silver iodide increases the ice contents of these clouds, while growth of ice particles occurs earlier in the seeded clouds than in the placebo. In the case of dry ice the clouds also show a tendency to live longer. No seeding effect on liquid water content could be substantiated.

Results of statistical analysis of rainfall changes in response to the randomised seeding are not available at the time of writing.

4.2.5 Results: Radar

The 5 cm wavelength (C-band) weather radar at Bethlehem is used for the tracking of the response of a complex as a whole to the seeding, as opposed to the role of the instrumented aircraft which focus only on the turrets. This data is used (Moolman, 1988) to interpret radar-calculated accumulated rainfall volumes at cloud base in terms of the time of seeding, to keep track of the merging and splitting of complexes in terms of the time of seeding and to interpret seeding response in terms of the distance of seeding from the main complex. A fixed Z-R relationship of $Z = 200R^{1,4}$ (Z = radar reflectivity factor in dBZ, R = rainfall in mm/h) is used.

Results of an analysis by Rosenfeld and Mintz (1988) using Bethlehem radar data also deserve some attention. This study derived from radar measurements the 3-D structure of rainshafts of about 3 000 summer convective rain cells estimates of evaporation of rain falling from convective clouds, using the fixed Z-R relationship mentioned above. They found that, with lifetime peak intensities at the cloud base of 1, 10 and 80 mm/h respectively, about 50%, 25% and 15% of the rain evaporated by 1 km below cloud base. At 1,6 km below cloud base the above percentages of evaporative loss are doubled.

4.2.6 **Results: Microphysics**

In-cloud observations during BEWMEX and the initial years of BPRP indicated that precipitation development in summertime convective clouds in the experimental area typically develops via the IRG mechanism (Krauss, et al, 1987). However, the onset of the ice process is strongly related to the width of the cloud drop size distribution (DSD) which, in turn, is strongly dependent on the cloud base height (Bruintjes, 1988) and, therefore, cloud base temperature. More recent microphysical observations have determined that the precipitation formation mechanism in warm base clouds seems to activate earlier and be much more efficient than in cold base clouds. Bruintjes (1988) provides convincing evidence for the presence of either coalescence by itself or the CRG mechanism on warm cloud base rain-days. However, the occurrence of warm base clouds is infrequent during "dry" summers and is more frequent in "wet" summers like the 1987/88 season. The implication of these microphysical observations is that, during dry years when the IRG mechanism is dominant, the microphysical processes could be made more efficient by seeding at warmer temperatures to produce more efficient graupel embryos than would naturally occur and which would develop into graupel at warmer temperatures than their natural counterparts (Bruintjes, 1988). This might reduce anvil losses of embryos in strong updraft regions (which are common during "dryer" summers).

4.2.7 Results: Cloud modelling and meso-scale studies

The numerical cloud model developed at the National Centre for Atmospheric Research (NCAR) in the USA was used at NCAR during 1989 to successfully simulate cloud development in the BPRP area using data collected on special study days in which special radiosonde ascents were carried out and special data-gathering aircraft flights were undertaken (Bruintjes, 1989). These modelling efforts follow on earlier work by Reuter (1988) and are augmented by studies on the meso-scale organisation of convection in the BPRP area (Estiê and Steyn, 1988). An important contribution in this data area is the study by Steyn and Bruintjes (1989) in which they develop a convective cloud "climatology" for the BPRP area using radar observed cloud data for one summer season.

4.3 Programme for Atmospheric Water Supply
(PAWS: 1983 - 1989)

4.3.1 General description

PAWS is a multiphase, randomised, summertime convective cloud-seeding experiment in the Eastern Transvaal conducted under the auspices of the Water Research Commission by the CSIR and Cloud Quest. During Phase I (1983-87) the experimental area consisted of those parts of a radar observation circle of about 100 km radius centred on Nelspruit and roughly to the east of the Escarpment rim, i.e. including a substantial area of western Lowveld. During the 1987-88 season the PAWS radar was shifted to Carolina to meet two requirements:

* Surrounding terrain at Nelspruit forced the use of a 3 degree low-level scan, and even at this elevation there was terrain blocking the radar beam from the southern around to the north-western quadrant - problems that excluded many clouds from the potential sample. The new site allows a full circle at a low-level scan of 1,4 degrees.

* The radar observation circle at the new site, which is by

definition the experimental area, straddles the headwaters of major rivers, the Komati, Usutu and the Vaal. The new experimental area includes portions of eastern Highveld and western Lowveld.

The experimental unit used is the medium-sized, isolated multicellular storm, where a storm is defined as "any contiguous volume all of which exhibits reflectivity in excess of a threshold value" (SWA and CIC, 1986(d)). In practice, a radar reflectivity value of 30 dBZ has been used as a threshold. The foregoing definition makes it clear that the primary observation platform for this experiment has been the ground-based radar. The specific targets identified for seeding are actively growing turrets on the flanks of the selected cloud complex.

Apart from the radar and the aircraft, the PAWS database was derived from a network of 10 automatic weather stations, 16 recording raingauges in a 30 x 30 km grid (at Badplaas), 17 daily total raingauges and a radiosonde sounding system.

4.3.2 Physical hypothesis and experimental procedure

The exploratory Phase I of PAWS was not designed in terms of a chain-of-events physical seeding hypothesis. Instead, it was intended that, through the randomised seeding experiment, Phase I would lead to the formulation of such a physical hypothesis by proving statistically significant seed/no seed differences in any of some 250 individual radar-observed storm properties selected as response variables for the statistical analyses. Table 4.3 presents a full listing of these response variables (taken from Galpin, 1988). Values for these response variables were determined for five 10-minute time periods relative to the start of seeding (at time = zero): -10 to zero, zero to 10, 10 to 20, 20 to 30 and 30 to 40 minutes after seeding.

The nature of the more than 30 variables for which seed/no seed differences were shown to be statistically significant by Morgan,

TABLE 4.3 : RESPONSE VARIABLES, DEDUCED FROM RADAR OBSERVATIONS, USED IN PAWS STATISTICAL ANALYSES (FROM GALPIN, 1988)

GROUP 1 - GEOMETRY, TIME

1 Duration of storm
2 Time of origin
3 Speed of movement
4 Direction of movement
5 Mean X co-ordinate
6 Mean Y co-ordinate
7 Mean range
8 Envelope decision time
9 Volume at decision time
10 Peak dBz at decision time

GROUP 2 - TOP, DEPTH, VOLUME, MASS

11 Echo top - maximum
12 Echo top - maximum rate of increase
13 Echo top - mean
14 Echo top - time to maximum
15 Echo top - time to maximum rate of increase
16 Echo top - persistence
17 Echo top - maximum ratio
18 Depth - maximum
19 Depth - maximum rate of increase
20 Depth - mean
21 Depth - time to maximum
22 Depth - time to maximum rate of increase
23 Depth - persistence
24 Depth - maximum ratio
25 Volume - maximum
26 Volume - maximum rate of increase
27 Volume - time integral
28 Volume - mean
29 Volume - time to maximum
30 Volume - time to maximum rate of increase
31 Volume - persistence
32 Volume - maximum ratio
33 Mass for whole storm - maximum
34 Mass for whole storm - maximum rate of increase
35 Mass for whole storm - time integral
36 Mass for whole storm - mean
37 Mass for whole storm - time to maximum
38 Mass for whole storm - time to maximum rate of increase
39 Mass for whole storm - persistence
40 Mass for whole storm - maximum ratio
41 Mass above cut-off altitude - maximum
42 Mass above cut-off altitude - maximum rate of increase
43 Mass above cut-off altitude - time integral
44 Mass above cut-off altitude - mean
45 Mass above cut-off altitude - time to maximum
46 Mass above cut-off altitude - time to maximum rate of increase
47 Mass above cut-off altitude - persistence
48 Mass above cut-off altitude - maximum ratio

GROUP 3 - AREA, RAIN, PRECIPITATION, RATIOS

49 Area 3° - maximum
50 Area 3° - maximum rate of increase
51 Area 3° - time integral
52 Area 3° - mean
53 Area 3° - time to maximum
54 Area 3° - time to maximum rate of increase
55 Area 3° - persistence
56 Area 3° - maximum ratio
57 Area cut-off - maximum
58 Area cut-off - maximum rate of increase
59 Area cut-off - time integral
60 Area cut-off - mean
61 Area cut-off - time to maximum
62 Area cut-off - time to maximum rate of increase
63 Area cut-off - persistence
64 Area cut-off - maximum ratio
65 Rainflux 3° - maximum
66 Rainflux 3° - maximum rate of increase
67 Rainflux 3° - mass
68 Rainflux 3° - mean
69 Rainflux 3° - time to maximum
70 Rainflux 3° - time to maximum rate of increase
71 Rainflux 3° - persistence
72 Rainflux 3° - maximum ratio
73 Rainflux cut-off - maximum
74 Rainflux cut-off - maximum rate of increase
75 Rainflux cut-off - mass
76 Rainflux cut-off - mean
77 Rainflux cut-off - time to maximum
78 Rainflux cut-off - time to maximum rate of increase
79 Rainflux cut-off - persistence
80 Rainflux cut-off - maximum ratio
81 Precipitable water - maximum
82 Precipitable water - maximum rate of increase
83 Precipitable water - time integral
84 Precipitable water - mean
85 Precipitable water - time to maximum
86 Precipitable water - time to maximum rate of increase
87 Precipitable water - persistence
88 Precipitable water - maximum ratio
89 Mass time integral/rain mass - 3°
90 Mass time integral/rain mass - cutoff
91 Mean mass/rain mass - 3°
92 Mean mass/rain mass - cut-off

TABLE 4.3 : CONTINUED

GROUP 4 - VERTICAL CENTROIDS

93 Vertical centroid - maximum
94 Vertical centroid - maximum rate of increase
95 Vertical centroid - mean
96 Vertical centroid - time to maximum
97 Vertical centroid - time to maximum rate of increase
98 Vertical centroid - persistence
99 Vertical centroid - maximum ratio
100 Z weighted vertical centroid - maximum
101 Z weighted vertical centroid - maximum rate of increase
102 Z weighted vertical centroid - mean
103 Z weighted vertical centroid - time to maximum
104 Z weighted vertical centroid - time to maximum rate of increase
105 Z weighted vertical centroid - persistence
106 Z weighted vertical centroid - maximum ratio
107 Delta vertical centroid - maximum
108 Delta vertical centroid - maximum rate of increase
109 Delta vertical centroid - mean
110 Delta vertical centroid - time to maximum
111 Delta vertical centroid - time to maximum rate of increase
112 Delta vertical centroid - persistence
113 Delta vertical centroid - maximum ratio

GROUP 5 - SPARE

114 Discriminant function
115 Mass of the 3° rainflux/area time integral at 3°
116 Rainflux at 3° at the beginning of the time period of interest
117 Rainflux at 3° at the end of the time period of interest

GROUP 6 - REFLECTIVITY

119 Peak dBz whole storm - maximum
120 Peak dBz whole storm - maximum rate of increase
121 Peak dBz whole storm - mean
122 Peak dBz whole storm - time to maximum
123 Peak dBz whole storm - time to maximum rate of increase
124 Peak dBz whole storm - persistence
125 Peak dBz whole storm - maximum ratio
126 Mean dBz whole storm - maximum
127 Mean dBz whole storm - maximum rate of increase
128 Mean dBz whole storm - mean
129 Mean dBz whole storm - time to maximum
130 Mean dBz whole storm - time to maximum rate of increase
131 Mean dBz whole storm - persistence
132 Mean dBz whole storm - maximum ratio
133 Mean dBz 3° - maximum
134 Mean dBz 3° - maximum rate of increase
135 Mean dBz 3° - mean
136 Mean dBz 3° - time to maximum
137 Mean dBz 3° - time to maximum rate of increase
138 Mean dBz 3° - persistence
139 Mean dBz 3° - maximum ratio
140 Mean dBz cut-off - maximum
141 Mean dBz cut-off - maximum rate of increase
142 Mean dBz cut-off - mean
143 Mean dBz cut-off - time to maximum
144 Mean dBz cut-off - time to maximum rate of increase
145 Mean dBz cut-off - persistence
146 Mean dBz cut-off - maximum ratio
147 Maximum height 45'S - maximum
148 Maximum height 45'S - maximum rate of increase
149 Maximum height 45'S - mean
150 Maximum height 45'S - time to maximum
151 Maximum height 45'S - time to maximum rate of increase
152 Maximum height 45'S - persistence
153 Maximum height 45'S - maximum ratio
154 Height peak dBz - maximum
155 Height peak dbz - maximum rate of increase
156 Height peak dBz - mean
157 Height peak dBz - time to maximum
158 Height peak dBz - time to maximum rate of increase
159 Height peak dBz - persistence
160 Height peak dBz - maximum ratio

GROUP 7 - MASS=F(HEIGHT)

161 Mass=f(height) : mean - mean
162 Mass=f(height) : mean - maximum
163 Mass=f(height) : mean - minimum
164 Mass=f(height) : mean - maximum rate of increase
165 Mass=f(height) : mean - maximum rate of decrease
166 Mass=f(height) : standard deviation - mean
167 Mass=f(height) : standard deviation - maximum
168 Mass=f(height) : standard deviation - minimum
169 Mass=f(height) : standard deviation - maximum rate of increase
170 Mass=f(height) : standard deviation - maximum rate of decrease
171 Mass=f(height) : -skew - mean
172 Mass=f(height) : -skew - maximum
173 Mass=f(height) : -skew - minimum
174 Mass=f(height) : -skew - maximum rate of increase
175 Mass=f(height) : -skew - maximum rate of decrease
176 Mass=f(height) : mode - mean
177 Mass=f(height) : mode - maximum
178 Mass=f(height) : mode - minimum
179 Mass=f(height) : mode - maximum rate of increase
180 Mass=f(height) : mode - maximum rate of decrease

TABLE 4.3 : CONTINUED

GROUP 8 - PEAK(DBZ)=F(HEIGHT)

181 dBz=f(height) : mean - mean
182 dBz=f(height) : mean - maximum
183 dBz=f(height) : mean - minimum
184 dBz=f(height) : mean - maximum rate of increase
185 dBz=f(height) : mean - maximum rate of decrease
186 dBz=f(height) : standard deviation - mean
187 dBz=f(height) : standard deviation - maximum
188 dBz=f(height) : standard deviation - minimum
189 dBz=f(height) : standard deviation - maximum rate of increase
190 dBz=f(height) : standard deviation - maximum rate of decrease
191 dBz=f(height) : -skew - mean
192 dBz=f(height) : -skew - maximum
193 dBz=f(height) : -skew - minimum
194 dBz=f(height) : -skew - maximum rate of increase
195 dBz=f(height) : -skew - maximum rate of decrease
196 dBz=f(height) : mode - mean
197 dBz=f(height) : mode - maximum
198 dBz=f(height) : mode - minimum
199 dBz=f(height) : mode - maximum rate of increase
200 dBz=f(height) : mode - maximum rate of decrease

GROUP 9 - ΣVOLUME=F(DBZ)

201 ΣVolume=f(dBz) : mean - mean
202 ΣVolume=f(dBz) : mean - maximum
203 ΣVolume=f(dBz) : mean - minimum
204 ΣVolume=f(dBz) : mean - maximum rate of increase
205 ΣVolume=f(dBz) : mean - maximum rate of decrease
206 ΣVolume=f(dBz) : standard deviation - mean
207 ΣVolume=f(dBz) : standard deviation - maximum
208 ΣVolume=f(dBz) : standard deviation - minimum
209 ΣVolume=f(dBz) : standard deviation - maximum rate of increase
210 ΣVolume=f(dBz) : standard deviation - maximum rate of decrease
211 ΣVolume=f(dBz) : -skew - mean
212 ΣVolume=f(dBz) : -skew - maximum
213 ΣVolume=f(dBz) : -skew - minimum
214 ΣVolume=f(dBz) : -skew - maximum rate of increase
215 ΣVolume=f(dBz) : -skew - maximum rate of decrease
216 ΣVolume=f(dBz) : mode - mean
217 ΣVolume=f(dBz) : mode - maximum
218 ΣVolume=f(dBz) : mode - minimum
219 ΣVolume=f(dBz) : mode - maximum rate of increase
220 ΣVolume=f(dBz) : mode - maximum rate of decrease

GROUP 10 - Σ3 DEGREES AREA=F(DBZ)

221 ΣArea=f(dBz) : mean - mean
222 ΣArea=f(dBz) : mean - maximum
223 ΣArea=f(dBz) : mean - minimum
224 ΣArea=f(dBz) : mean - maximum rate of increase
225 ΣArea=f(dBz) : mean - maximum rate of decrease
226 ΣArea=f(dBz) : standard deviation - mean
227 ΣArea=f(dBz) : standard deviation - maximum
228 ΣArea=f(dBz) : standard deviation - minimum
229 ΣArea=f(dBz) : standard deviation - maximum rate of increase
230 ΣArea=f(dBz) : standard deviation - maximum rate of decrease
231 ΣArea=f(dBz) : -skew - mean
232 ΣArea=f(dBz) : -skew - maximum
233 ΣArea=f(dBz) : -skew - minimum
234 ΣArea=f(dBz) : -skew - maximum rate of increase
235 ΣArea=f(dBz) : -skew - maximum rate of decrease
236 ΣArea=f(dBz) : mode - mean
237 ΣArea=f(dBz) : mode - maximum
238 ΣArea=f(dBz) : mode - minimum
239 ΣArea=f(dBz) : mode - maximum rate of increase
240 ΣArea=f(dBz) : mode - maximum rate of decrease

GROUP 11 - CONTROL

241 Average mixing ratio in the lowest 60 mb
242 Cloud condensation level temperature
243 Buoyancy at 500 mb
244 Temperature at cloud condensation level/buoyancy at 500 mb
245 Number of tracks for the day
246 Cumulative 3° area time integral for the day
247 Maximum volume of any storm for the day
248 Maximum rate of increase of volume for the day
249 Maximum tops of any storm for the day
250 Maximum dBz of any storm for the day

Reuter and Mather (1988) in the original statistical analysis of Phase I, led to the postulation of a physical seeding hypothesis which, presumably, will be further investigated during the current and future phases of the project. Table 4.4 presents this hypothesis as paraphrased from a note by Mather (1989). The spectre of bias, i.e. significant pre-seeding differences between certain response variables, has necessitated a re-analysis (see 4.3.4 below) which might cause the forementioned hypothesis to be modified or replaced during future experiments.

An important aspect of the Phase I experiment concerns the possibility that seed/no seed differences could be influenced by the mere presence of the sampling aircraft through so-called APIPS(aircraft produced ice particles). For this reason the "no seed" treatment in this experiment was divided into two sub-treatments: "no seed/sample" and "no seed/ no sample". Statistically significant differences between these two "no seed" samples would indicate the influence of APIPS and affect the design of future seeding experiments.

The experimental procedure leading to an actual cloud-seeding during Phase I was as follows:

* Data on the synoptic situation is used to decide if a specific day is a "go" or a "no-go" day.

* On a "go" day, reflectivity values from the radar determine the launching of the seeding aircraft (Lear jet) - if two storm cells with closed contours greater than 30 dBZ, containing reflectivities greater than 40 dBZ, are found within the experimental area.

* After take-off, the Lear jet flies to one of the storm cells identified by radar as an experimental possibility. A visual inspection is carried out according to the following "visual" criteria:

TABLE 4.4 : **DRAFT SEEDING HYPOTHESIS FOR PAWS**

1. Seeding causes the freezing of small waterdrops which grow as graupel and which have higher trajectories - because of lower densities - than water drops. These higher particle trajectories should appear as increases in the rates of rise of radar reflectivities in seeded clouds soon after treatment.

2. Large melted graupel reach the ground some minutes later than smaller drops from unseeded storms, producing higher radar reflectivities at low scan angles some 20 to 30 minutes after decision time.

3. The higher trajectories cause greater dispersion of the less dense graupel particles, thus the precipitation from seeded storms cover larger areas than unseeded storms.

4. It is primarily the longer residence times in the cloud caused by the higher trajectories that permit the graupel to grow larger than the waterdrops, and it is this larger residence time that harvests more water from the cloud, thereby increasing the efficiency of the precipitation process. Thus, the proposed mechanism requires larger, longer-lasting clouds for success.

(i) reasonable cloud dimensions, such as good width-to-height proportions, not excessively sheared and having well-defined bases,

(ii) having one or more cloud turrets actively growing through the -10°C level,

(iii) separated from other experimental storms by at least 20 nautical miles.

* If the storm cell passes the visual inspection, the (decision) time is recorded and the radar operator informed that an experiment has been declared. In the first two seasons of Phase I the radar operator then opened a sealed envelope containing a treatment (seed/no seed) instruction (from a pre-specified random sequence) and informed the crew. To ensure experimental "blindness" during the third season an automatic method was used for treatment allocation, which precluded treatment knowledge by the participants.

* Three treatments are possible: "seed and sample", "no seed and sample", "no seed and no sample". When the treatment is "no seed and no sample" the pilot flies in the vicinity of the storm cell for a few minutes to assist in the radar identification of the cell. In the case of either "seed and sample" or "no seed and sample" the pilot penetrates all rapidly-growing turrets on the flanks of the storm between the -5° and the -15°C levels to make micro-physical measurements. If the treatment was "seed and sample", dry ice pellets are dispenses while within the turrets, and the treatment period continues until either 120 seconds of seeding has taken place (i.e. 23 kg of dry ice has been used) or until no more rapidly-rising turrets are available. For the "no seed and sample" treatment, the pilot flies through the turret as if seeding, and for the same period as if seeding was taking place, but without dispensing any seeding material.

* Additional criteria for selection of an experimental unit, which only arose during the radar data reduction stage, were:

  (a) minimum radar reflectivity always above 30 dBZ,

  (b) speed of movement less than 80 km/hr,

  (c) being between 10 and 80 km from the Nelspruit radar, but not over foreign territory,

  (d) first being recorded between 09:00 and 17:00,

  (e) volume between 3 and 750 km^3,

  (f) ratio of temperature at the convective condensation level and the buoyancy at 500 m greater than 2 (based on aircraft soundings).

4.3.3 Test cloud summary

During the three seasons 1984-87 a total of 169 storms were declared test cases for the randomised seeding experiment, but, after application of all the criteria mentioned in 4.2 above, the data set was reduced to 38 "seed and sample" cases, 19 "no seed and sample" cases and 27 "no seed and no sample" cases.

4.3.4 Results: statistical

Initial statistical analyses of the 250 radar-measured response variables for part or all of the three seasons of the randomised seeding experiment (SWA and CIC, 1986(c); Morgan, et al, 1988) have been superseded by new analyses (Galpin, 1988; Galpin, Grosh and Auret, 1988). These new analyses were deemed necessary to cope with the problem of bias in the pre-seeding sample conditions and also because incorrect definitions of three of the four 10-minute post-seeding "time windows" had been used in some of the original analyses.

The introductory re-analysis by Galpin (1988) confirmed that a sampling aircraft effect might be present, in other words, that APIPS might "contaminate" the "no seed and sample" treatment. The follow-up analyses by Galpin, et al. (1988), showed by regression analysis that the total accumulated radar-measured rainfall over the full 40-minute post-seeding window contained no seeding effect. This study is to be extended to focus on individual 10-minute post-seeding windows.

Further re-analysis by Galpin and Auret (1988) uses re-randomisation (permutation) and analysis of covariance techniques. The latter technique is utilised to take care of possible biases in the pre-decision time values of the three treatment groups. The randomisation tests show that certain storm properties differ significantly between treatments during the 10 minutes before decision time, and thus indicate that bias may be present. The covariance analysis, which takes possible bias into account, uses storm properties 1 to 10 and 241 to 250 (Table 4.3) as covariates. These variables relate mainly to values at decision time, to synoptic conditions of the day and to meso-scale conditions. They are therefore "independent" of the time period being examined and are regarded as control properties by the PAWS researchers. The covariance analysis confirms that between 10 and 24 storm variables (out of the remaining 230), depending on the treatment under consideration, exhibit initial bias. The results of a simultaneous interpretation of the randomisation and covariance analyses are still pending at the time of writing. However, the published statistical results in Galpin and Auret (1988) appear to be in conflict with those of Mather (1988). Whereas the latter shows a number of storm variables as being significant during the last two time windows (20-40 minutes after seeding), the Galpin and Auret results show only one variable as significantly different for these time windows (after allowing for bias) for the "seed and sample" versus "no seed and no sample" (i.e. APIPS-free) treatments. This anomaly, though appearing to threaten the plausibility of the physical seeding hypothesis detailed in Table 4.4, is less serious than it seems. It is wholly due to differences in sample stratification and more limited data sets used by Galpin and co-workers.

Recently, as part of the process to resolve anomalies and attain a "unified" set of PAWS results, Grosh and Mather (1989) provided information on further analyses of PAWS data which was accepted as definitive by the PAWS steering committee. Table 4.5 and Figure 4.1 present these results. In this case the "no seed and sample" data was included with the "no seed and no sample" data. Furthermore, there now seems to be agreement that pre-seeding bias is not statistically significant. However, both researchers have verbally indicated that the physical (cause-effect) importance of "larger" pre-seeding storm variables for the production of "larger" post-seeding effects cannot be discounted without further study. Cloud modelling has been suggested as one avenue to investigate this point.

An important innovation in those PAWS statistical analyses still in progress (Galpin and Auret, 1988) is the inclusion of additional covariates such as the amount of seeding material, duration of seeding and the number of seeded turrets. This type of variable has often been overlooked in overseas seeding experiments and might contribute to the indefinite nature of the results of most historical cloud- seeding experiments.

4.3.5 Results: Radar

As stated previously, a 5 cm wavelength weather radar, first at Nelspruit and currently at Carolina, is being used for the tracking of the response of the isolated multicellular target storms to the seeding. These storm trade properties are the response variables referred to in the foregoing statistical analysis section (4.3.4). The Z-R relationship used for radar reflectivity/rainfall volume conversions is $Z = 200\ R^{1,6}$ (SWA and CIC, 1986(d)). The radar data was also used for "climatological" studies relating to storm speeds and lifetimes and geographical effects on the direction of storm movement.

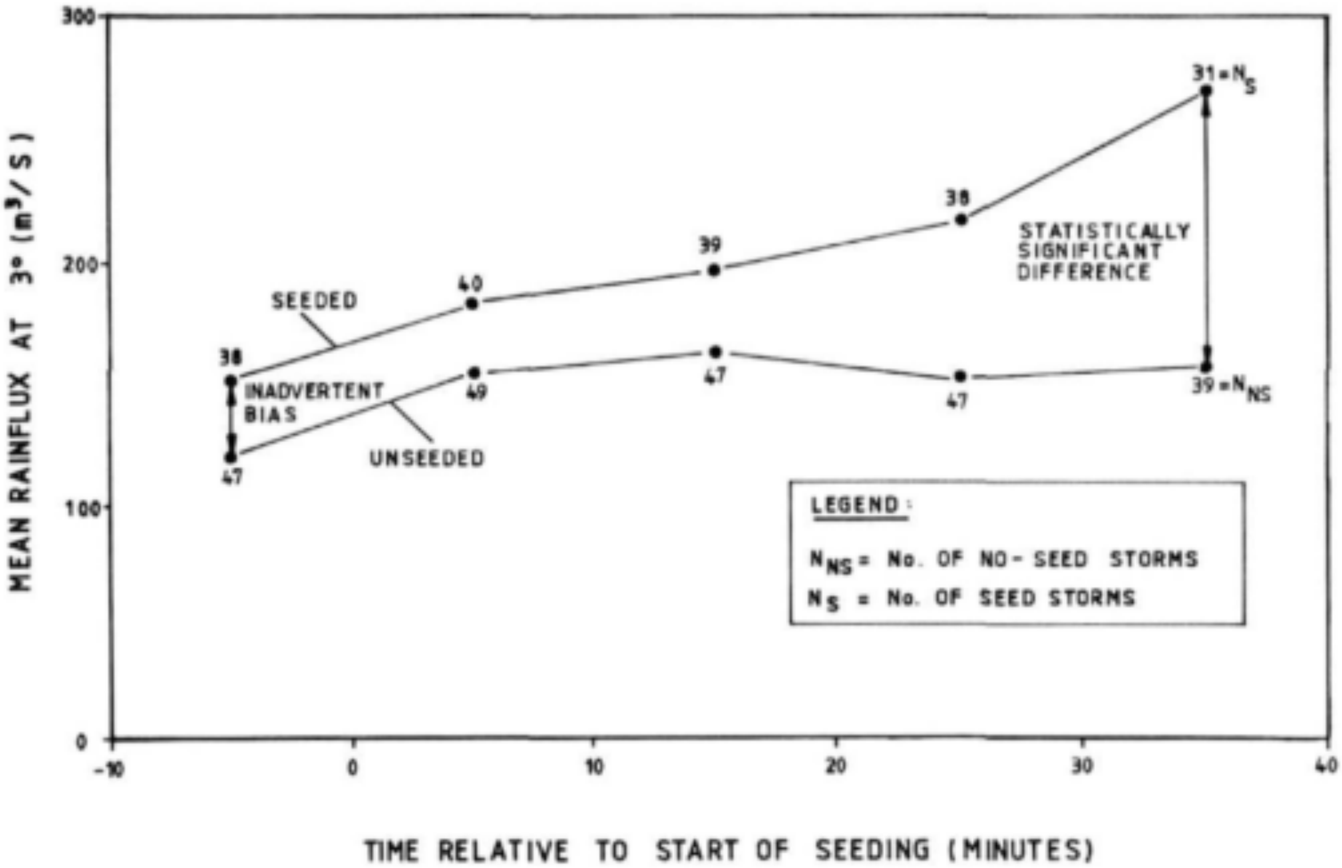
TABLE 4.5 : **PERCENTAGE DIFFERENCE IN MEANS FOR SELECTED PAWS DATA : GROSH AND MATHER (1989) *****

Radar variable type	Radar variable no	Time window (minutes) after decision time				
		-10 - 0	0 - 10	10 - 20	20 - 30	30 - 40
Rainflux at 3°	(68)	27	17	17	32 **	76 *
Storm Vol	(28)	20	17	19	26 **	42 *
Storm Area at 3°	(52)	16	7	10	16	43 *
		Sample size				
No-seed		47	49	47	47	39
Seed		38	40	39	38	31

*** $\frac{\text{Seed - No Seed}}{\text{No Seed}} \times 100$

** significant at 10% level

* significant at 5% level



PAWS: SUMMARY OF MEAN RAINFLUX RESPONSE TO SEEDING (GROSH AND MATHER, 1989)

FIGURE 4.1

An important direction of radar research currently in progress relates to improving the accuracy of radar rainfall measurements (Grosh, 1988). This includes work on the Z-R relationship, on sub-beam effects (using vertical Doppler radar) which degrade the Z-R relationship accuracy, on aircraft- mounted radar (3 cm, range gate locked 1 800 m in flight direction) measurements and on assumptions underlying the radar storm tracking software. Initial results include that gauge calibrated radars can be expected to be within 25% of an accurate gauge rainfall value on average; that the best means of radar gauge calibration is with a distributed network of gauges throughout the target area; that the effect of differential raindrop fall speeds could cause major differences between radar and surface level gauge measurements; and that the maximum permitted tracking velocity in the radar tracking software affects the findings of significant seeding influences on rainstorms. The implications of these findings for PAWS are at present under consideration.

4.3.6 Results: Microphysical studies

In-cloud observations have, _inter alia_, focused on the importance of the coalescence and ice mechanism in PAWS clouds, the microphysical "signature" of APIPS, the effects of turbulence on raindrop formation and the relationship between storm electrical forces and precipitation development. The dominance of the CRG mechanism in precipitation formation is fairly strongly indicated so for Morgan, _et al_ (1988). An important realisation in the PAWS work appears to be the fact that "it is almost impossible for a single aircraft to follow the effects of the treatment on the evolving precipitation formation mechanisms" (Grosh and Mather, 1988), because the "aircraft's sample volume capabilities are just too small compared to the volume of the cloud". This difference is of the order of m^3 compared with tens of km^3. Consequently, the researchers seem to have accepted that a full formulation of a seeding hypothesis cannot be completed by microphysical measurements alone, but requires major inputs from remote radars. This approach represents a significant difference in focus between the PAWS and BPRP programmes to date - in the latter the randomised experiment is based solely on microphysical observations (see 4.2.4 above).

4.3.7 Results: Cloud modelling and meso-scale studies

Reuter (1988(a)), a member of the PAWS team, demonstrated the feasibility of 3-D modelling of the seeding of isolated cumulus congestus clouds, using data from the BPRP. The same author (Reuter, 1988(b)) modelled the influence of aircraft induced turbulence on rainfall formation in seeded clouds and concluded that no major effect needs to be considered.

A number of meso-scale studies have been completed to date. These studies led to descriptions of natural rainfall areal and temporal variability in the PAWS area, of the meteorological controls on rainfall, of PAWS area clouds and of radar climatology.

5 PROVISIONAL RAINFALL MODIFICATION SCENARIO FOR USE IN SOUTH AFRICAN IMPACT STUDIES

5.1 Introduction

The hydrological, agricultural and other impacts of operational cloud-seeding will be determined by the changes induced by seeding in the natural rainfall. Systematisation of these changes into a "rainfall modification scenario" provides an interface between meteorological/cloud-seeding research and potential end-user impact research, the subject of this report.

Assessment, at the research level, of the potential impacts of rainfall stimulation can occur by at least three routes:

(i) field experiments under actual cloud-seeding conditions;

(ii) field experiments under simulated augmented rainfall conditions, i.e. by some form of irrigation;

(iii) theoretical experiments by use of appropriate rainfall-runoff, crop yield and timber yield models.

Any assessment of impact by routes (ii) or (iii) obviously hinges on the assumed or expected rainfall modification scenario. Even route (i) experiments would require some antecedent understanding of the likely rainfall modifications that would result from the cloud-seeding to ensure an appropriate experimental design.

In this chapter consideration is given to a provisional scenario for seeding-induced rainfall changes appropriate for use in South African rainfall stimulation impact studies.

Such a scenario can be devised by answering the question:

How, and by how much, are the quantifiable characteristics of natural rainfall changed by cloud-seeding?

This question can be rephrased in various ways, depending on the research interest of the questioner:

* How is the intensity/depth/duration/frequency relationship of the rainfall altered?

* How are the statistical parameters - mean/standard deviation/skewness/probability density function - of the hourly/daily/monthly/seasonal/annual rainfall totals altered?

* How is the natural time series of hourly/daily/monthly/annual rainfall totals altered?

Furthermore, the research interest of the questioner might require the extension of the rainfall modification scenario from the micro- (point) scale to the meso- (catchment) scale. The following question should thus accompany the foregoing three questions:

* How is the spatial distribution of rainfall characteristics altered?

Answers to these questions are dependent on available experimental data sources. In particular, the experimental units utilized in the particular cloud-seeding experiments, will determine how the foregoing questions are answered. The experimental unit in PAWS and BPRP is the <u>target cloud</u>, but in projects like Israeli I and II and Whitetop the experimental unit was the <u>rain-day</u>. Clearly, use of cloud-based seeding effects offers an opportunity for more sophistication in the deriviation of a modified rainfall scenario than rain-day seeding effects, but at the cost of vastly increased complexity and data requirements. These issues are addressed later in this chapter, but, prior attention needs to be given to the experimental data sources.

5.2 Cloud-seeding data sources

The quantification of the seeding effects on natural rainfall relies on the data produced by cloud-seeding projects that have been scientifically supported and documented. It can be inferred from the material presented in Chapters 3 and 4 that only two cloud-seeding experiments which offer an appropriate level of documentation have achieved enough scientific credibility to warrant their choice as data sources for the establishment of rainfall modification scenarios for use in South African impact studies: Israeli II and PAWS. (The BPRP has the potential to be a suitable source of data for this purpose, but it has to be omitted at this stage because a statistical analysis of the randomised cloud-seeding experiment using radar-track variables, or gauged rainfall, has so far not been reported).

The following diferences between the Israeli II project and the South African cloud-seeding requirements preclude the use of Israeli II results for South African impact studies:

(i) Cloud systems seeded in Israeli II were winter cumuli organised in postfrontal bands which display a narrow range of cloud base temperatures (5°C to 8°C), whereas the most promising South African seeding targets are summertime semi-isolated cloud complexes - specifically, the turrets on the flanks of these complexes - with cloud base temperatures in the range 5°C to 16°C.

(ii) Broadcast patrol seeding at cloud-base was used in the Israeli project whereas the appropriate South African approach appears to be to penetrate all actively growing turrets at approximately the -10°C level and to seed continuously inside the turrets at a constant rate until all active turrets on a particular complex are treated.

(iii) Israeli clouds seem to develop rainfall almost exclusively through the IRG mechanism whereas South African seeding targets display a mix of IRG/CRG mechanisms with, occasionally, also the pure coalescence mechanism present.

At this stage, therefore, the derivation of a likely rainfall modification scenario has to be principally based on the PAWS data set. This data set comprises the following relevant data types:

(i) Radar-derived measurements of physical attributes of seeded and non-seeded "target" clouds, the most useful of which, both in statistical and physical terms (see section 4.3.4 above), seem to be rainflux (at 3°) and storm area (at 3°). This data set spans the operational days between October 1984 and March 1987.

(ii) Radar-derived storm tracks and time histories of all storm echoes that exceeded 30 dBZ on operational days during the period October 1982 to the present.

(iii) Point rainfalls at a number of daily or recording rainfall gauges throughout the PAWS area (see section 4.3 above) during the period October 1982 and the present. (Some of the daily gauges have records spanning many decades).

These data sets are described in detail in the following sections.

5.3 Derived physical attributes of PAWS target clouds

As indicated in section 4.3.4 above, the two radar observed attributes of target clouds that reveal the greatest seeding effect in statistical terms and that also happen to be meaningful in terms of deriving a modified rainfall time series, are mean rainflux and mean storm area (both at 3°). A full listing of this data set for the two time windows that show greatest statistical significance, i.e. 20 to 30 minutes and 30 to 40 minutes after decision time, appears in Appendix A, along with the equivalent data sets for other time windows up to 60 minutes after decision time.

5.3.1 Basic statistics

At this point it would be useful to briefly consider the exact nature of the storm area and rainflux observations. Storm area is calculated by summing of all contiguous radar screen pixels displaying a reflectivity, Z, exceeding 30 dBZ. Multiplication by the unit area represented by a pixel yields the storm area. Up to two sweeps are possible per 10 min. window, in which case a mean is calculated. For each pixel inside the aforesaid contiguous area the rainfall intensity, R, in mm/h is derived by applying the Z/R relationship. The rainflux for each pixel is now calculated by multiplying each R by the unit pixel area. Summing of the individual pixel rainfluxes over the aforesaid contiguous reflectivity zone yields the storm rainflux. Rainflux is therefore a function of storm area.

The basic statistics of the most relevant rainflux and storm area data reported for the PAWS experiment are listed in Table 5.1. These statistics have been made available by Mather (1989). This table reflects the increased mean values, reported earlier in Table 4.5, of the variables under consideration for the seed vs no-seed cases. The values shown reveal that the seed sample was inadvertently favoured by storms with larger initial areas, displaying larger initial rainfluxes.

5.3.2 Frequency distributions of target cloud attributes

Histograms depicting the relative frequency of rainflux and of storm area for each of the three time windows concerned, juxtaposing the seed and the no-seed cases, are presented in Fig. 5.1 to 5.6. An example of the cumulative frequencies for rainflux is shown in Figure 5.7. The following differences between the two sets of cases are apparent:

(i) For both post-seeding time windows there is a clear shift to the right (i.e. to larger values) in the histograms, which, of course, is reflected in the increased means shown in Table 5.1.

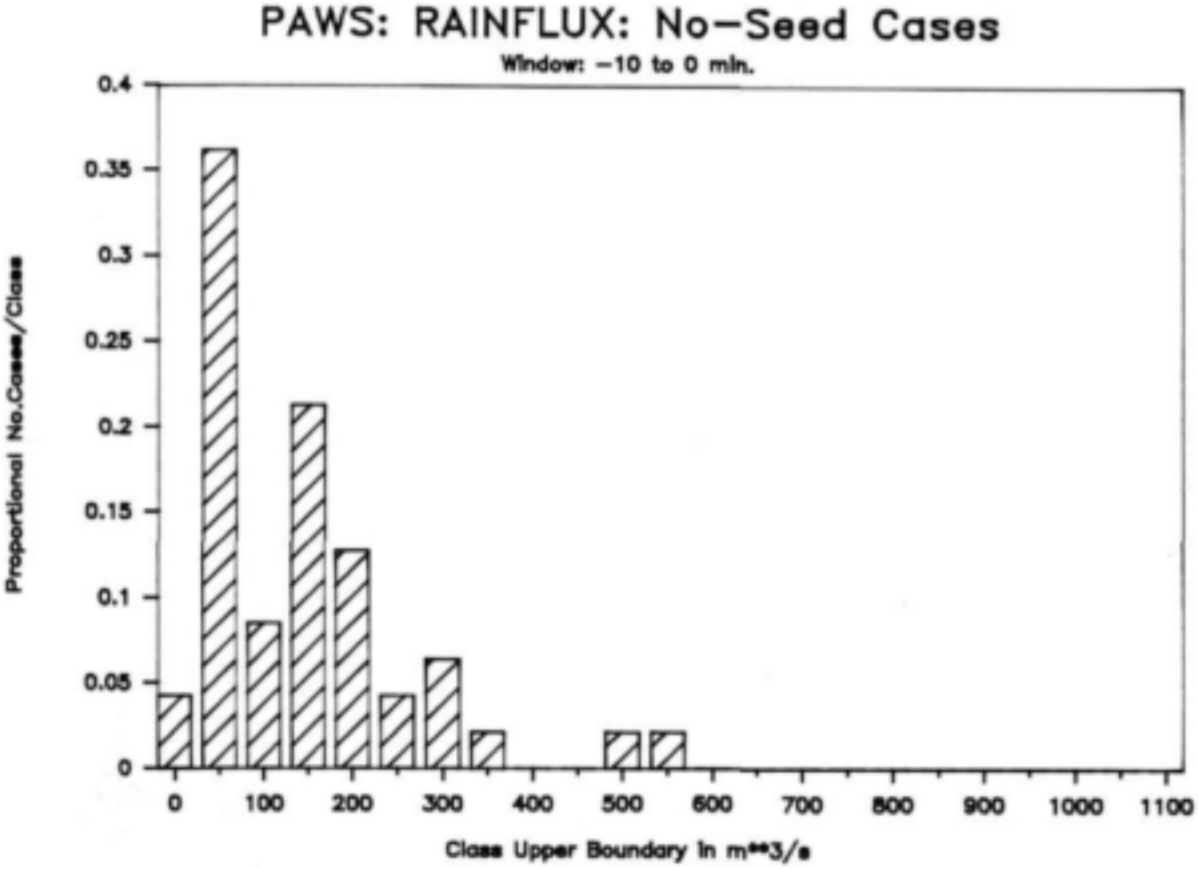
TABLE 5.1 **SOME BASIC STATISTICS OF PAWS DATA* ON RAINFLUX AND STORM AREA (BOTH AT 3°)**

Case	Rainflux (m^3/s)					Storm Area (km^2)				
	mean	st.dev.	min.	max.	no.	mean	st.dev.	min.	max.	no
			Time Window : -10 to 0 min							
No-Seed	117	119	0	521	47	38	24	0	134	47
Seed	152	159	0	620	38	44	44	40	196	38
			Time Window : 20 to 30 min.							
No-Seed	145	172	0	780	47	53	50	0	196	47
Seed	201	224	5	1091	38	61	48	2	190	38
			Time Window : 30 to 40 min.							
No-Seed	139	165	3	809	39	49	48	3	154	39
Seed	245	280	4	1197	31	69	55	5	199	31

*Reported in Appendix A.

(ii) For both sets of post-seeding time windows the seed cases have a markedly lower frequency of very small values (i.e. rainflux less than 100 m^3/s and storm area less than 20 km^2). However, to some extent this difference is also present in the histograms of the pre-seeding window (-10 to zero min.).

(iii) The 30-40 minute time window reveals a greater frequency of very large values in the seed cases for both rainflux and storm area. Very large values are absent in the initial rainflux samples, but the initial storm area sample for the seed case does contain one very large value.


PAWS: RAINFLUX: No-Seed Cases
Window: -10 to 0 min.
Proportional No.Cases/Class
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

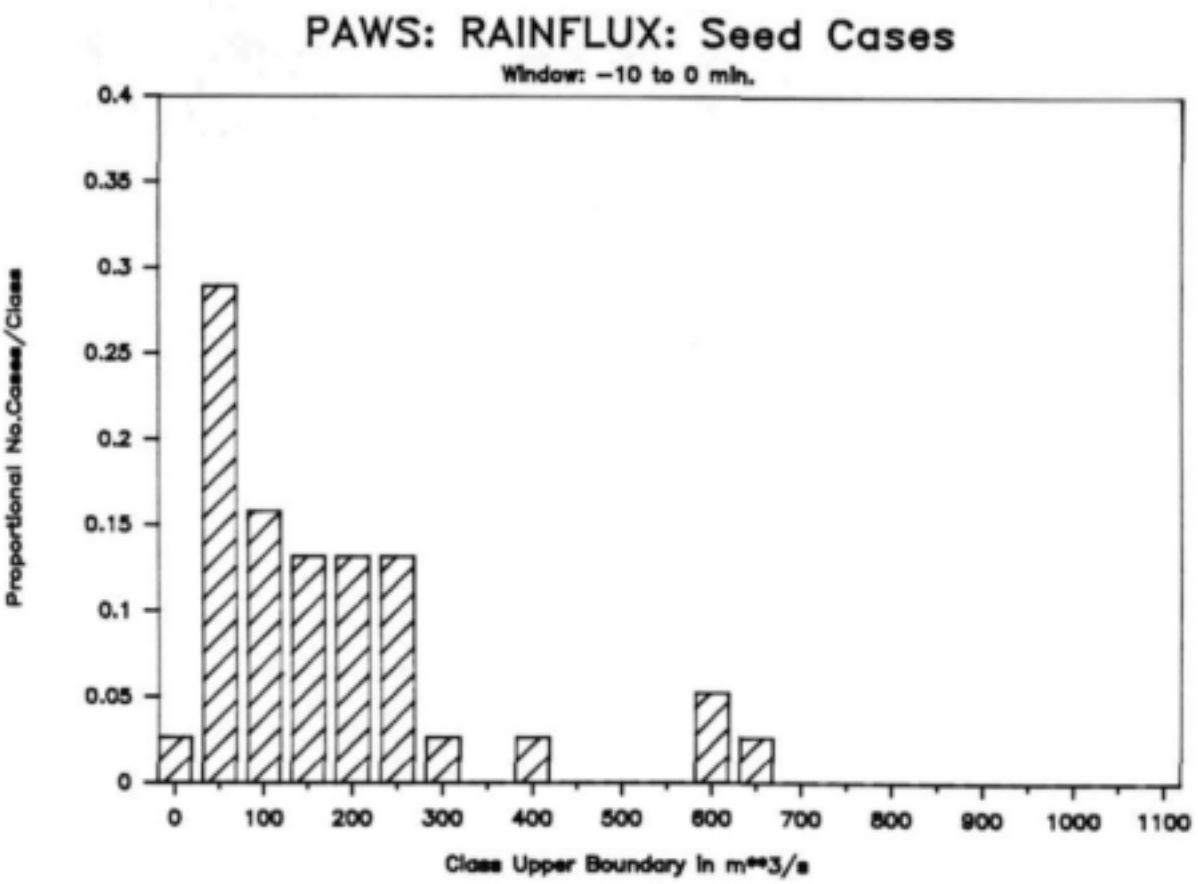
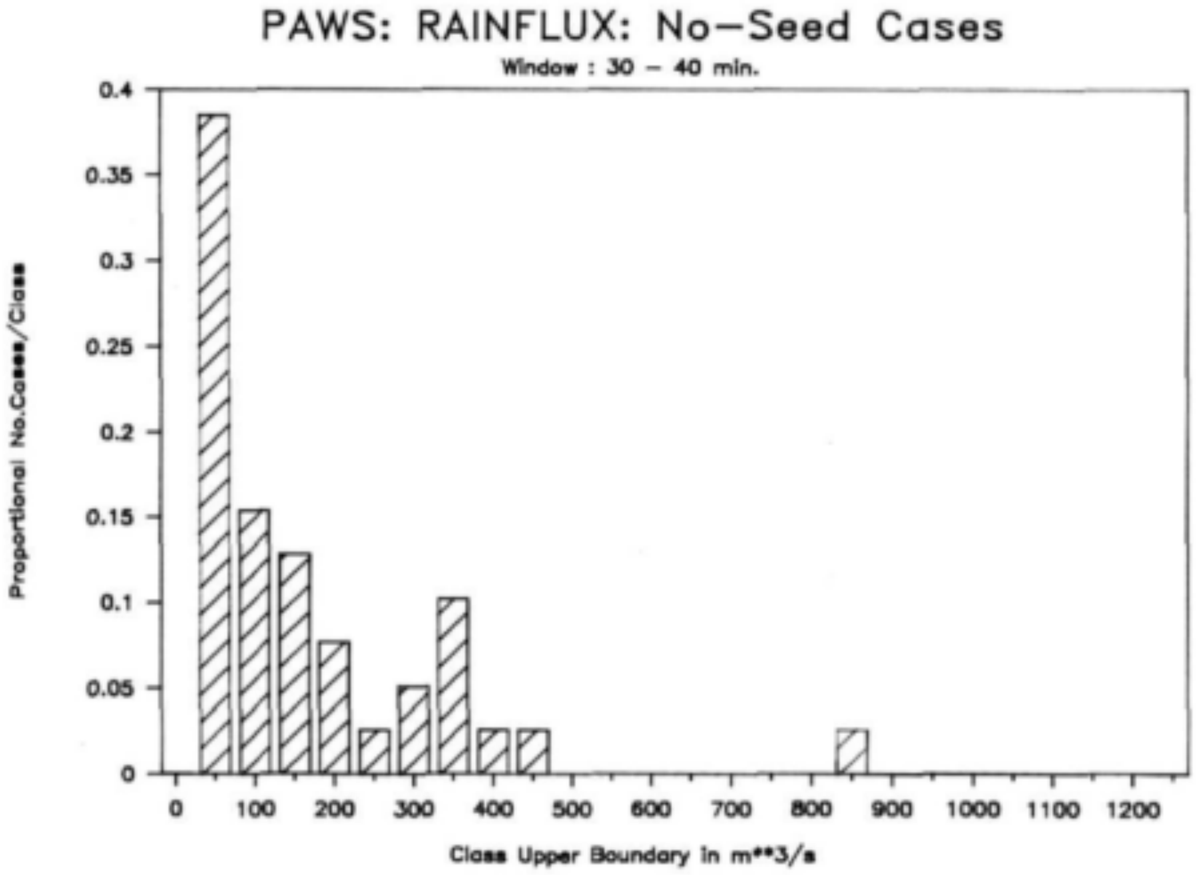

PAWS: RAINFLUX: Seed Cases
Window: -10 to 0 min.
Proportional No.Cases/Class
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

FIGURE 5.1


PAWS: RAINFLUX: No-Seed Cases
Window : 30 - 40 min.
Proportional No.Cases/Class
Class Upper Boundary in m**3/s
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05

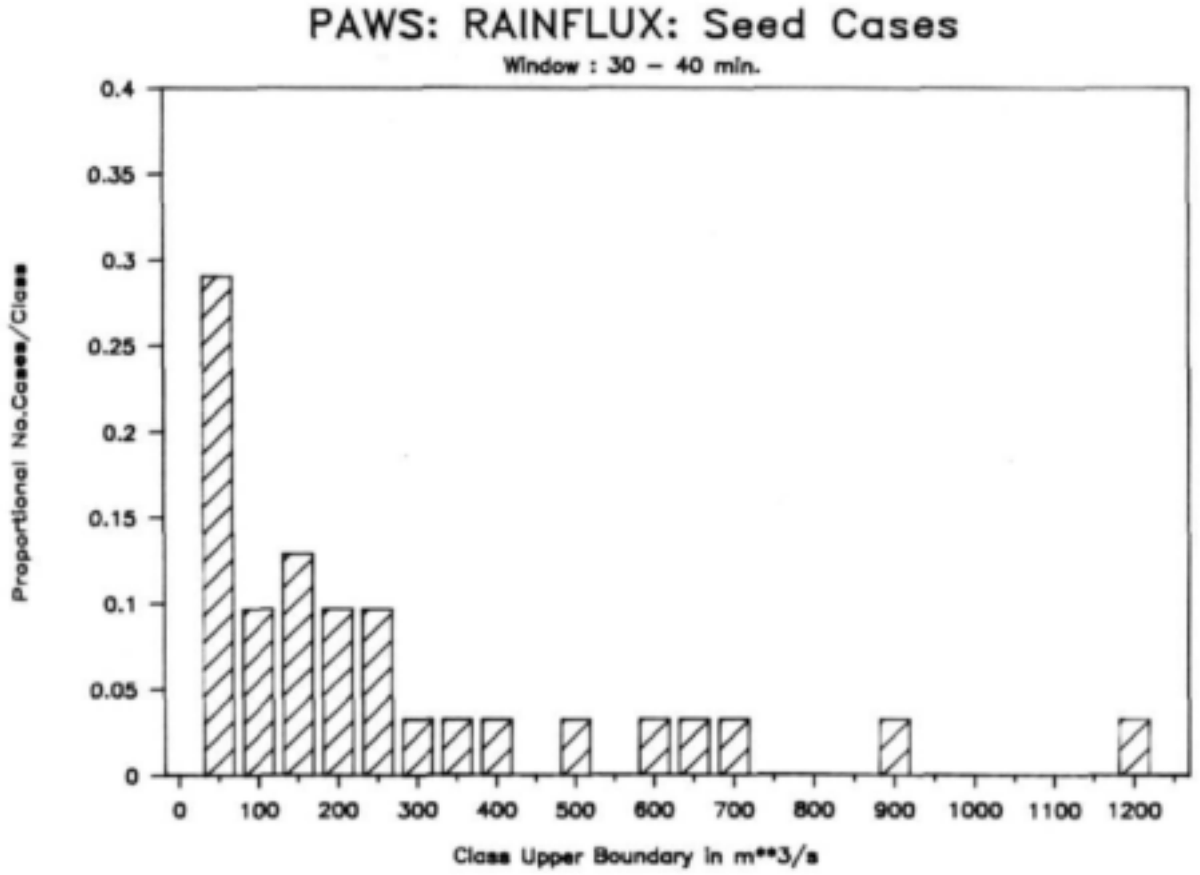
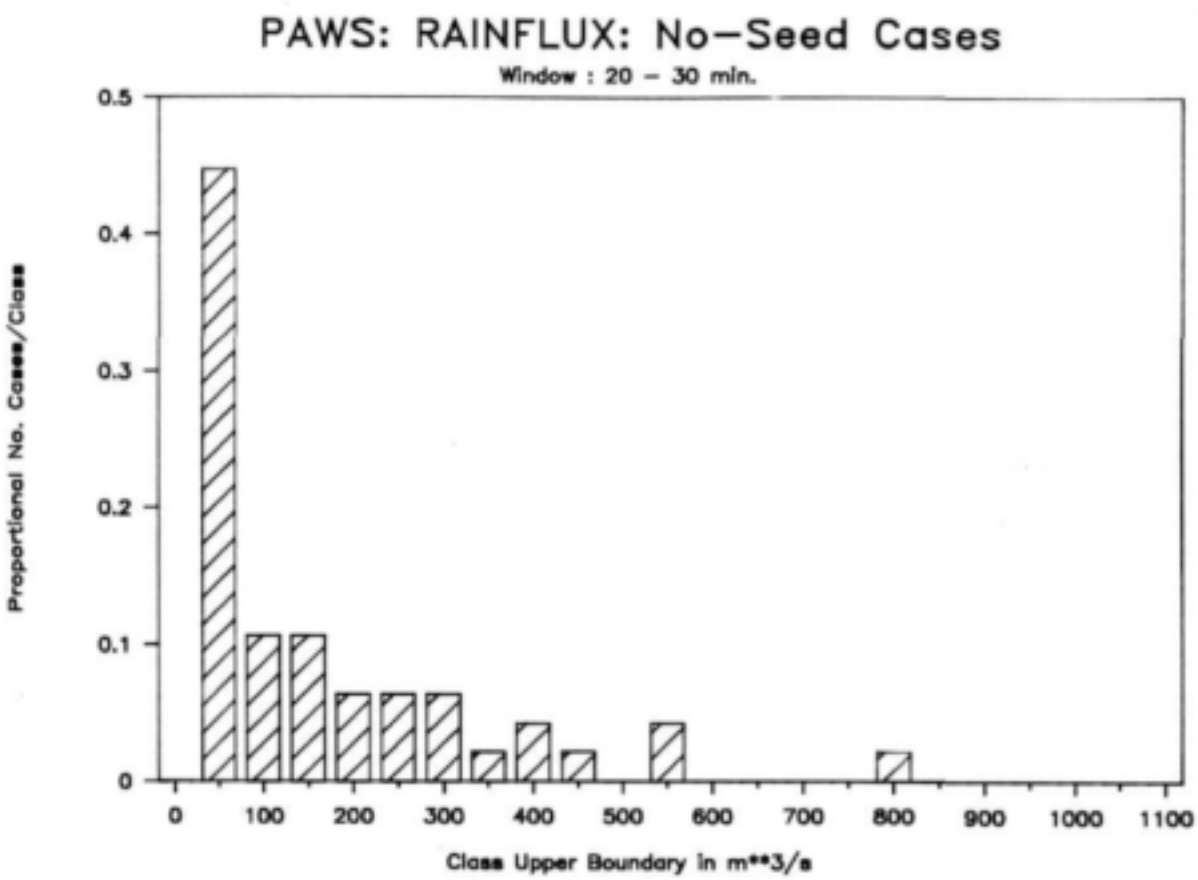

PAWS: RAINFLUX: Seed Cases
Window : 30 - 40 min.
Proportional No.Cases/Class
Class Upper Boundary in m**3/s
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05

FIGURE 5.3


PAWS: RAINFLUX: No-Seed Cases
Window : 20 - 30 min.
Proportional No. Cases/Class
0
0.1
0.2
0.3
0.4
0.5
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

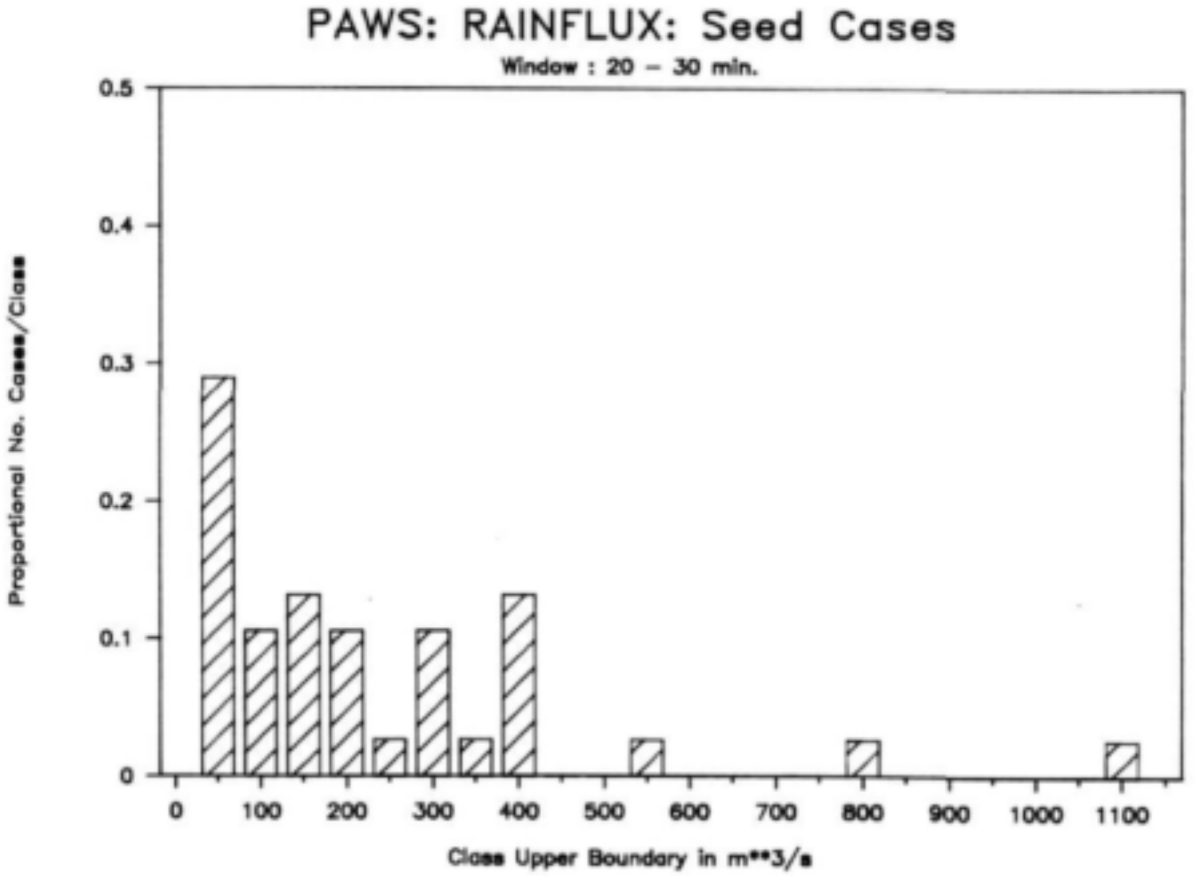
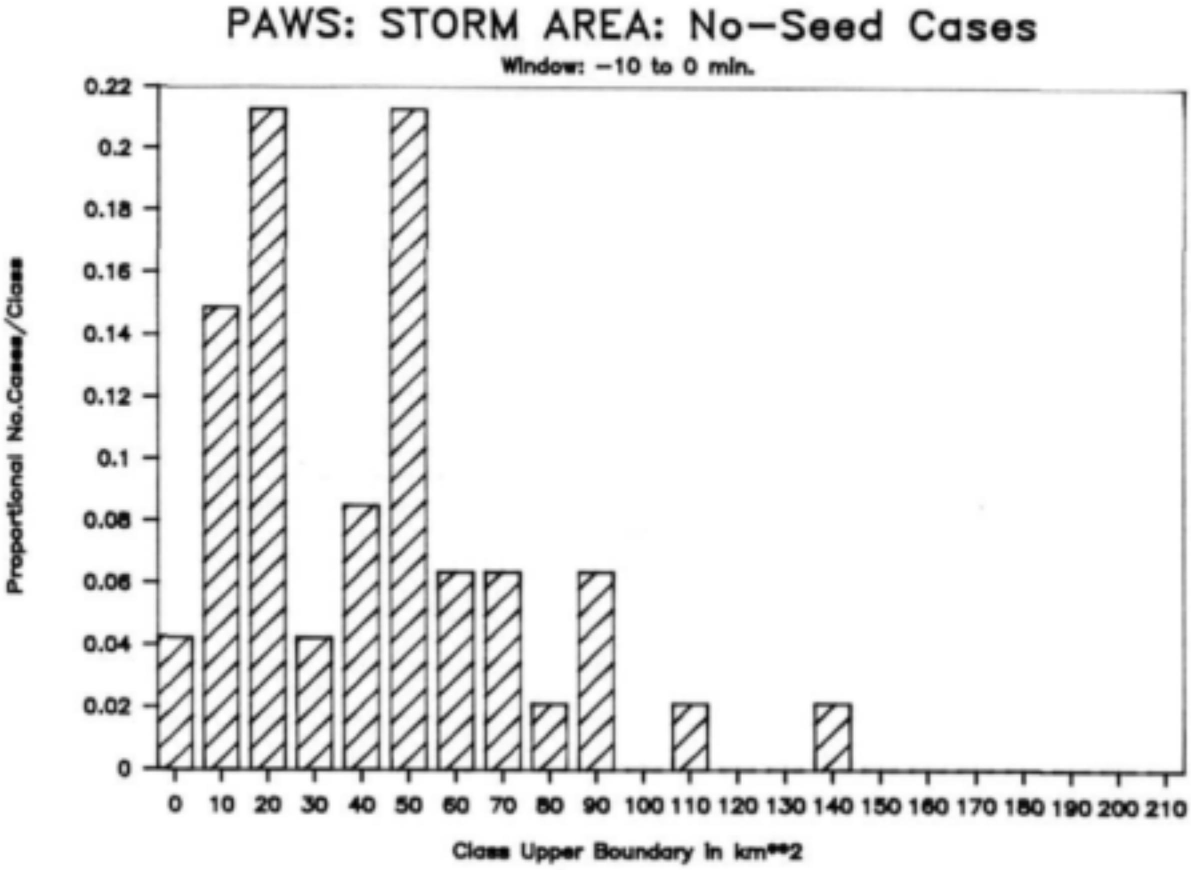

PAWS: RAINFLUX: Seed Cases
Window : 20 - 30 min.
Proportional No. Cases/Class
0
0.1
0.2
0.3
0.4
0.5
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

FIGURE 5.2


PAWS: STORM AREA: No-Seed Cases
Window: -10 to 0 min.
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Proportional No.Cases/Class
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

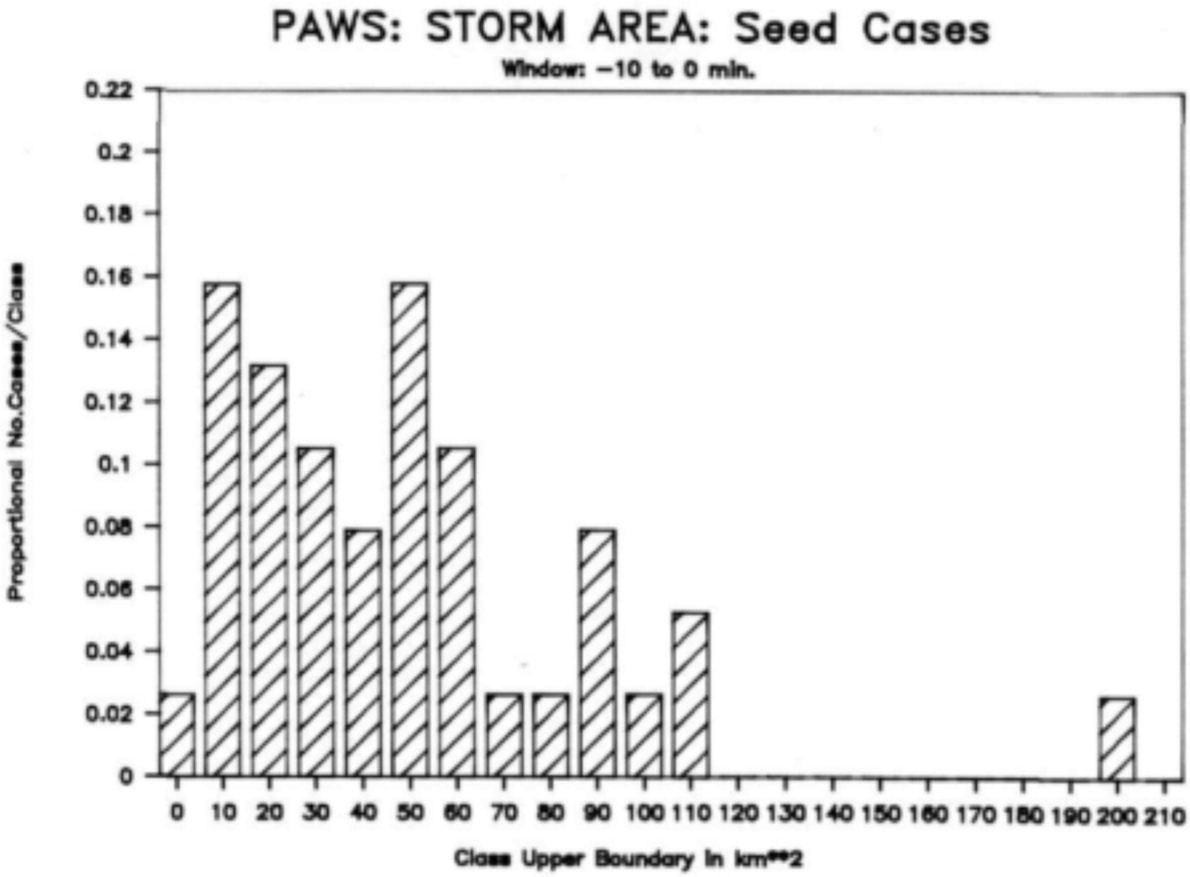
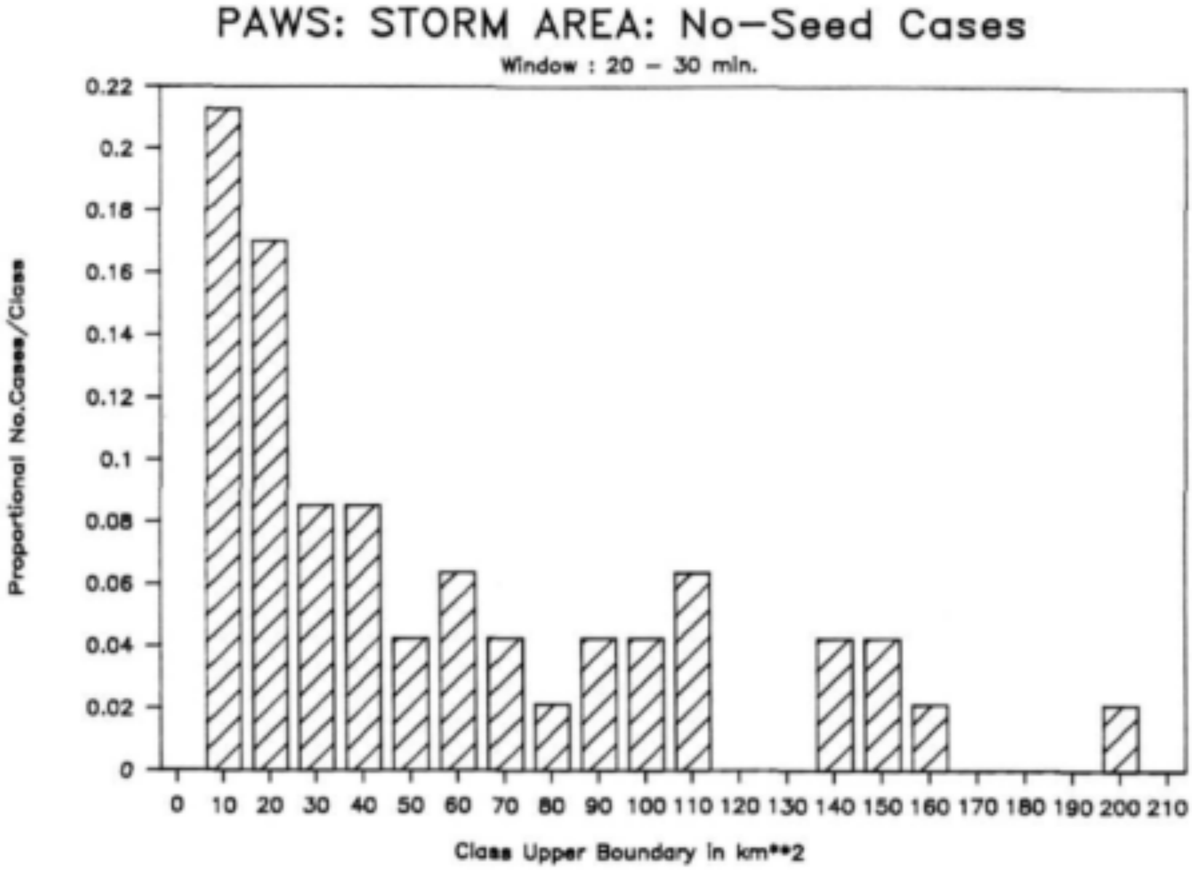

PAWS: STORM AREA: Seed Cases
Window: -10 to 0 min.
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Proportional No.Cases/Class
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

FIGURE 5.4


PAWS: STORM AREA: No—Seed Cases
Window : 20 – 30 min.
Proportional No.Cases/Class
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

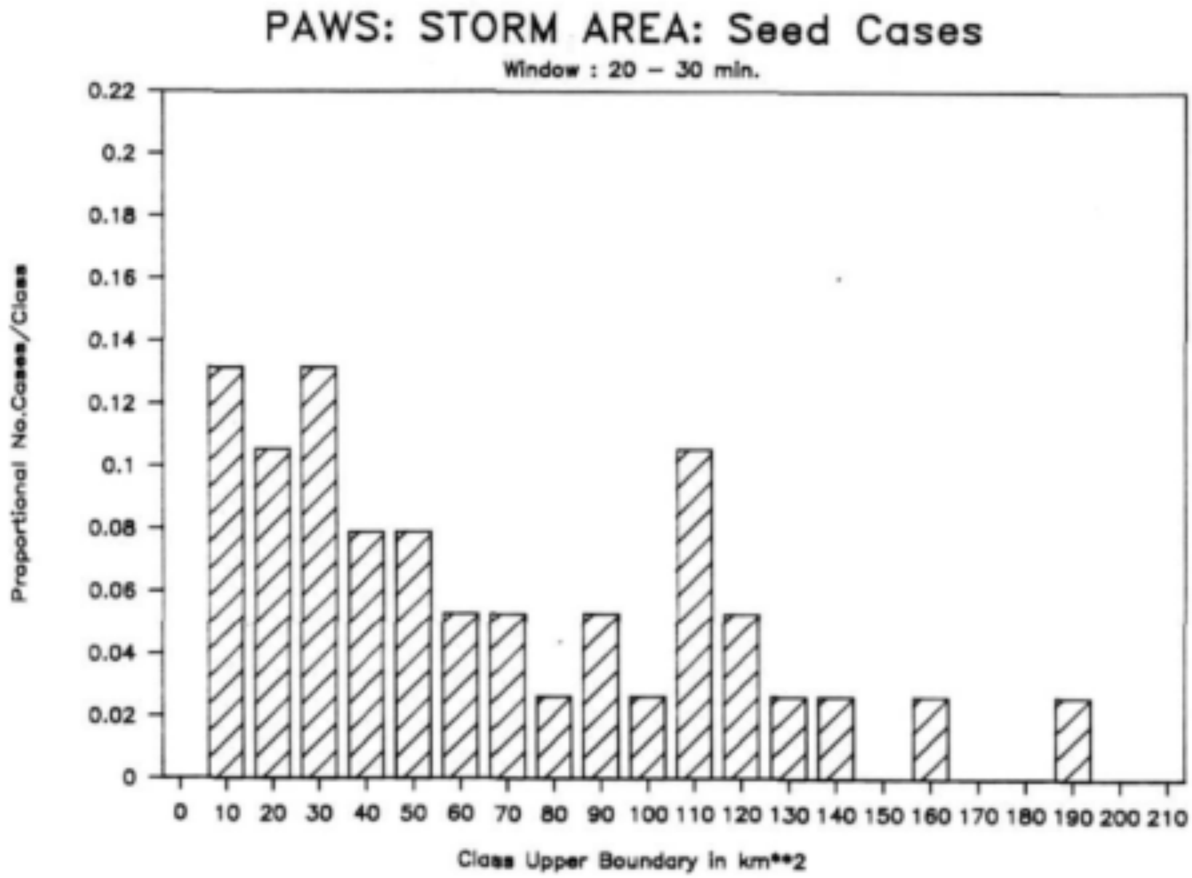
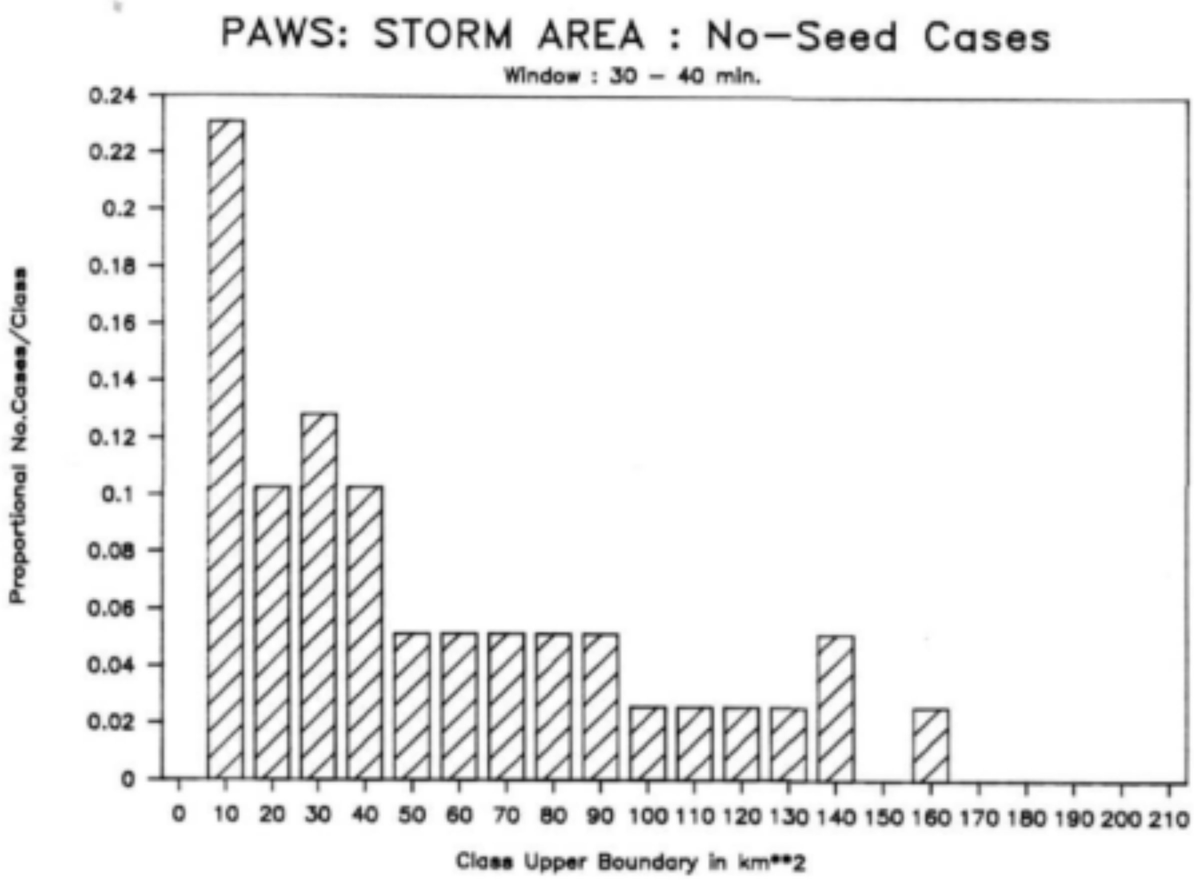

PAWS: STORM AREA: Seed Cases
Window : 20 – 30 min.
Proportional No.Cases/Class
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

FIGURE 5.5


PAWS: STORM AREA : No-Seed Cases
Window : 30 - 40 min.
Proportional No.Cases/Class
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

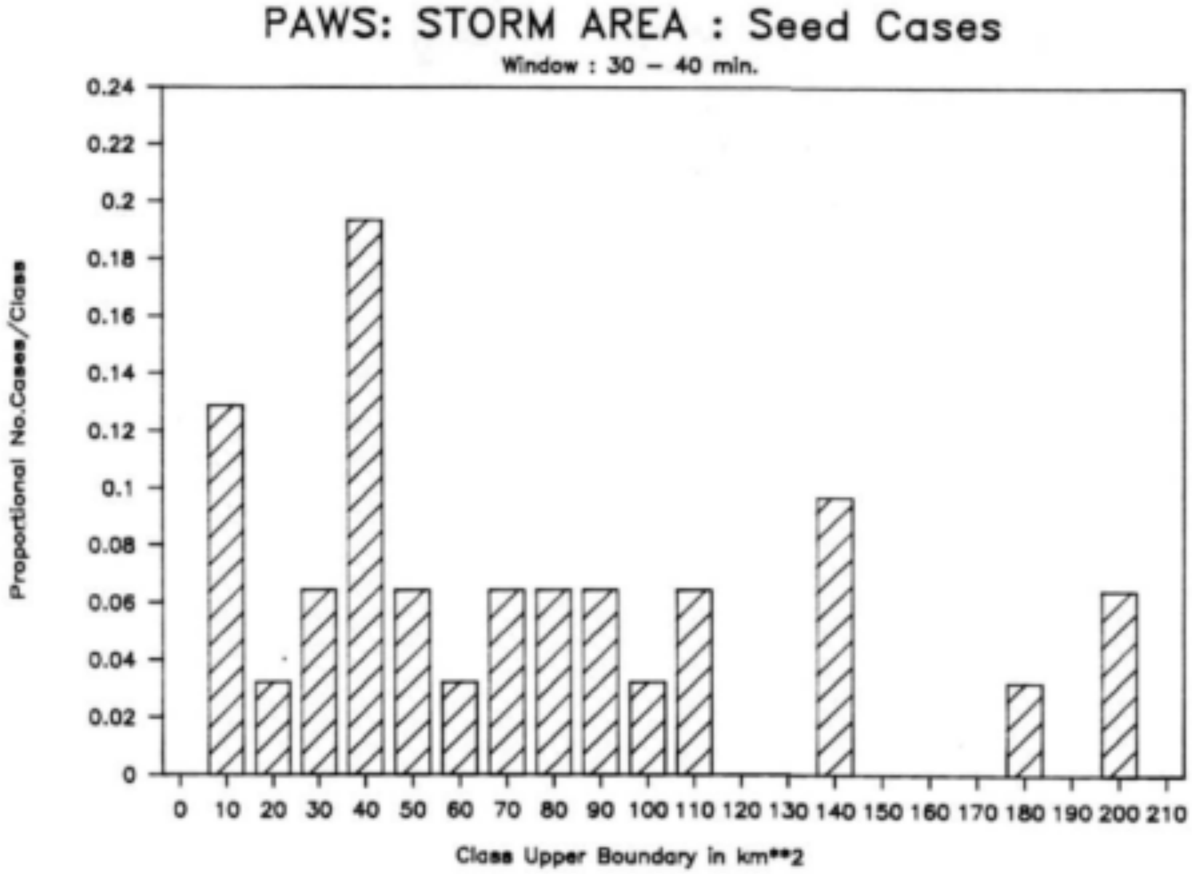
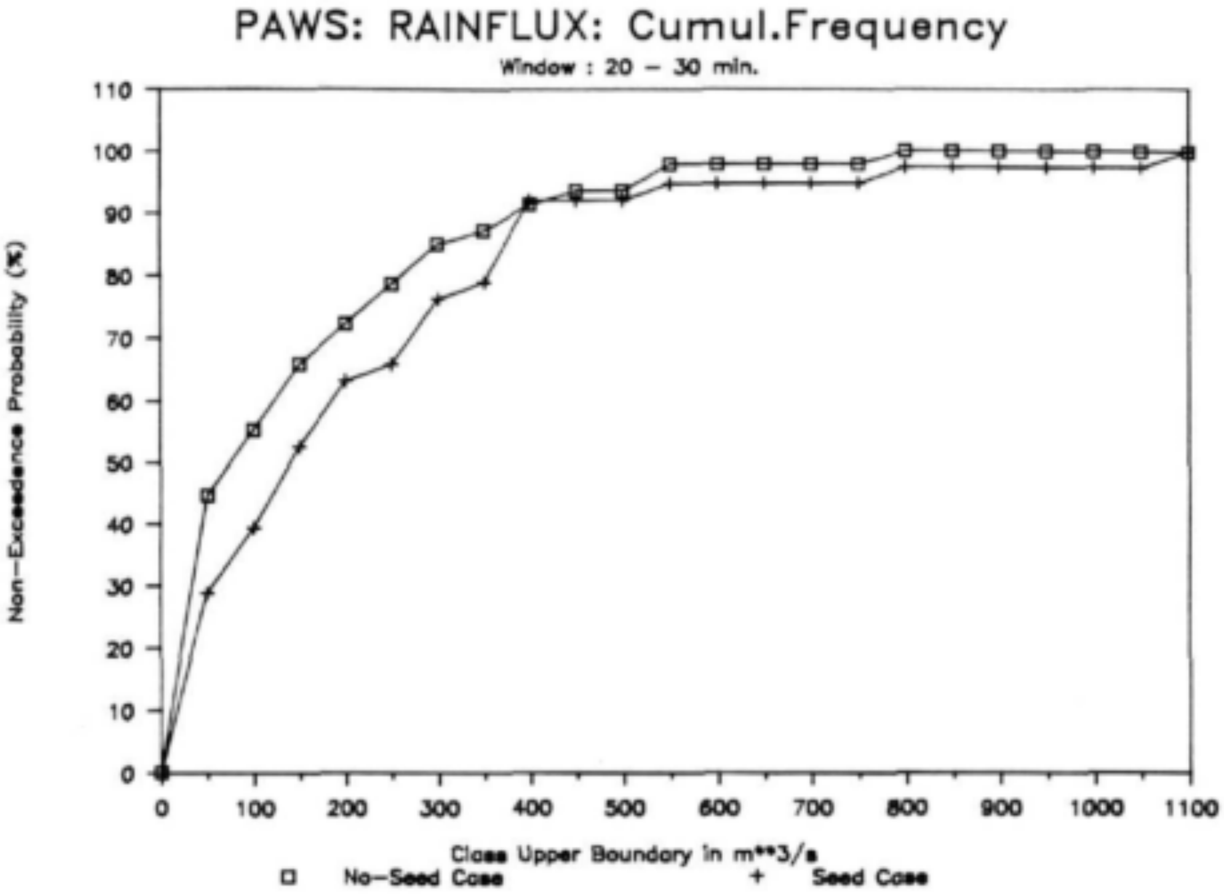

PAWS: STORM AREA : Seed Cases
Window : 30 - 40 min.
Proportional No.Cases/Class
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

FIGURE 5.6


PAWS: RAINFLUX: Cumul.Frequency
Window : 20 – 30 min.
Non-Exceedence Probability (%)
Class Upper Boundary in m**3/s
No-Seed Case
Seed Case

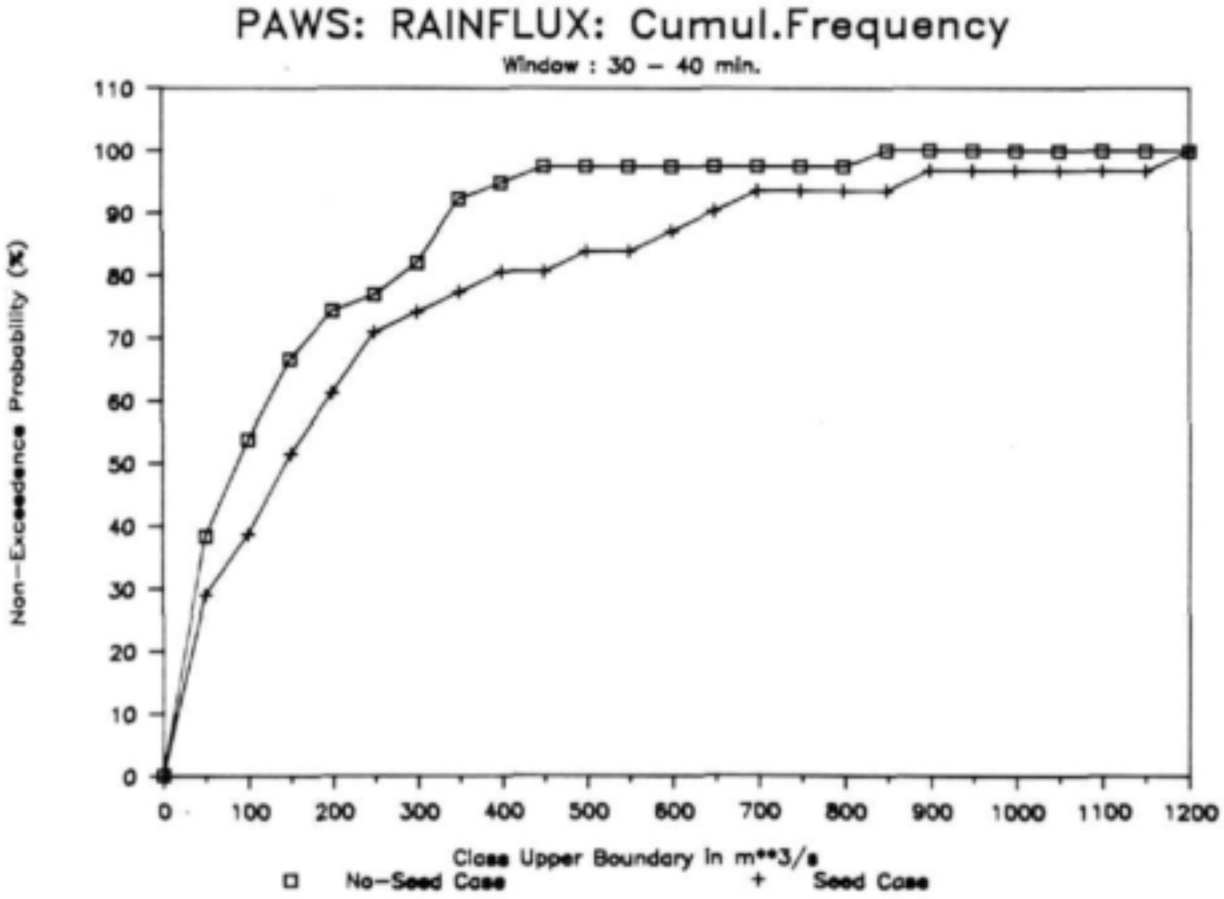

PAWS: RAINFLUX: Cumul.Frequency
Window : 30 – 40 min.
Non-Exceedence Probability (%)
Class Upper Boundary in m**3/s
No-Seed Case
Seed Case

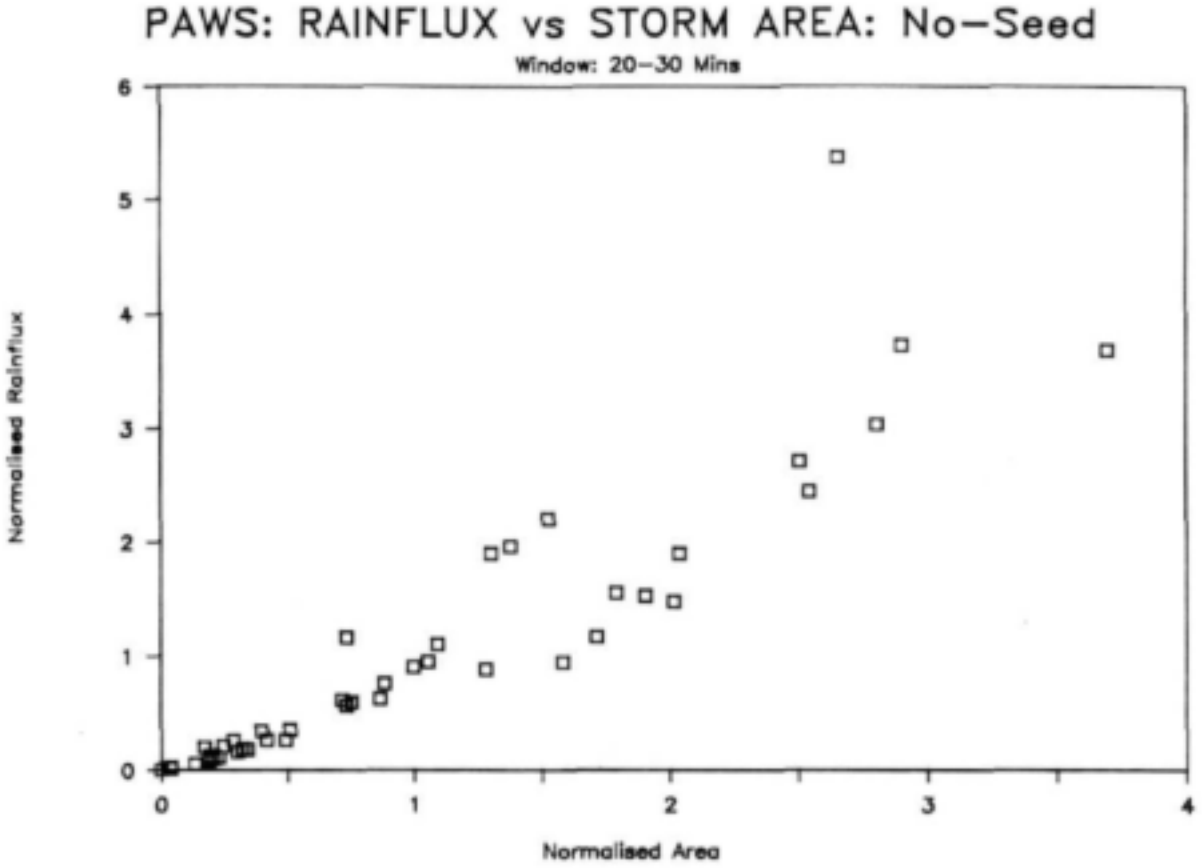
FIGURE 5.7

5.3.3 Outliers and the relationship between rainflux and storm area

The last observation in the previous sub-section raises both the spectre of "outlier" influences on the apparent seeding effects and the question of how to allow for outliers in the derivation of a modification scenario. To examine this provisionally, the paired values of rainflux and storm area for all cases were plotted on a normalised basis, i.e. each value divided by its corresponding mean, as shown in Figs. 5.8 and 5.9. Each set of paired values displays a strikingly linear relationship, which is to be expected as rainflux is a function of storm area (see 5.3.1), but which, for each of the four cases, is marred by a single "outlier". The seed case "outliers" relate to an event on 16/11/84 and the no-seed "outliers" to an event on 27/11/86.

A naïve, but plausible, interpretation of the "outliers" in Figures 5.8 and 5.9 is that they represent storms in which the rainfall mechanisms achieved a much greater efficiency than the norm for PAWS convective clouds. A glance at the data in Appendix A reveals that the no-seed rainflux "outliers" for the event on 27/11/86 are also accompanied by storm volume "outliers". In contrast, the storm volumes associated with the seed rainflux "outliers" for the event on 16/11/84 are not unduely large. This contrast might be indicative of an extraordinary seeding effect on 16/11/84. However, mindful of the nature of the rainflux calculation (as outlined in 5.3.1 above) which makes rainflux a function of storm area, we thought it might be more informative to look at mean rainfall intensity for pointers to outliers and individual seeding effects.

Average rainfall intensity values were derived as the quotient of every pair of rainflux and storm area values and used to produce scatterplots of average intensity versus storm area. These are shown as Figs. 5.10 and 5.11 for the two post-seeding windows of interest. No useful relationships are evident in these scatterplots, except, perhaps, a mere intimation of lower and upper envelopes - upper envelopes in the region of 20 mm/h, regardless of seeding and lower envelopes for storms larger than about 20 km^2 of approximately 5 mm/h. What does stand out,


PAWS: RAINFLUX vs STORM AREA: No-Seed
Window: 20-30 Mins
Normalised Rainflux
Normalised Area
0
1
2
3
4
5
6

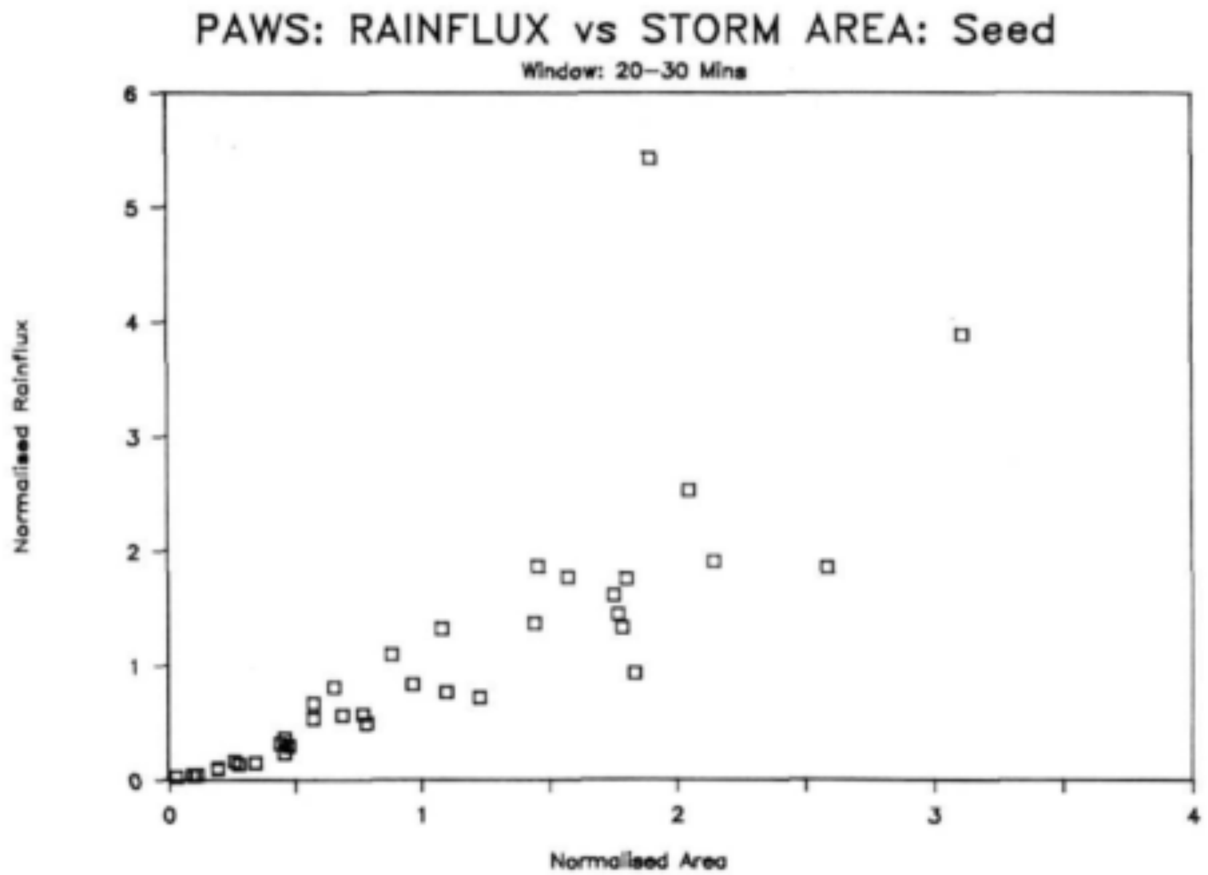
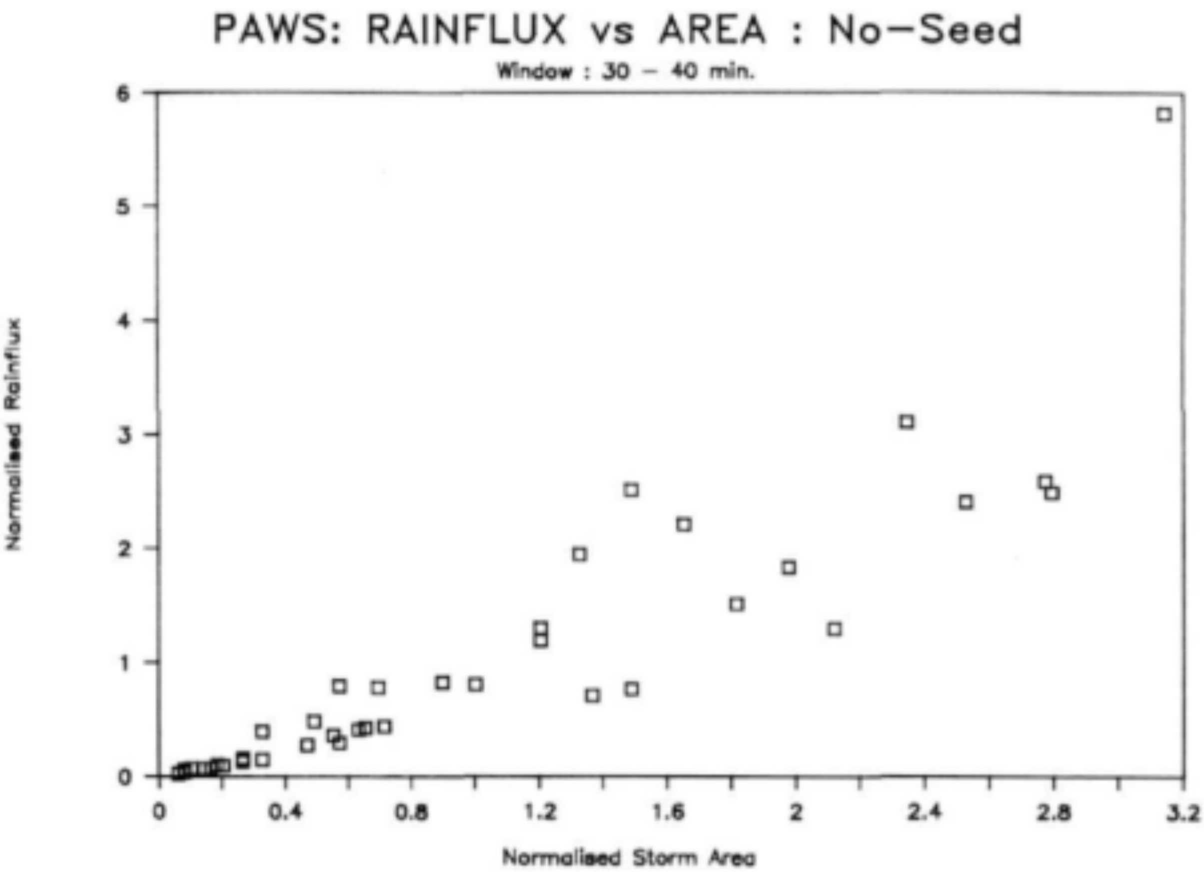

PAWS: RAINFLUX vs STORM AREA: Seed
Window: 20-30 Mins
Normalised Rainflux
Normalised Area
0
1
2
3
4
5
6

FIGURE 5.8


PAWS: RAINFLUX vs AREA : No-Seed
Window : 30 – 40 min.
Normalised Rainflux
Normalised Storm Area
0
1
2
3
4
5
6
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2

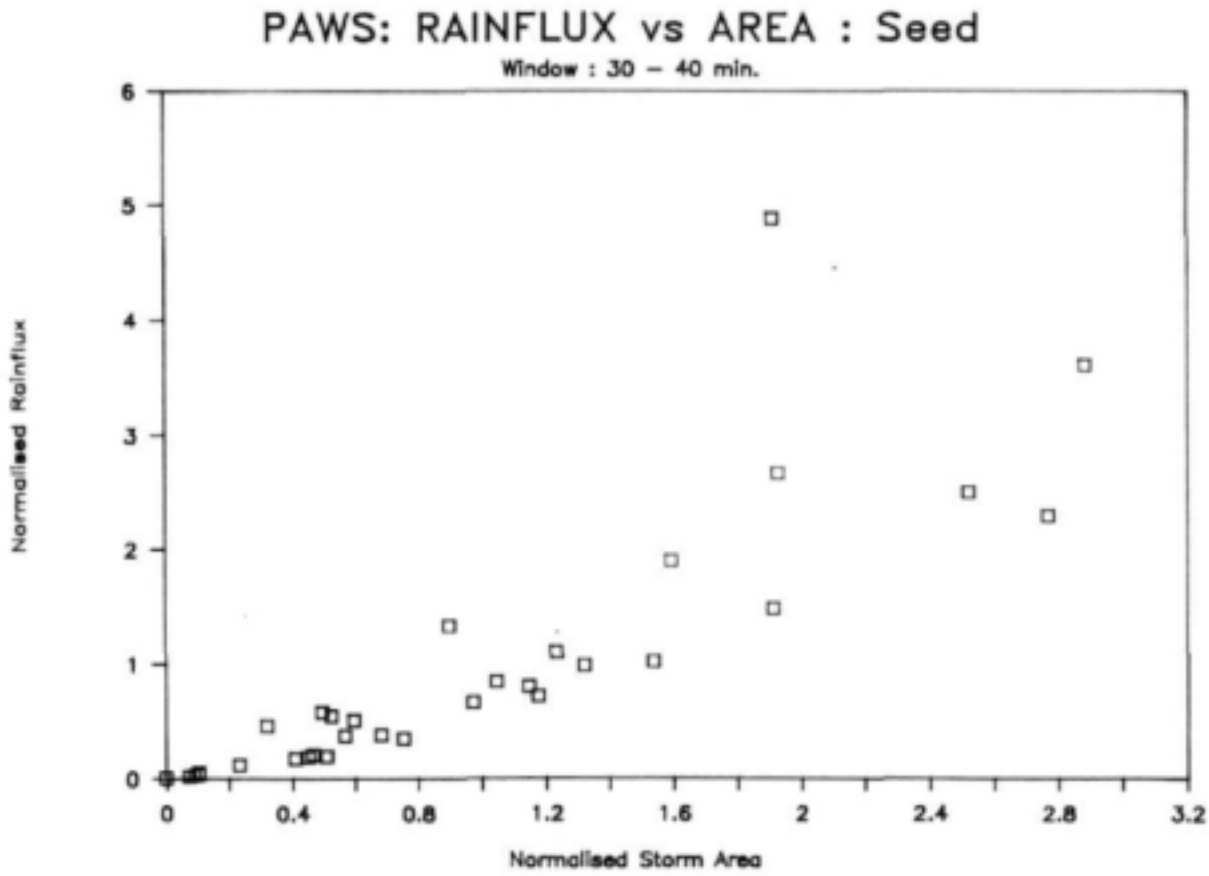
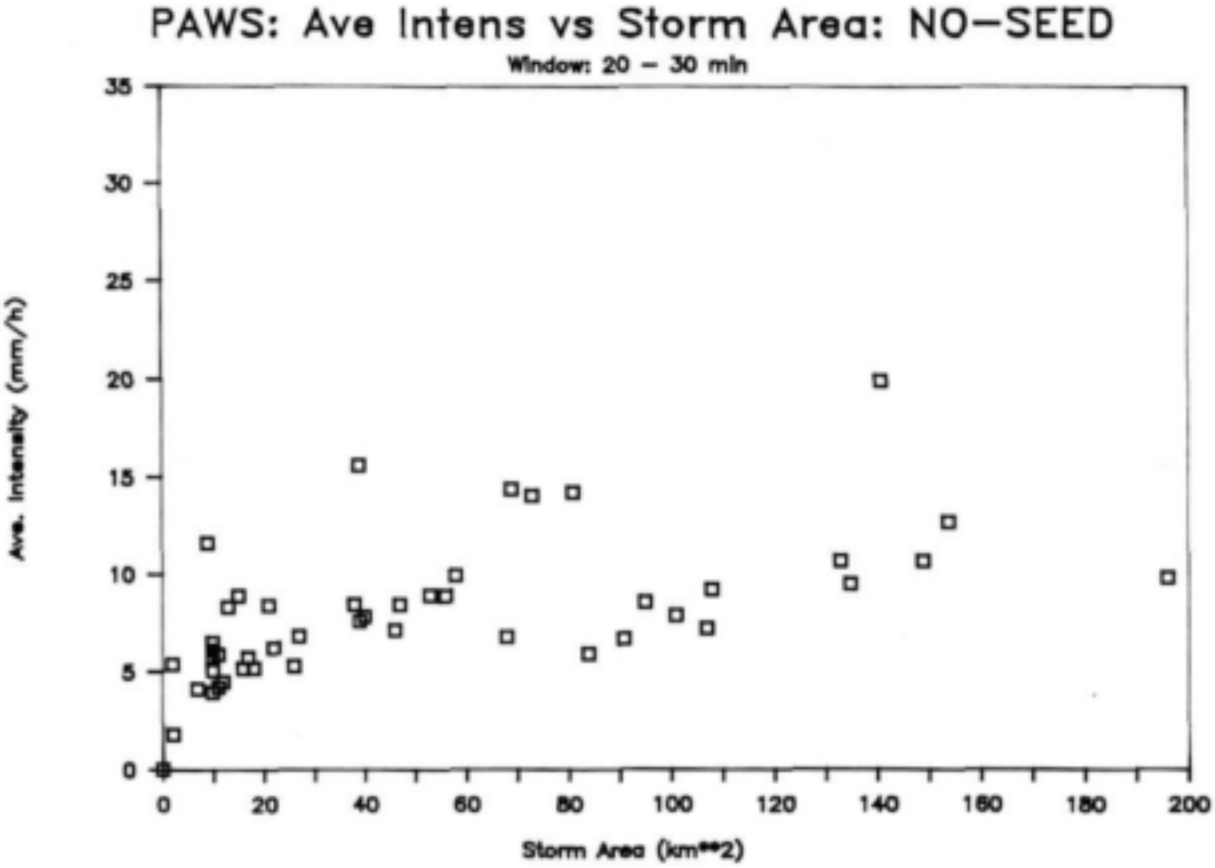

PAWS: RAINFLUX vs AREA : Seed
Window : 30 – 40 min.
Normalised Rainflux
Normalised Storm Area
0
1
2
3
4
5
6
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2

FIGURE 5.9


PAWS: Ave Intens vs Storm Area: NO-SEED
Window: 20 – 30 min
Ave. Intensity (mm/h)
Storm Area (km**2)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200

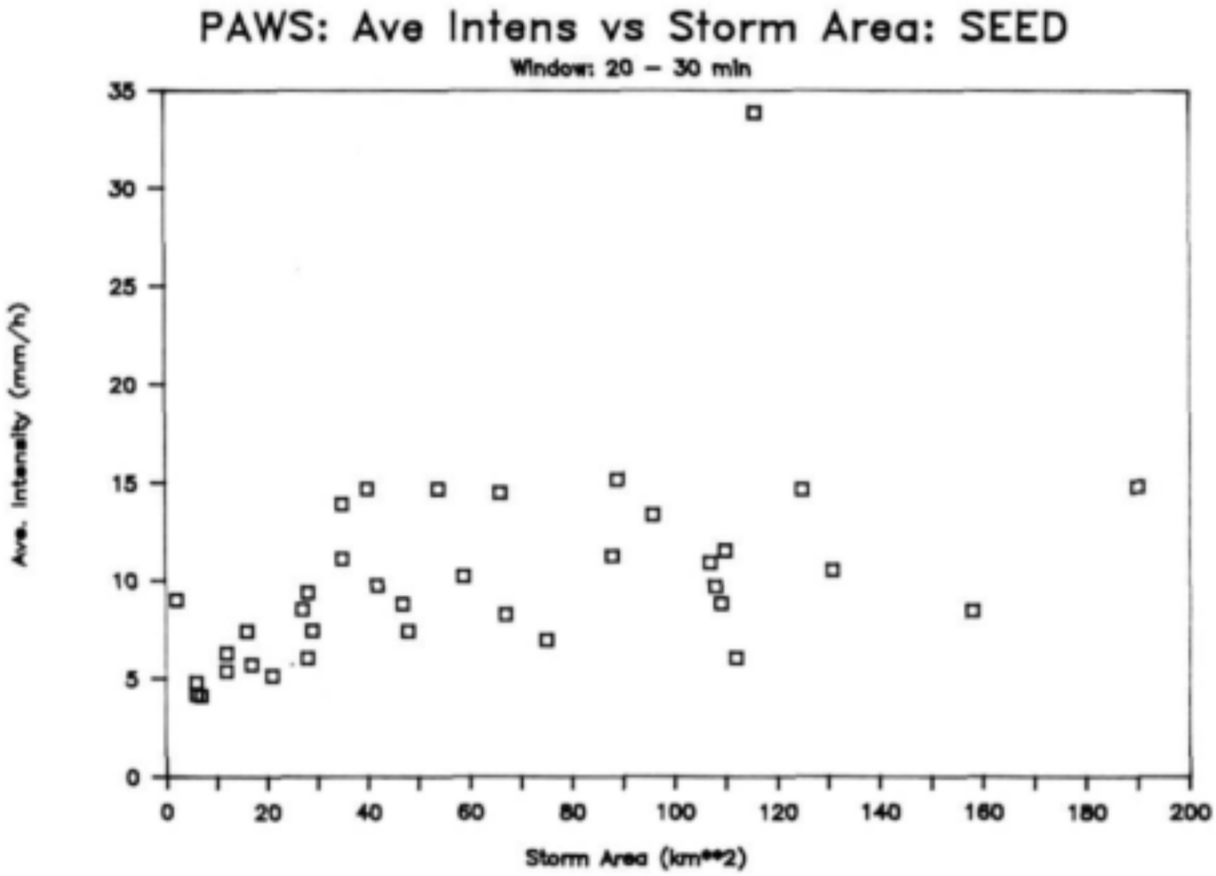
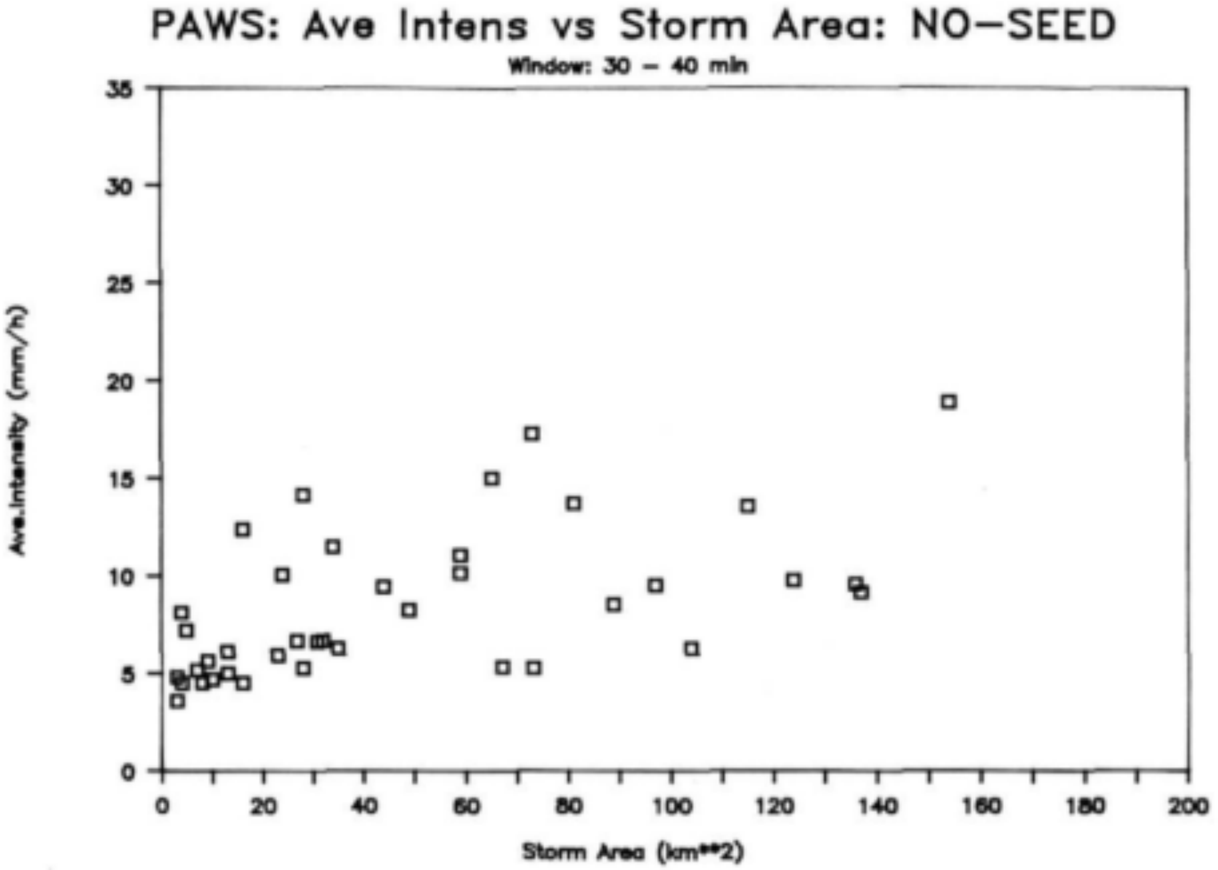

PAWS: Ave Intens vs Storm Area: SEED
Window: 20 – 30 min
Ave. Intensity (mm/h)
Storm Area (km**2)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200

FIGURE 5.10


PAWS: Ave Intens vs Storm Area: NO-SEED
Window: 30 - 40 min
Ave.Intensity (mm/h)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200
Storm Area (km**2)

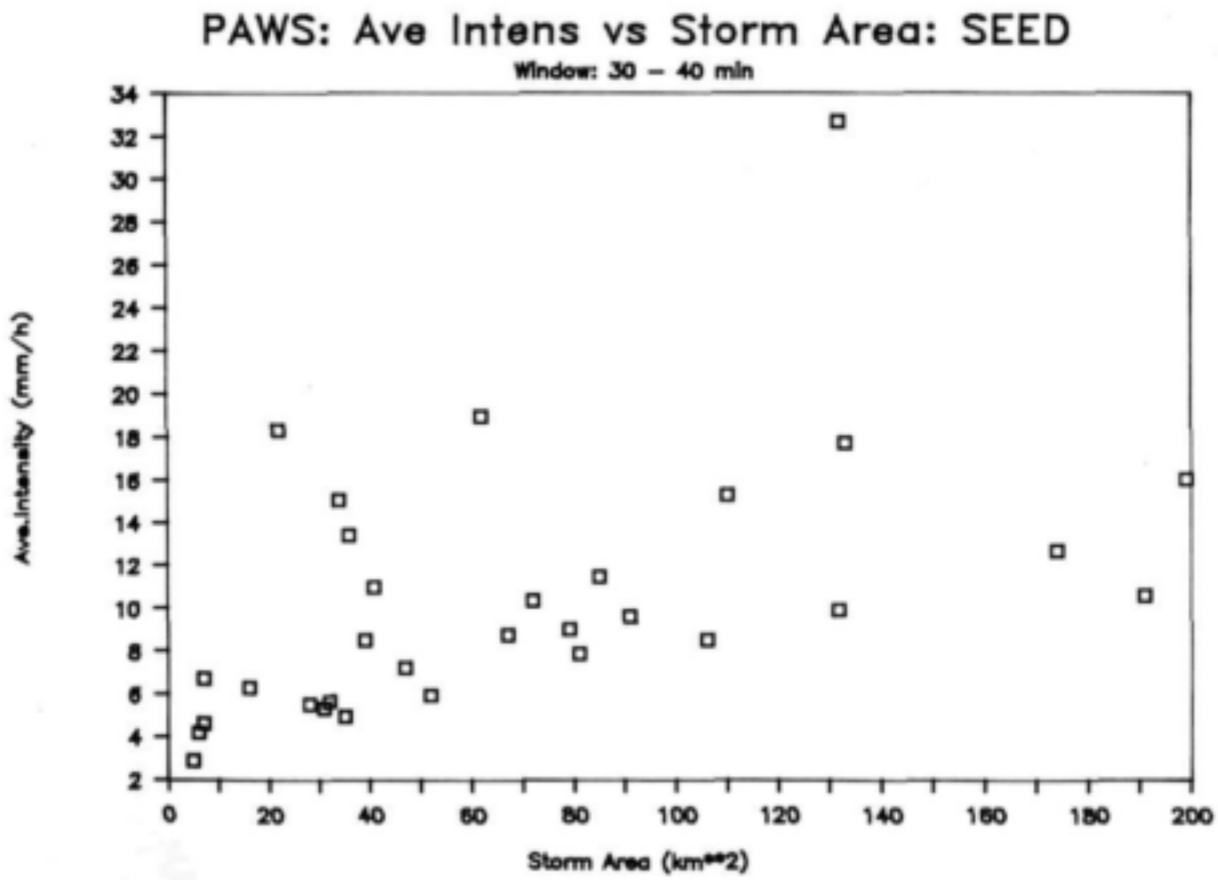

PAWS: Ave Intens vs Storm Area: SEED
Window: 30 - 40 min
Ave.Intensity (mm/h)
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
0
20
40
60
80
100
120
140
160
180
200
Storm Area (km**2)

FIGURE 5.11

however is a single seeded average intensity value well above 30 mm/h in each window - the 16/11/84 event. The apparent outlier no-seed event on 27/11/86 shown in Figs 5.8 and 5.9 does not feature in these scatterplots and is therefore considered to have been an artifact of a somewhat spurious juxtaposition of two sets of dependent variables.

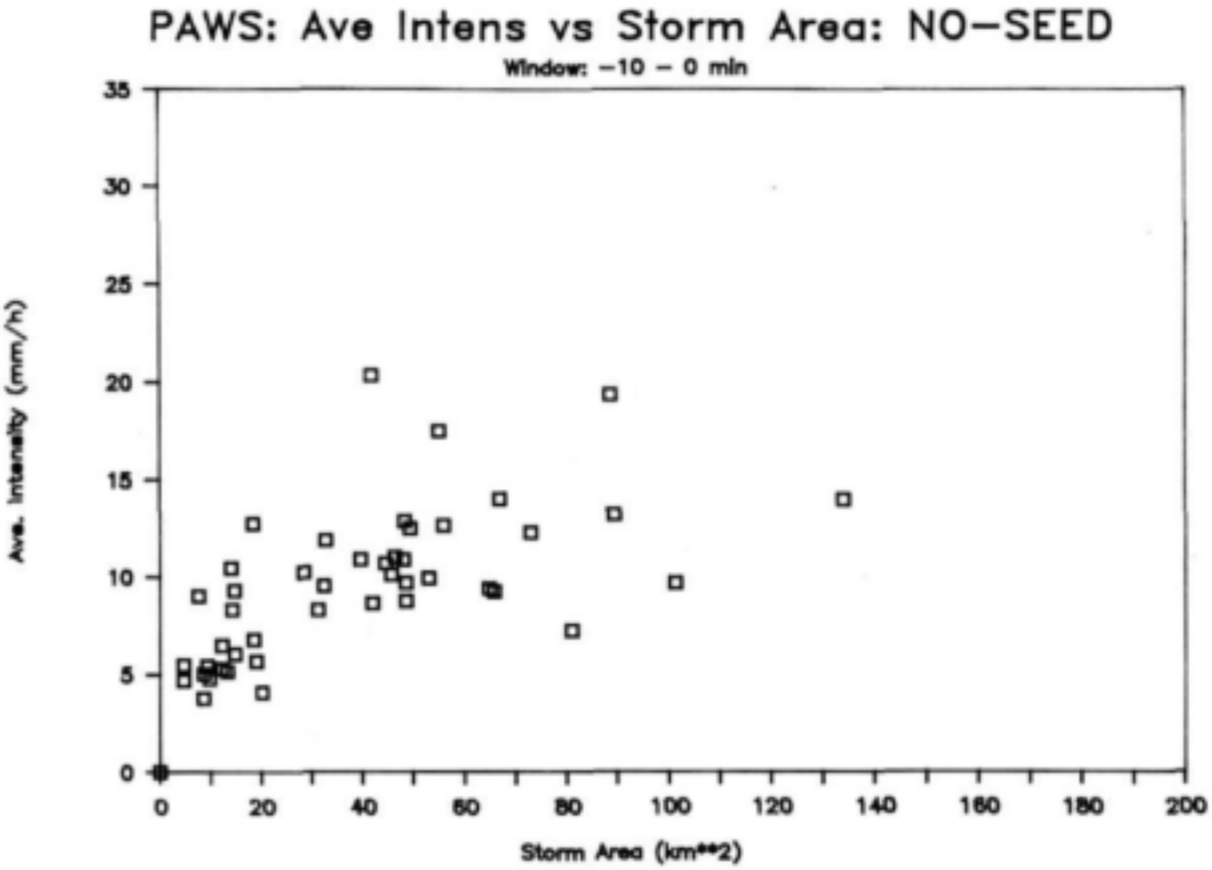
The scatterplot for the pre-seeding window shown in Fig. 5.12 reveals one reasonably high average intensity value (at 26,3 mm/h) in the seed sample - which happens to be the event of 16/11/84. It seems therefore that the apparent outlier detected in the two post-seeding window samples started off prior to seeding as a near-outlier. Consequently, the possiblity of an extroardinary seeding effect on that date must be regarded as quite remote.

The task at hand here is not to prove seeding effects, but to distill from the PAWS results useful concepts and relationships that can be employed in impact studies. The concept of average rainfall intensity introduced in this section falls in this category. We therefore endorse average rainfall intensity as a derived cloud attribute, along with mean rainflux and mean storm area, applicable to the derivation of a provisional modified rainfall scenario for South Africa. Now the question remains whether the PAWS data exhibits any evidence for a seeding effect on rainfall intensity. Unfortunately, the seed/no-seed ratios reported in Table 5.2 do not signify a large seeding effect in terms of average rainfall intensity. These, and other considerations regarding "true" seeding effects, are explored in the subsequent section.

5.4 The anatomy of the average seeded storm

5.4.1 Seed/No-Seed ratios from PAWS

At this point the scene is set to postulate a storm-based average seeding effect for summer cumuli in South Africa that can be employed in impact studies. As stated above the physical attributes that seem most useful to describe the anatomy of the seeded storms, both in terms of the seeding effects indicated by PAWS and in terms of the data


PAWS: Ave Intens vs Storm Area: NO-SEED
Window: -10 - 0 min
Ave. Intensity (mm/h)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200
Storm Area (km**2)

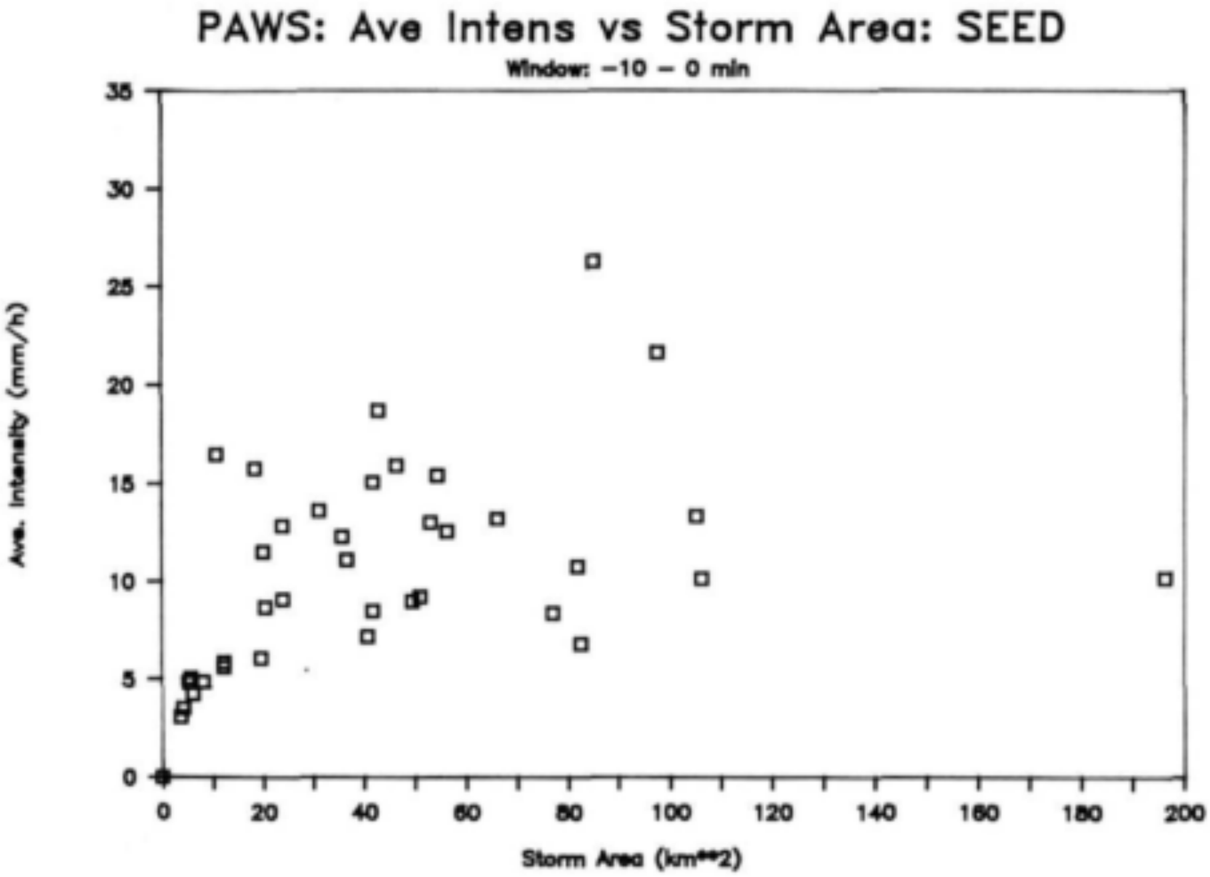

PAWS: Ave Intens vs Storm Area: SEED
Window: -10 - 0 min
Ave. Intensity (mm/h)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200
Storm Area (km**2)

FIGURE 5.12

requirements of impact studies, are the storm rainfall volume (rainflux), storm area and average storm rainfall intensity. Accordingly, the PAWS information described in sections 4.3 and 5.3 and presented in Appendix A, has been consolidated into one table of seed/no-seed ratios of means, as shown in Table 5.2. To facilitate assessment of the influence of initial bias on apparent seeding effects, the seed/no-seed ratios for each time window are compared with those during the pre-decision time window (-10 to 0 minutes) for identical samples. This is necessary because the later time windows represent fewer storms (i.e. smaller samples) than the initial window, due to shorter duration storms dropping out of contention. Furthermore, the post-decision windows include storms for which no observations during the initial window are recorded. Finalisation of the apparent seeding effects awaits the discounting of the influence of the initial bias which is evident in Table 5.2.

5.4.2 Discounting the initial bias

The differences between the seed/no-seed ratios of the pre-decision time window (-10 to 0 minutes) and of the post-decision time windows shown in Table 5.2 indicate the apparent seeding effects of PAWS in terms of the means of the storm attributes. These pre-decision ratios quantify the initial bias in the respective samples. Obviously, quantification of the true seeding effect requires the discounting of the influence of this initial bias on the eventual seed/no-seed ratios. Prior to a discussion of ways to achieve this, attention needs to be given to alternative approaches that can serve to quantify the initial bias. These are as follows:

(i) Expressing seed/no-seed ratios in terms of the samples that happen to exist for the various time windows, regardless of disparities in sample size: This approach, as shown in Table 4.5, is favoured in the PAWS project on the grounds that it preserves the randomised nature of the data sets and that it allows any possible seeding effect on storm duration to benefit the seed samples (Mather, 1990). We do not favour this approach because it might obscure the possible existence of a causal link between apparent seeding effects and a possible preponderance of "large" events in the initial (-10 to zero) seed sample. Also, because it represents the proverbial comparison of mixed "apples and pears" with "apples" alone, this approach inevitably (and unnecessarily) leads to ambiguous findings.

TABLE 5.2 **CONSOLIDATED TABLE OF SEED/NO-SEED RATIOS OF MEANS OF STORM ATTRIBUTES OBSERVED IN PAWS***

Time window pair (minutes)	Sample size (S:NS)***	Rainflux (at 3°)	Storm area (at 3°)	Ave. storm intensity**
-10-0		1,31	1,21	1,17
20-30	37:46	1,50	1,26	1,25
-10-0		1,46	1,39	1,25
30-40	31:39	1,76	1,43	1,23
-10-0		1,23	1,17	1,15
40-50	25:31	1,75	1,55	1,23
-10-0		1,20	1,18	1,17
50-60	19:23	1,80	1,62	1,31

* Raw data reported in Appendix A; time windows cut off at 60 minutes because sample size gets unacceptably small beyond this duration.

** Expressed as rainflux/storm area, both at 3°

*** S=seed; NS = no-seed; sample sizes for initial and later time windows are equalised and refer to identical events.

(ii) Adding zeros to both the no-seed and seed samples for all storms for which no data exists in each specific time window considered, so that sample sizes are equalised accross all windows. Table 5.3 illustrates the effects of additional zeros and lists the seeding ratios that result. We do not favour this method because the statistical and physical interpretations of adding zeros are problematic.

(iii) Equalising sample sizes by treating each time window separately and comparing its attributes with only those members of the initial sample that correspond to the same storm events as the time window under consideration. This approach is preferred for use here because it is transparent, statistically sound and obviates the risk of inflating the apparent seeding effect. In Table 5.2 the ratios for the initial time windows are paired with each individual time window ratio according to this approach.

Once the initial bias has been quantified, as shown in Table 5.2, its influence on apparent seeding effects can be discounted by one of three methods:

TABLE 5.3 **SEED/NO-SEED RATIOS DETERMINED BY ADDITION OF ZEROS TO WINDOW SAMPLES TO EQUALISE SAMPLE SIZE***

Window (min)	Original sample size		Number of zeros added		Rainflux (m^3/s)				Area (km^2)			
					Original		Zeros incl		Original		Zeros incl	
	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS
-10-0	38	47	2	5	152	117	144	106	44	38	42	34
20-30	38	47	2	5	201	145	191	131	61	53	58	48
30-40	31	39	9	13	245	139	190	104	69	49	54	37
40-50	25	31	15	21	263	150	164	89	73	50	46	30
50-60	19	23	21	29	301	167	143	74	90	56	43	25

	Seed/No-Seed Ratios	
	Rainflux	Storm Area
-10-0	1,36	1,24
20-30	1,46	1,21
30-40	1,83	1,46
40-50	1,84	1,53
50-60	1,93	1,72

* In total 40 storms were seeded but 2 of these produced no echoes over 30 dBZ prior to decision time. Similarly, of the 52 no-seed storms in the experiment, 5 did not produce a pre-decision echo over 30 dBZ.

(i) **Prediction by linear regression:** This method was tentatively proposed by Grosh (1989) and is based on the difference between a time-integrated seed case response variable observed over 0-40 minutes and the same response variable predicted by linear regression. The following regression equation is calculated from the no-seed data:

$$y'_{ns} = a + bx_{ns}$$

where ns = no-seed case, y' = predicted sum of 0 to 40 minute observations of the variable under consideration, x = -10 to 0 minute observation of the particular variable, a and b are regression constants.

The time-integrated value of the equivalent seed case variable is now predicted by means of the same equation and compared with the observed time-integrated value of the seed case variable:

$$y'_s = a + b\ x_s$$

where s = seed case, and the rest as defined above.

The "true" seeding effect is now given by the following fraction of (y_s/y_{ns}), the seed/no-seed ratio based on time-integrated values:

$$(y_s - y'_s)\ /\ (y_s - y_{ns})$$

where ns and s = as before, y = observed time-integrated value and y' predicted time-integrated value.

The accuracy of this estimation of the true seeding effect is obviously dependent on the R^2 value achieved by the linear regression. This approach can be illustrated by an example using the PAWS data on rainflux (at 3°) and a linear regression based on the no-seed case reported by Galpin, Grosh and Auret (1988):

$$y'_{ns} = 98,53 + 3,88\, x_{ns} \text{ with } R^2 = 0,64$$

The calculation unfolds as follows:

	Case	
Rainflux (m^3/s)	**Seed**	**No-Seed**
Initial - x	152	119
Predicted - y'	688	560
Observed - y	859	618

The "true" seeding fraction is now

$$(y_s - y'_s) \;/\; (y_s - y_{ns})$$

$$= (859 - 688) \;/\; (859 - 618)$$

$$= 0,71$$

i.e. about 70 % of the apparent rainflux increase (time-integrated) is due to seeding.

We do not favour this approach for use here on the following grounds: The R^2 values achieved by using initial rainflux and initial storm area as predictors are not high (0,64 and 0,59 respectively; Galpin, Grosh and Auret (1988)). Consequently, the confidence limits of the above estimate of the predicted value, y', will be quite wide, leading to severe uncertainty in the interpretation of the "true" seeding fraction.

(ii) **Discounting by the double ratio method:** This is a variation of the well-established model used as a treatment effect model in cloud-seeding experiments (Gagin, 1986; Flueck, 1986), with a two-area target-control design with only the target area available for treatment. The form of the model is:

$$SR = (y_s/y_{ns}) . (x_{ns}/x_s)$$

where SR = seeding effect for a specific time window expressed as a ratio

s,ns = seed and no-seed, respectively

y = mean response variable value during specific time window

x = mean response variable value during -10 to 0 minute window.

The right-hand ratio in the above SR equation is conventionally filled by the no-seed/seed ratio for the control area and is meant to compensate for systematic effects that may result from the choice of the specific control and target areas and for the accidental bias introduced by the random selection of events/days for either seeding or no-seeding. The SR value should then equal unity if seeding had no effect and if the sample is sufficiently large. A pre-requisite for this model's validity is that the no-seed control and target data should be "well" - correlated.

In PAWS a control area was not used, but if the possibility of a causal link between large initial response variable values and later large values were to be entertained, then the double ratio model might be applicable, with the initial time window (-10 to 0 minutes) taking the place of the conventional control area - if initial and later values are well-correlated. Unfortunately, these correlations are not altogether convincing, as already pointed out under (i) above, and therefore the double-ratio results cannot avoid a certain amount of ambiguity.

Table 5.4 shows the double ratio estimates of seeding effects for PAWS. According to its multiplicative character this model states that, if the initial seed case observations are "inflated" by (100 + p) % relative to the no-seed case, then the later observations will be inflated by (100 + p) % as well, and vice versa. Therefore, to find the "true" seeding effect the post-seeding observations must be deflated by 1/(100 + p)%. In terms of the PAWS project this multiplicative form of discounting of the initial bias is likely to produce a lower limit type of estimate of the true seeding effect.

(iii) **Discounting by simple subtraction:** Here it is assumed that the initial bias represents a ratio that stays more or less constant during the lifetime of the storm. The initial (-10 to zero) seed/no-seed difference expressed as a ratio or percentage of the no-seed case is viewed as having an additive effect on later time window seed/no-seed ratios, as opposed to the multiplicative effect inferred by the double ratio model in (ii) above. The initial seed/no-seed difference as a ratio is now subtracted from the ratios of the later time windows to produce the "true" seeding effect during these time slots. Table 5.5 presents the estimates of seeding effects by this method. Because of its additive character it is likely that this initial bias correction produces an upper limit type of estimate of true seeding effects.

5.4.3 Interpretation of "true" seeding effects

The "true" seeding effect values displayed in Tables 5.4 and 5.5 appear somewhat anomalous when one bears in mind that the calculation of each rainflux value boils down to the product of each storm area and average rainfall intensity pair (see 5.3.1). Consequently, it is not unreasonable to expect that for each time window the product of "true" seeding effects on mean storm area and average intensity would roughly equal the seeding effect on rainflux. This is clearly not the case for the 20-30 minute and for the 30-40 minute windows, regardless of the table in use. For example, from Table 5.5 the rainflux "true" seeding ratios for these two windows should be close to:

1,05. 1,08	=	1,13	(actual = 1,19)
1,04. 0,98	=	1,02	(actual = 1,30)

These anomalies deserve some attention from the PAWS researchers. However, for our purposes it seems prudent to abandon the average storm intensities calculated by us and to adhere to the data formally

TABLE 5.4 **"TRUE" SEEDING EFFECTS (AS % OF NO-SEED MEAN VALUES) IN PAWS AS CALCULATED BY THE DOUBLE RATIO METHOD***

Time window (minutes)	Sample size (S : NS)	Rainflux (at 3°)	Storm area (at 3°)	Ave. storm intensity**
20 - 30	37 : 46	15	4	7
30 - 40	31 : 39	21	3	-2
40 - 50	25 : 31	42	32	7
50 - 60	19 : 20	50	37	12

* Ratios used are from Table 5.2
** Expressed as rainflux/storm area, both at 3°

TABLE 5.5 **"TRUE" SEEDING EFFECTS (AS % OF NO-SEED MEAN VALUES) IN PAWS AS CALCULATED BY SIMPLE SUBTRACTION OF THE INITIAL BIAS**

Time window (minutes)	Sample Size (S:NS)	Rainflux (at 3°)	Storm area (at 3°)	Ave. storm intensity*
20 - 30	37 : 46	19	5	8
30 - 40	31 : 39	30	4	-2
40 - 50	25 : 31	52	38	8
50 - 60	19 : 23	60	44	14

* Expressed as rainflux/storm area, both at 3°

provided by the PAWS team, i.e. rainflux and storm area values. By inverse reasoning a "true" seeding effect can now be inferred for average storm intensity as follows, using Table 5.5 as example:

20-30 min:	1,19/1,05	=	1,13
30-40 min:	1,30/1,04	=	1,25
40-50 min:	1,52/1,38	=	1,10
50-60 min:	1,60/1,44	=	1,11

5.4.4 Choice of "true" average seeding effects for impact studies

As stated previously, the values in Tables 5.4 and 5.5 represent lower and upper limits of seeding effects, respectively. For the purposes of impact studies we decided to, for both rainflux and storm area and for each window, propose use of the mean value from these two tables, but rounded to the nearest full 5% in recognition of the uncertainties involved in the overall observation and deduction procedures. Average rainfall intensity is inversely deduced from the values chosen for the former two storm attributes (as described in 5.4.3) so that each triplet of values consitutes an approximate mass balance during each time window. Table 5.6 presents the seeding effects proposed for determination of the average anatomy of "seeded" storms to be used in impact studies.

TABLE 5.6 PROPOSED "TRUE" SEEDING EFFECTS FOR USE IN IMPACT STUDIES (AS % OF NO-SEED MEAN VALUES)

Time window (minutes)	Rainflux	Storm area	Ave. storm intensity
0-10	0	0	0
10-20	0	0	0
20-30	15	5	10
30-40	25	5	20
40-50	50	35	10
50-60	55	40	10

5.5 A plausible catchment average seasonal seeding effect

It might be enlightening for subsequent detailed discussions of the data elements and tasks required for development of credible augmented rainfall time series to assess, albeit in a naive way, the average modified seasonal rainfall scenario that can be derived from average seeding opportunities, average seasonal rainfall characteristics and average seeding effects achievable inside a large catchment area. Target areas for impact studies are addressed lated in this report; nevertheless, for argument's sake we choose the upper Vaal River catchment above Standerton (area = 8200 km^2) as a plausible target for this illustration. The PAWS average seeding effects consolidated in Table 5.6 are presumed to be applicable to the upper Vaal River area. However, as this target area lies between the PAWS and BPRP radar coverages, it seems prudent to use a combination of information from these two projects to define average seeding opportunities, seasonal rainfall characteristics and cloud climatology. The assessment unfolds as follows:

R_{seas} = Proportion of seasonal rain from those clouds regarded as suitable for seeding in either project, i.e. cloud clusters, complexes or "small" line-storms: For BPRP Steyn (1985) gives a proportion of about 50% for this source of rain, while SWA and CIC (1986 (c)) put this value at 65% for PAWS.

R_{day} = Proportion of convective rain that falls during daylight hours: Estimates for BPRP vary between 63% (Court and De Jager, 1979) and 52% (Maaren, 1984), while the PAWS equivalent is estimated at 59% (SWA and CIC, 1986 (c)).

R_{seed} = Proportion of "seedable" clouds that actually pass the experimental selection criteria and that end up as seeded : Both the BPRP (Weather Bureau, 1988) and the PAWS (Morgan, Reuter and Mather, 1988) figure for this proportion is 49%. Many of the rejections were related to experimental requirements; therefore this figure can be expected to be increased under operational conditions, perhaps as high as 80%.

R_{20+} = Proportion of rain from "seedable" clouds with lifetimes longer than 20 minutes (which according to PAWS results is the minimum lifetime after seeding to show seeding effect) : Here there does not exist a BPRP estimate yet, but an analysis of the basic PAWS rainflux results in Table 5.3 yields a ratio of total rainflux during all seeded storm windows 20 - 60 min. after decision time to total rainflux over the full 0-60 min period of 0,66. The equivalent no-seed ratio for rainflux is 0,58. In consideration of the fact that some storm lifetimes exceed 60 min, while, on the other hand, the PAWS selection procedures probably favour selection of longer duration storms, we surmise that the appropriate value for R_{20+} could lie in a range of 0,55 to 0,80.

$SE_{20/60}$ = percentage seeding effect in terms of rainflux on clouds with lifetimes longer than 20 minutes: Table 5.6 lists the "true" seeding effects estimated from PAWS results as between 15% for the 20-30 min window and 55% for the 50-60 min window, with a mean value approaching 40%.

The above estimates are summarised in Table 5.7, along with the assumed ranges and used in the calculation that follows:

Catchment average seasonal seeding effect for the upper Vaal River $= R_{seas} \cdot R_{day} \cdot R_{seed} \cdot R_{20+} \cdot SE_{20/60}\%$

Minimum value $= 0{,}60.\ 0{,}50.\ 0{,}50.\ 0{,}55.\ 40\ \%$

$= 3{,}3\%$

Maximum value $= 0{,}60.\ 0{,}60.\ 0{,}80.\ 0{,}80.\ 40\ \%$

$= 9{,}2\ \%$

The above assessment provides useful control limits for the development of modified rainfall time series. On a seasonal basis it seems that **the rainfall increases represented by such time series would not easily**

exceed 10% on average. The exact magnitude that can be achieved obviously depends on the number of operational days per season.

TABLE 5.7 DATA USED IN THE CALCULATION OF THE CATCHMENT AVERAGE SEASONAL SEEDING EFFECT (FOR SEASON OCTOBER TO MARCH).

Data type*	BPRP	PAWS	Assumed Range** or Value
R_{seas}	0,50	0,65	0,60
R_{day}	0,52-0,63	0,59	0,50-0,60
R_{seed}	0,49	0,49	0,50-0,80
R_{20+}	-	0,58	0,55-0,80
$SE_{20/60}$	-	15%-55%***	40%

* Defined in section 5.5
** Range motivated in section 5.5
*** Values relate to individual 10 minute windows after seeding decision.

5.6 Alternative approaches to the quantification of modified rainfall

The quantification of modified rainfall for impact assessment can be conceptualised as four different approaches:

* Naïve adjustments of seasonal, monthly or daily rainfall totals or means,

* unstratified statistical adjustments of rainfall time series,

* cloud-related stratified statistical adjustments of rainfall time series,

* single rainfall event adjustments by use of a dynamic storm model.

The choice of approach will depend on factors such as the detail of data available from the cloud-seeding projects used as data sources, which in turn dictates the resolution required from the supporting (or input) data.

5.6.1 Naïve adjustments

These adjustments take the shape of a **constant** increase in the mean seasonal rainfall or in each rainfall value in a time series.

(i) The mean value would be used in empirical relationships between mean seasonal rainfall and crop or water yield. Typical examples of this type of relationship are:

(a) Production functions of the type derived by Van Rooyen and Dannhauser (1988) for grass hay production on the Highveld:

$$Y = q\ (R/750)^{b}\ (1 - se^{-tN})\ (1 - ue^{-vP})$$

where Y = yield of dry matter in ton/ha.a
R = mm rain from mid-winter to mid-winter
N = applied nitrogen in kg/ha
P = applied phosphorus in kg/ha
q = maximum expected yield at 750 mm/a in ton/ha
b,s,u,t,v, = dimensionless parameters.

(b) Runoff response curves, such as that shown for the Vaal Dam catchment by Maaren (1984), which show percentage runoff in relation to MAP (mean annual precipitation) in a regional context over a range of rainfall totals.

(c) Empirical crop yield functions of the type developed by Crafford and Nott (1981) for grains and other summer crops of the Highveld Region:

$$\text{Yield (kg/ha)} = \frac{\text{rain}}{B} \times \frac{\text{soil depth}}{A} \quad C_1 \text{ or } C_2 \times D$$

where rain = average rainfall measured in millimetres for the period for which records are available but not exceeding ten seasons, from the time the preceding crop reaches physiological ripeness until the crop under study has reached physiological ripeness.

Soil depth = effective depth or required soil depth, in millimetres, whichever depth is the lesser.

A = wetting factors used to calculate required soil depth (table provided)

B = a factor based on the growth characteristics of the crop concerned at physiological ripeness (table provided)

C = a correction factor for air moisture regime. C_1 applies to maize and maize silage, and C_2 to grain sorghum and sunflowers (table provided)

D = metrication factor

(ii) The constant rainfall time series adjustment could be used in impact assessments by dynamic growth models to obtain "first approximation" impressions of the effect of augmented rainfall. Such a study was reported by De Jager (1989) who used the PUTU model in an exploratory analysis of the effects of a 20% blanket increase in all daily rainfalls on maize and wheat yield, using an adjusted daily rainfall time series for Bethlehem.

5.6.2 Unstratified statistical adjustments

The classic study of the hydrological consequences of rainfall augmentation by Lumb and Linsley (1971) serves as a good illustration of statistical adjustments of rainfall time series that are unstratified in terms of the weather or cloud type that produced each time period's rainfall. For application of the famous Stanford Watershed Model, Lumb and Linsley assume the following:

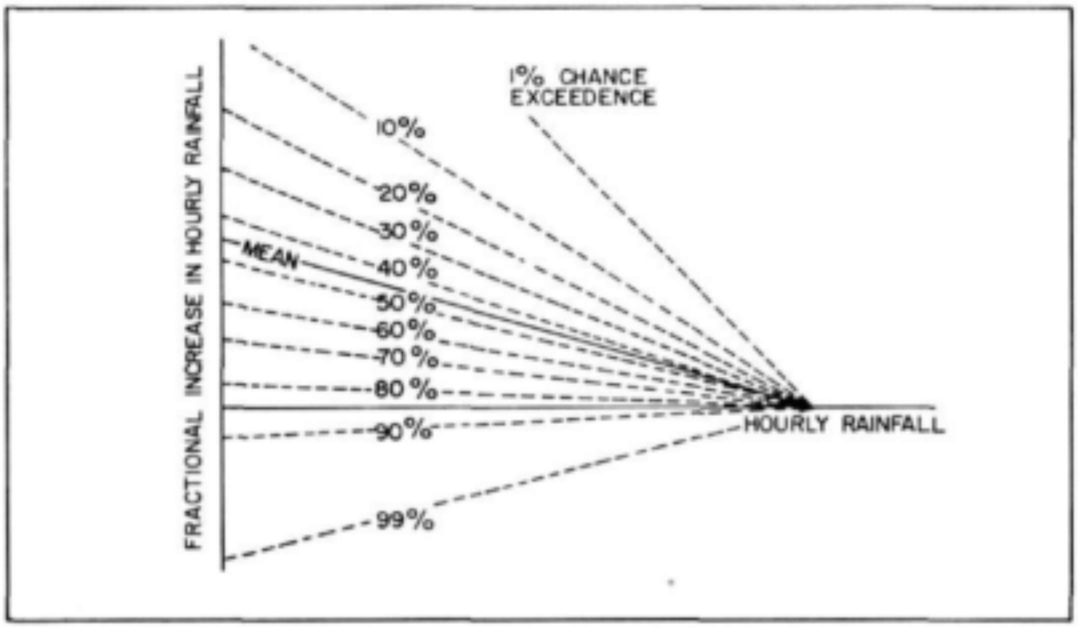
* 10% average increase in areal rainfall

* increases in hourly rainfall have a highly skewed distribution with a small number of occasions having large increases and a large number of cases having small or negative increases

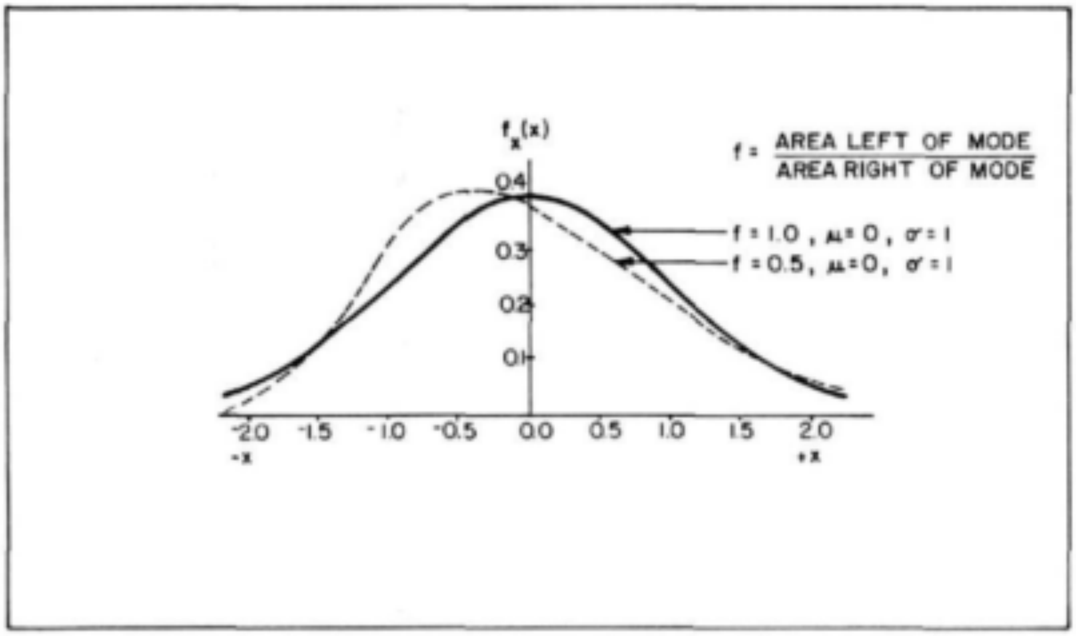
* the mean percentage increase in rainfall decreases linearly with rainfall rate increases on the grounds that at higher rainfall intensities the natural rainfall mechanisms operate efficiently and cannot be significantly altered by seeding.

* the number of hours of rainfall does not increase.

Fig. 5.13 depicts the statistical augmentation model employed in this case. The implication of this model is that the rainfall increases resulting from seeding are due to increased intensities but not to increased durations. The same cannot be implied for increased storm areas, for the following reasons: The hourly rainfalls used in the study are averaged over catchment areas of the order of 200 km^2. Increased hourly totals under conditions of area averaging can be either the result of intensity increases evenly distributed over the catchment or an increase in the high intensity sub-areas of the storms causing each hour's total rainfall, averaged over the 200 km^2.



STATISTICAL AUGMENTATION MODEL



SPLIT NORMAL DISTRIBUTION

STATISTICAL ADJUSTMENT MODEL
USED BY LUMB AND LINSLEY (1971)

FIGURE 5.13

5.6.3 Cloud-related stratified statistical adjustments

A principal weakness of the modified rainfall time series described in the previous sub-section is that it doesn't distinguish between rainfall from "seedable" as opposed to "non-seedable" clouds, i.e. it doesn't stratify the adjustments. Maaren (1984) accommodated this requirement indirectly in an exploratory study , by means of a daily rainfall-runoff model, of the hydrological response to rainfall augmentation of a subcatchment of Vaal Dam. Maaren stratified the record of two years of rain days available for his study in terms of seven weather type classes, of which only two - types V and VI - were considered seedable. This augmentation model comprised a constant increase of 5% in daily rainfall on all type V days and a 15% increase on all type VI days. Though highly instructive, Maaren's stratification nevertheless does not go far enough in that it does not recognise

* the variability of the magnitude of the rainfall increases from individual seeded storms,

* the random variability of occurrence of seedable clouds on each day,

* the resulting stochastic nature of the total daily seeding response at a point and

* the daily variability of sub-areas "swept" out by the seeded storms (inside the boundaries of the catchment of interest), which

* determines the stochastic nature of the areal distribution of rainfall inputs into the catchment.

The preceding five points spell out essential elements of any attempt to develop credible modified rainfall time series, both at a point and over an area. The remaining sections of this chapter deal with these elements and lead to proposals for the development of provisional modified rainfall time series. However, prior to this, reference must first be made to a fourth approach to rainfall adjustments to round off the topic of this section.

5.6.4 Rainfall adjustments by dynamic conceptual storm models

In a study of the sensitivity of output from a distributed rainfall-runoff model to rainfall input errors, Schultz (1985) points to the way in which dynamic storm models could be used to generate enhanced rainfall on a single event basis. The type of storm model referred to here is conceptually structured to represent storm areal growth and decay, rainfall intensity growth and decay, a moving centroid, and elliptical distortion. Additionally, its parameters can be related to attributes of observed events, covered by a "reasonable" network of rain-gauges or by radar-tracking procedures. By applying empirical seeding-induced changes, say, as per Table 5.6 to such observed attributes, modified synthetic storms can be generated from which augmented spatially distributed rainfall can be extracted for the specific storm duration. Clearly, such storm models would be useful to investigate cloudseeding impacts on a detailed event-by-event basis, with the focus on processes and their evolution on and in the soil. However, in the context of our brief which relates to long-term and average impacts, a single event approach to rainfall adjustments is not appropriate.

5.7 Variability of seeding responses

As intimated in 5.6.3 above, our next task is to examine the inter-storm variability of the rainfall increases from individual seeded storms. Of equal importance is the variability of incremental seeding effects during the lifetime of seeded storms.

In Figure 5.14 the mean growth/decay of rainflux during sequential windows is tracked, while the variability of incremental rainflux growth/decay is indicated by the values in Table 5.8. Figure 5.14 shows the (by now) familiar diverging rainflux values for seed and no-seed cases, which signify the seeding effect. But its truely interesting feature is that it shows that rainflux growth dominates until 40 minutes after decision time for seeded clouds, whereas the no-seed growth dominance ends 10 minutes earlier. Table 5.8 shows that the first 40 minutes after decision time also manifests the greatest seed/no-seed differences in variability of rainflux growth. Beyond 40 minutes after decision time the seed/no-seed relative variability of rainflux growth/decay is very similar, in spite of the greater decay of seed storms. Of importance, also, is the distribution of incremental rainflux growth/decay values. Figures 5.15 (a) to (d) indicate a clear central tendency around the mean for both seed and no-seed cases and, on

TABLE 5.8 : INCREMENTAL RAINFLUX GROWTH AND DECAY ON THE BASIS OF SEQUENTIAL PAIRS OF TIME WINDOWS

Window Pair (minutes)	Seed				No-Seed			
	No.	Mean	Std.Dev.	C **	No.	Mean	Std. Dev.	C
-10-0 to 20-30	37	52	157	3,0	46	20	121	6,1
20-30 to 30-40	31	15	127	8,5	39	-19	80	-4,2
30-40 to 40-50	25	-30	89	-3,0	31	-19	77	-4,1
40-50 to 50-60	19	-33	112	-3,4	23	-23	80	-3,5

* For the two seed and five no-seed storms without pre-decision echos rainflux is set to zero during the -10-0 minutes window.

** C_v = Coefficient of variation = std. dev./mean

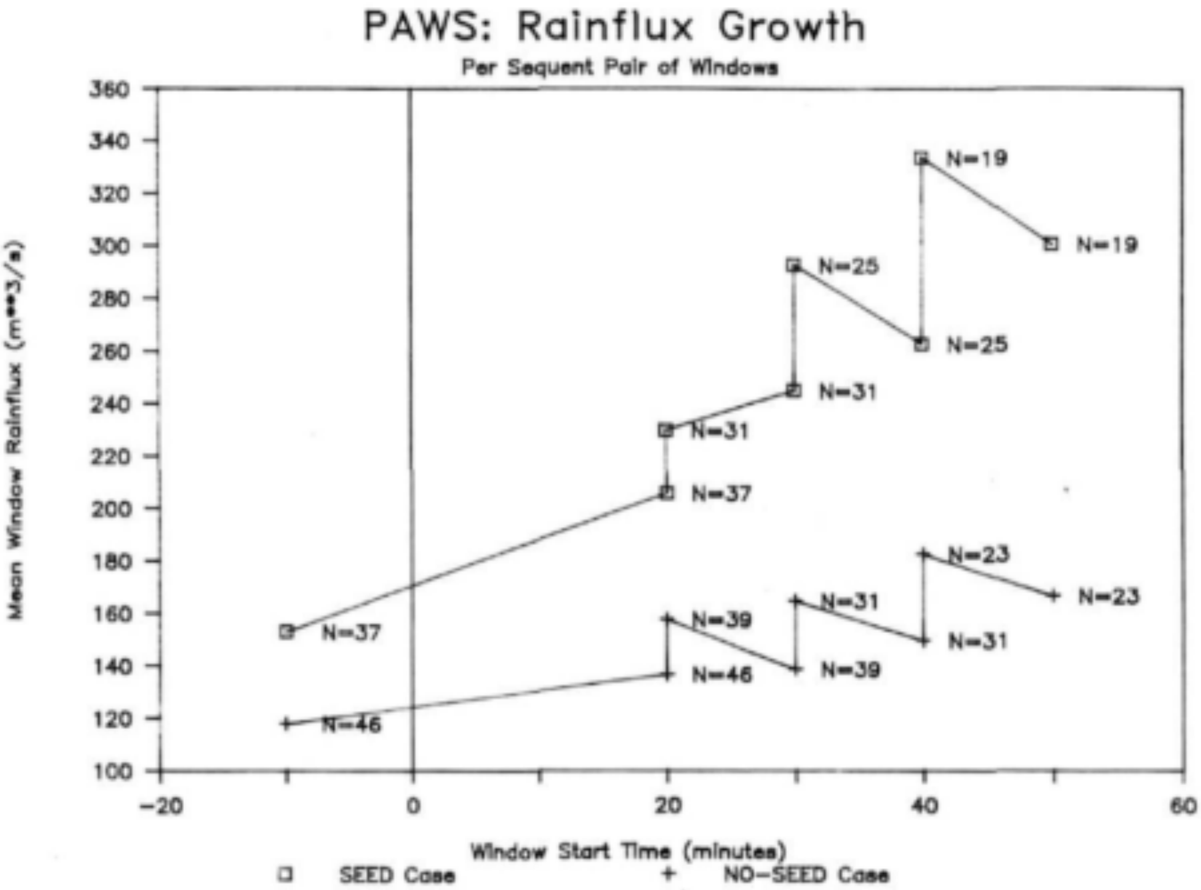
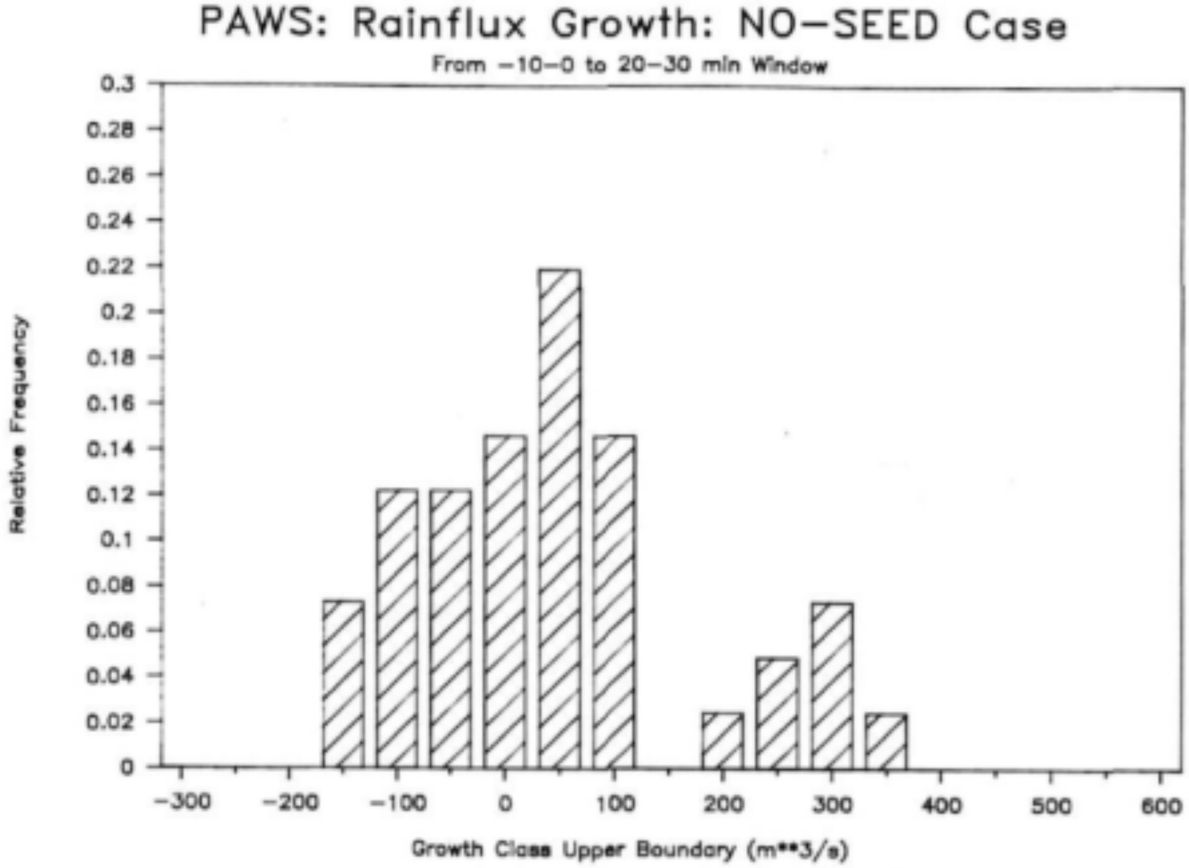

PAWS: Rainflux Growth
Per Sequent Pair of Windows
Mean Window Rainflux (m**3/s)
Window Start Time (minutes)
SEED Case
NO-SEED Case
N=37
N=31
N=25
N=19
N=46
N=39
N=23

FIGURE 5.14


PAWS: Rainflux Growth: NO–SEED Case
From –10–0 to 20–30 min Window
Relative Frequency
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
–300
–200
–100
0
100
200
300
400
500
600
Growth Class Upper Boundary (m**3/s)

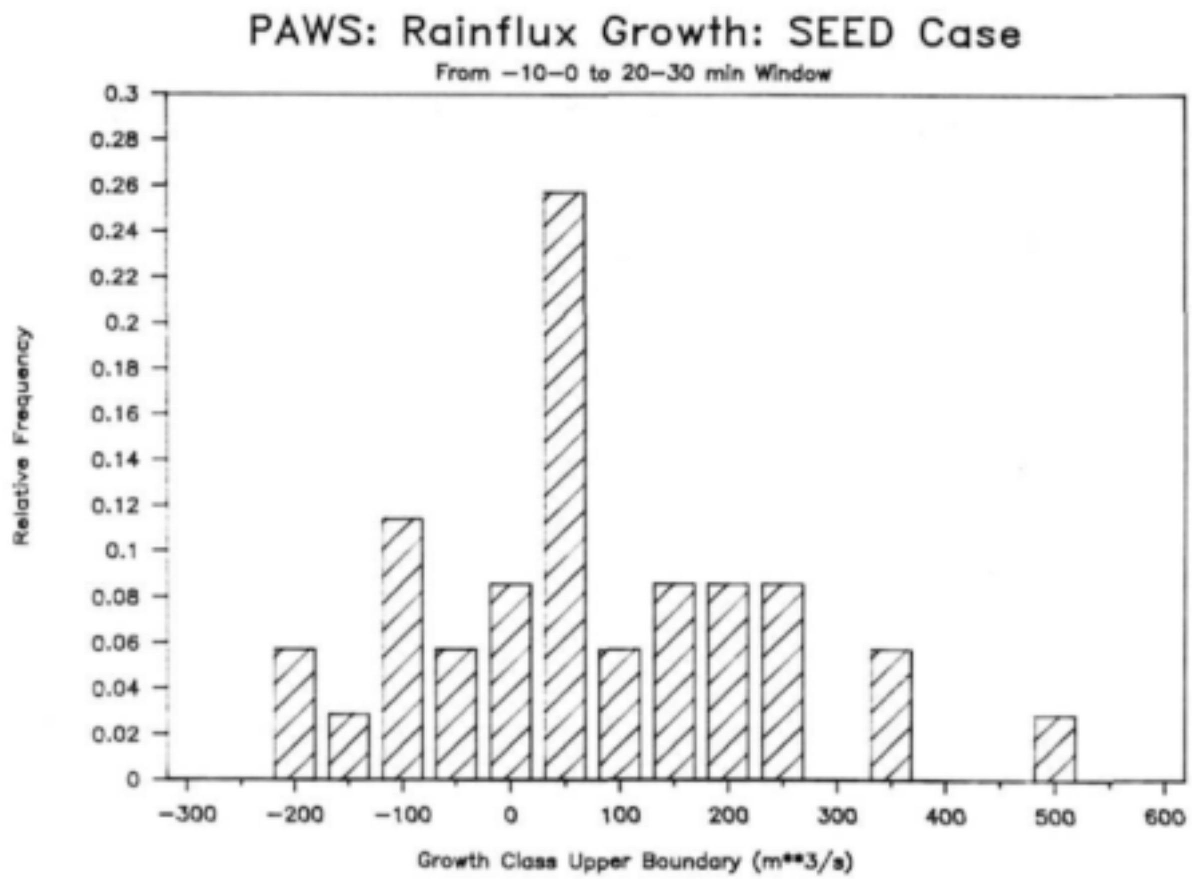
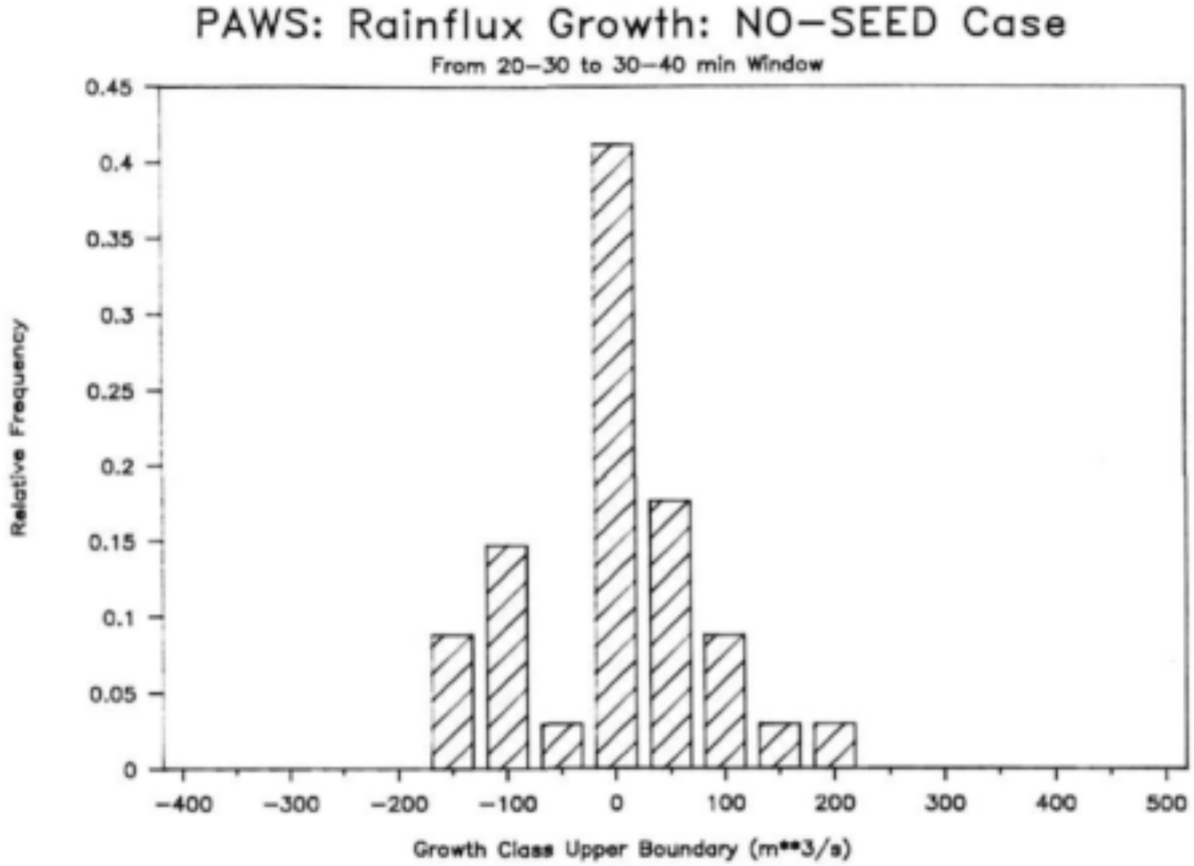

PAWS: Rainflux Growth: SEED Case
From –10–0 to 20–30 min Window
Relative Frequency
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
–300
–200
–100
0
100
200
300
400
500
600
Growth Class Upper Boundary (m**3/s)

FIGURE 5.15A


PAWS: Rainflux Growth: NO-SEED Case
From 20-30 to 30-40 min Window
Relative Frequency
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-400
-300
-200
-100
0
100
200
300
400
500
Growth Class Upper Boundary (m**3/s)

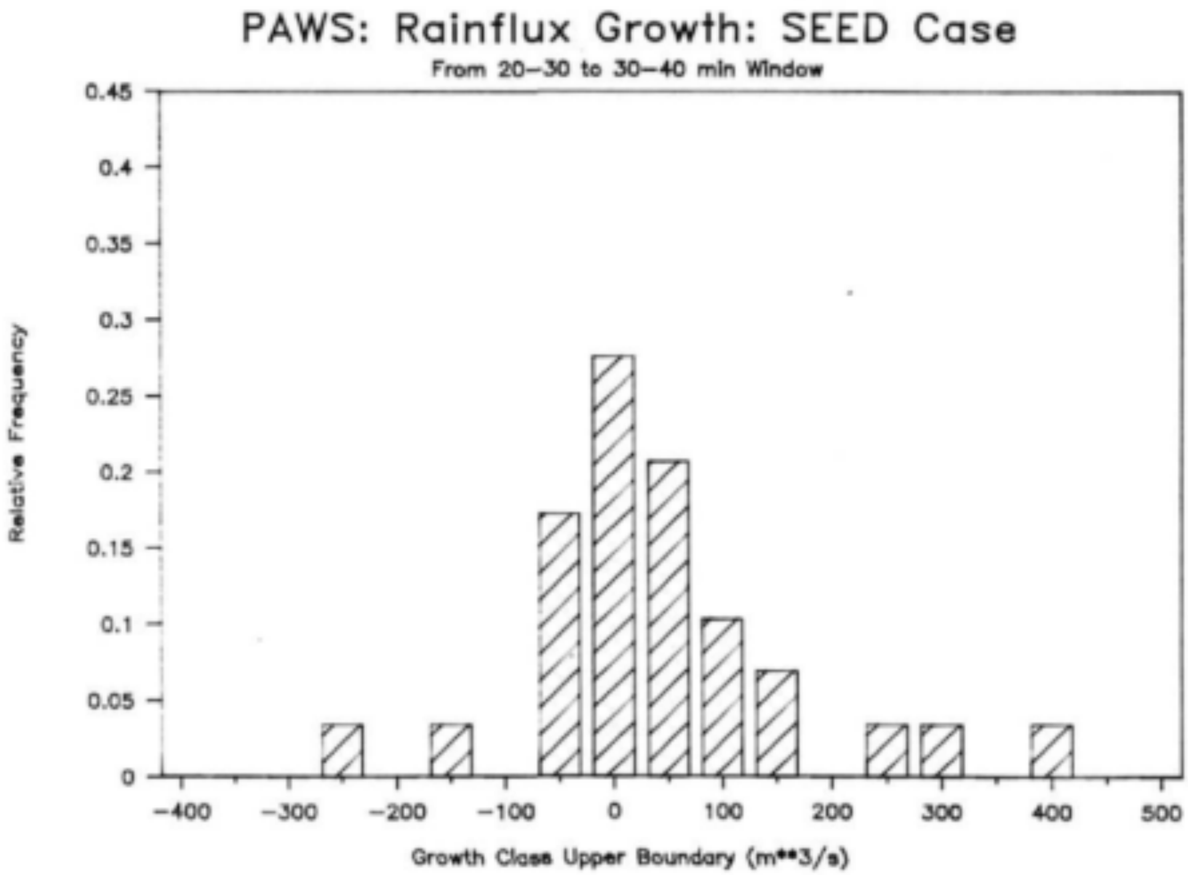
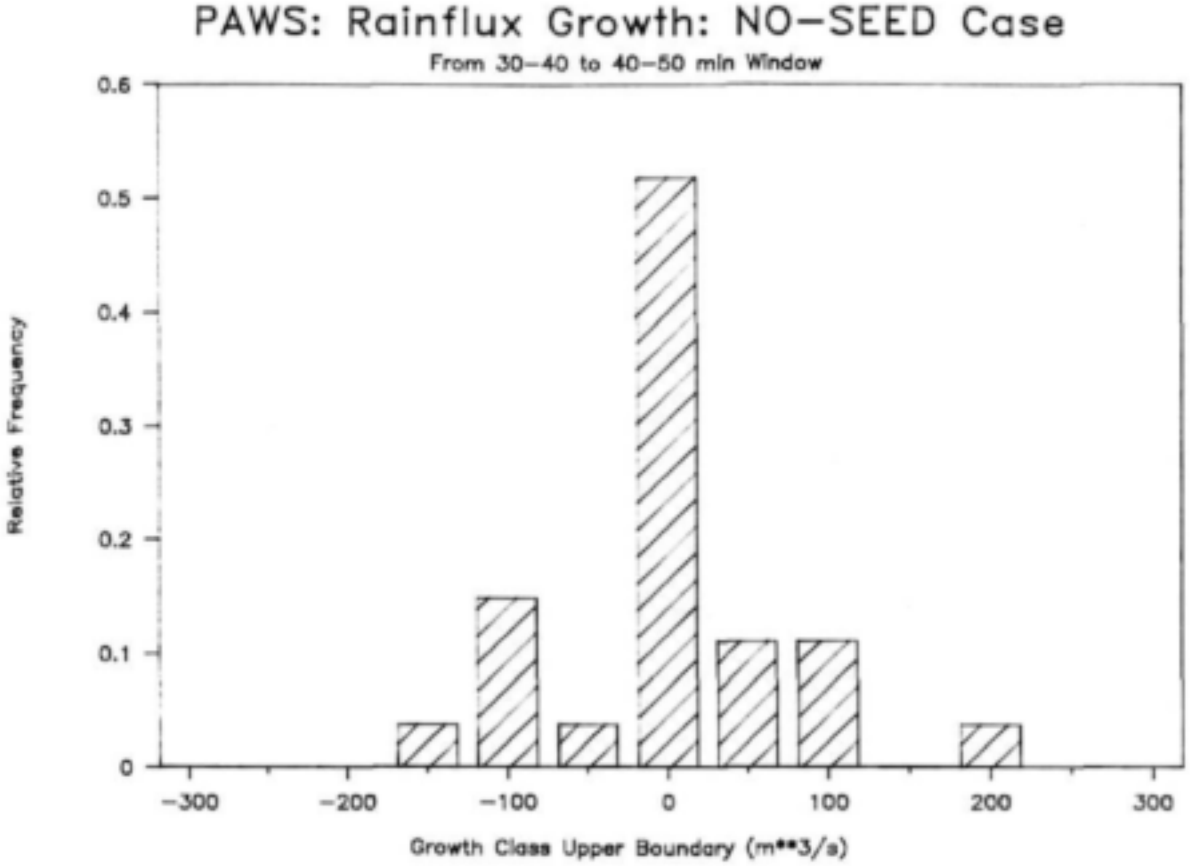

PAWS: Rainflux Growth: SEED Case
From 20-30 to 30-40 min Window
Relative Frequency
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-400
-300
-200
-100
0
100
200
300
400
500
Growth Class Upper Boundary (m**3/s)

FIGURE 5.15B


PAWS: Rainflux Growth: NO-SEED Case
From 30-40 to 40-50 min Window
Relative Frequency
0 0.1 0.2 0.3 0.4 0.5 0.6
-300 -200 -100 0 100 200 300
Growth Class Upper Boundary (m**3/s)

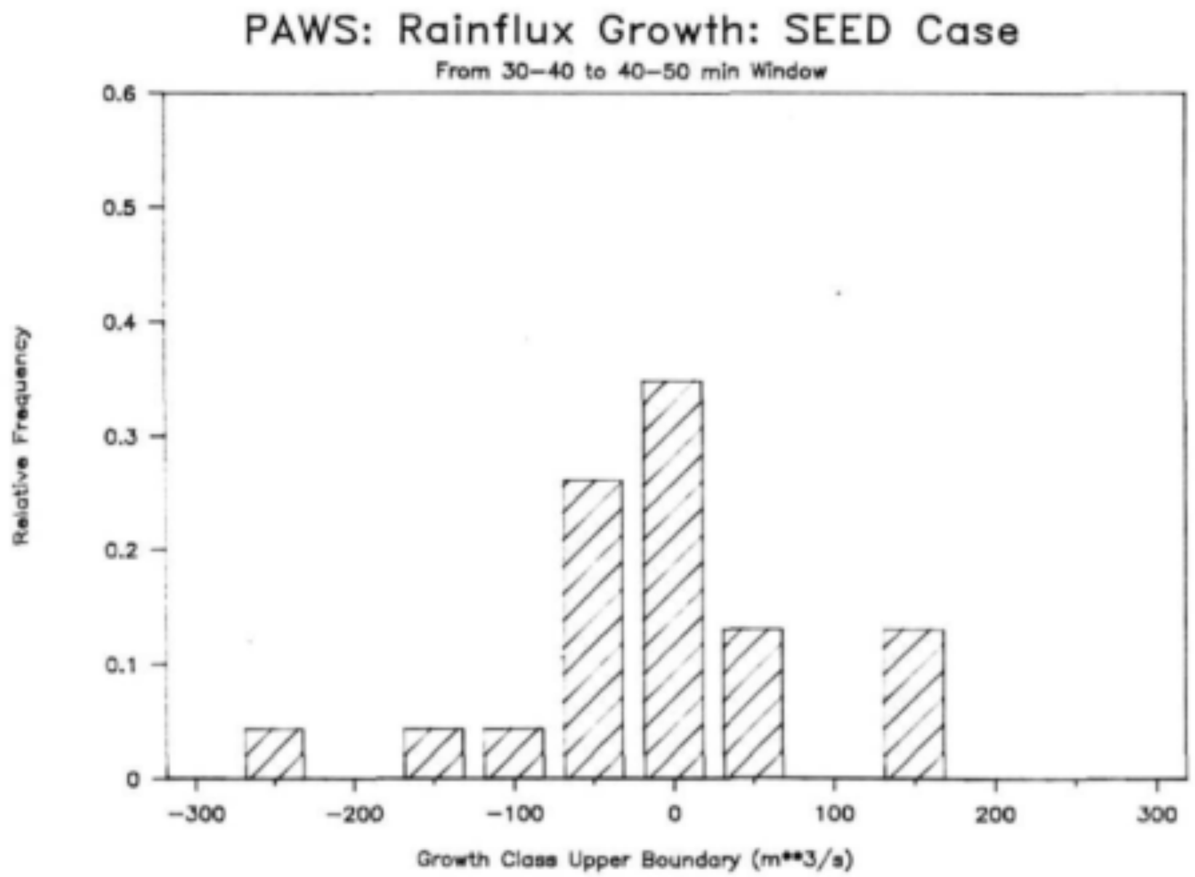
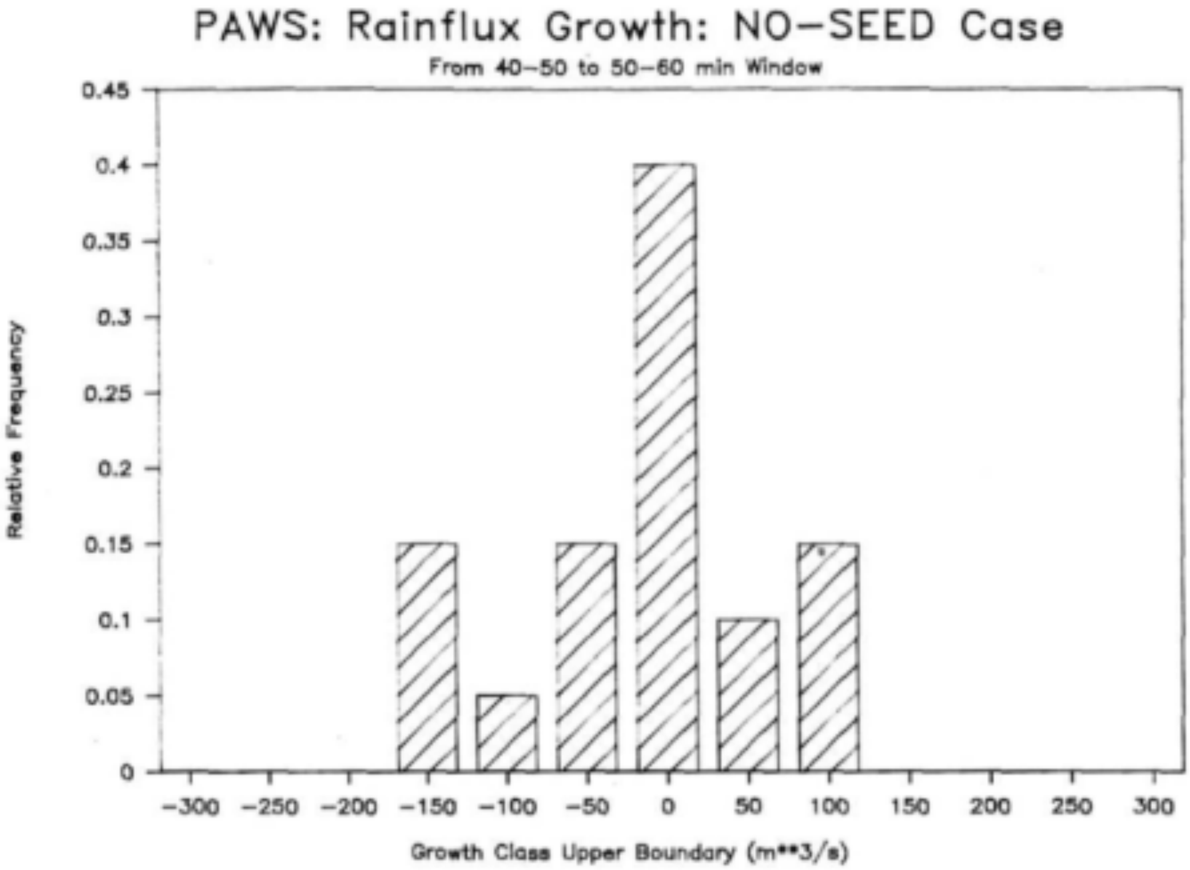

PAWS: Rainflux Growth: SEED Case
From 30-40 to 40-50 min Window
Relative Frequency
0 0.1 0.2 0.3 0.4 0.5 0.6
-300 -200 -100 0 100 200 300
Growth Class Upper Boundary (m**3/s)

FIGURE 5.15C


PAWS: Rainflux Growth: NO-SEED Case
From 40-50 to 50-60 min Window
Relative Frequency
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300
Growth Class Upper Boundary (m**3/s)

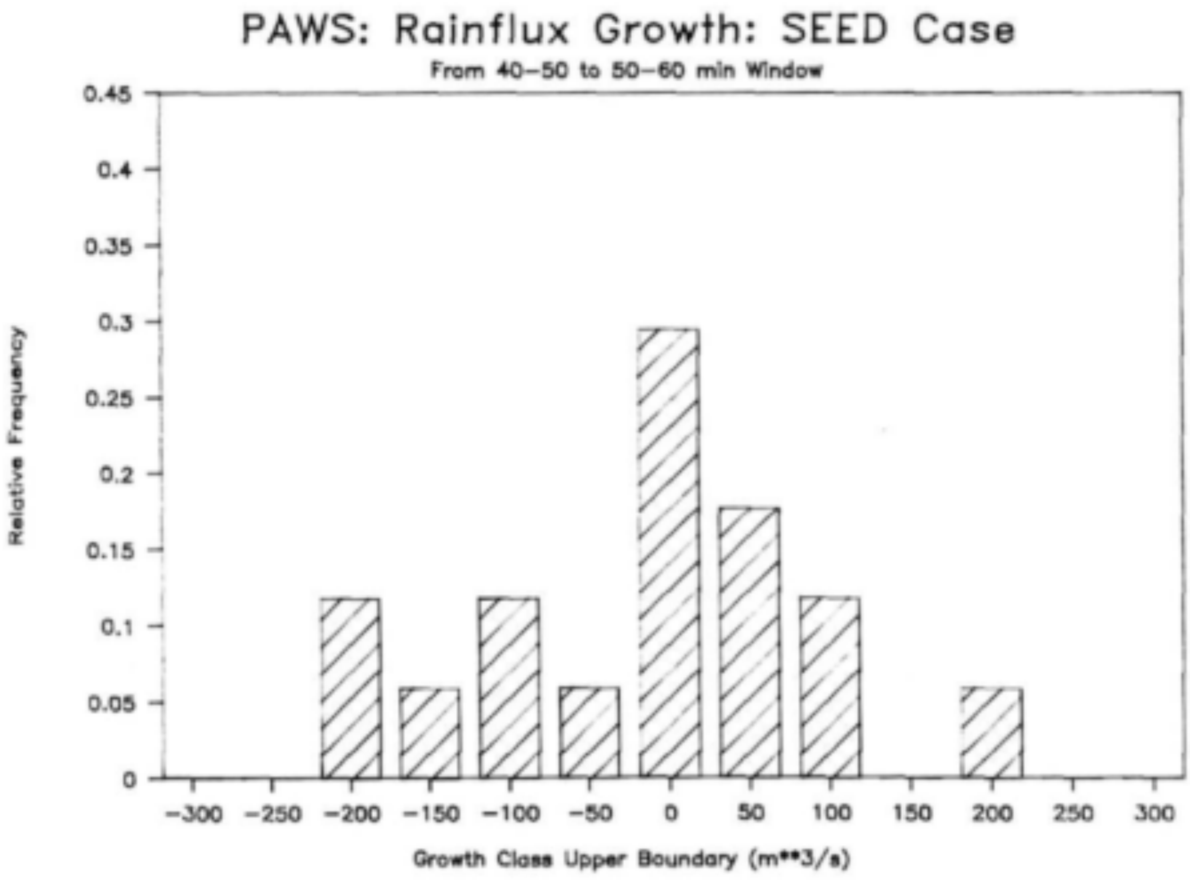

PAWS: Rainflux Growth: SEED Case
From 40-50 to 50-60 min Window
Relative Frequency
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300
Growth Class Upper Boundary (m**3/s)

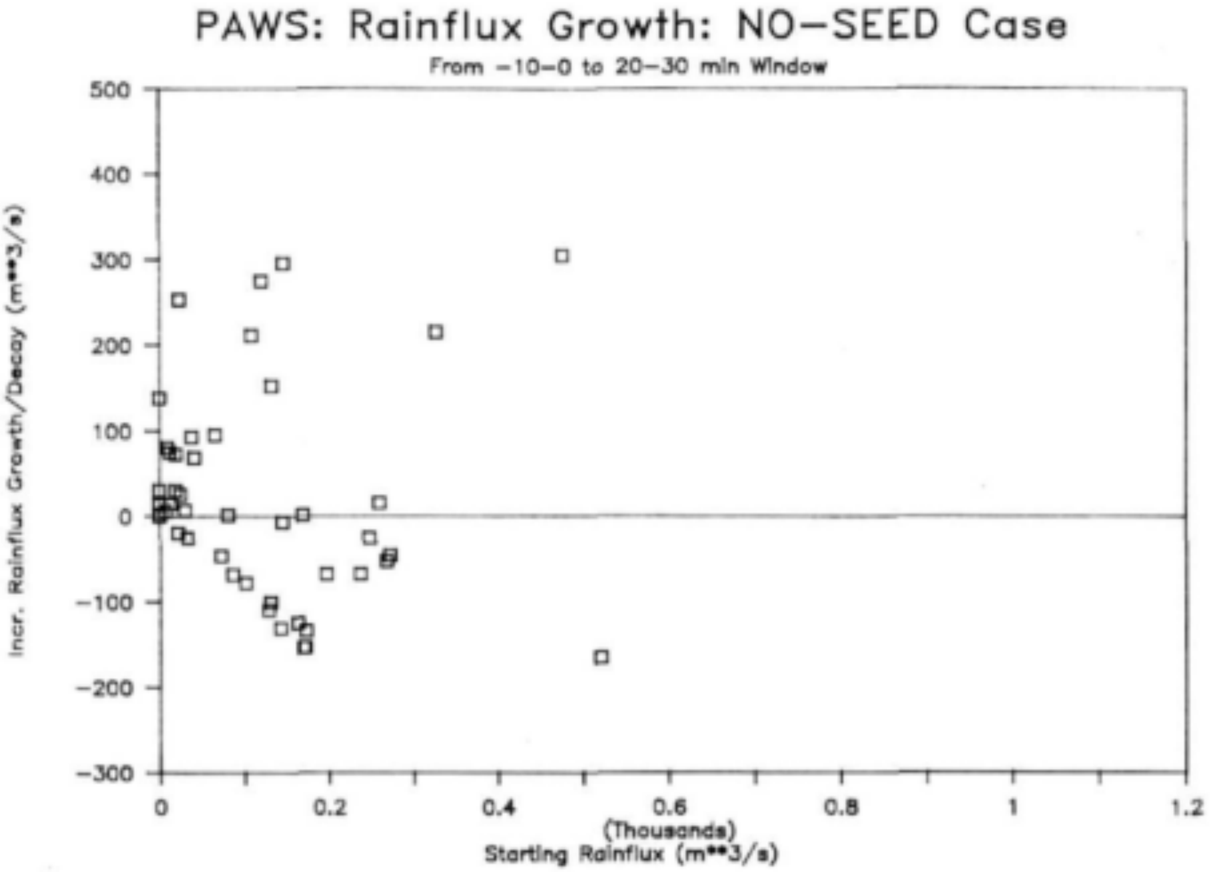
FIGURE 5.15D

average, a fairly symmetrical distribution. Without having attempted distribution fitting tests, we believe that a truncated Normal distribution would be a reasonable working hypothesis for incremental rainflux growth/decay, regardless of seeding.

As an aid to the examination of the inter-storm variability of seeding responses we plotted incremental rainflux growth/decay against starting rainflux values for sequential window pairs. Figures 5.16 (a) to (d) depict the results. Rainflux decay is of course bounded by the 1:1 line, but suprisingly, rainflux growth for seed cases seem to have an upper envelope for window pairs beyond 20 minutes after decision time. Figures 5.17 (a) and (b) display similar information in terms of growth ratios. In general, however, the incremental growth/decay values show no systematic patterns and appear to be fairly random.

A further characteristic that might reveal a variable seeding response is that of cloud lifetime as measured by storm duration. Fig. 5.18 reveals that cloud lifetime decay/storm survival rates for seeded clouds are virtually indistinguishable from those of unseeded clouds.

On the whole this cursory examination did not produce an abundance of "hard" quantified information on the variability of seeding responses. We surmise that use of incremental rainflux growth data stratified by specific cloud attributes or by factors such as synoptic type, in conjunction with a study of each target storm's post-decision history, might produce further information useful to the development of augmented rainfall time series. However, this work falls outside the scope of our study and has to await appropriate attention at some future date.


PAWS: Rainflux Growth: NO-SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

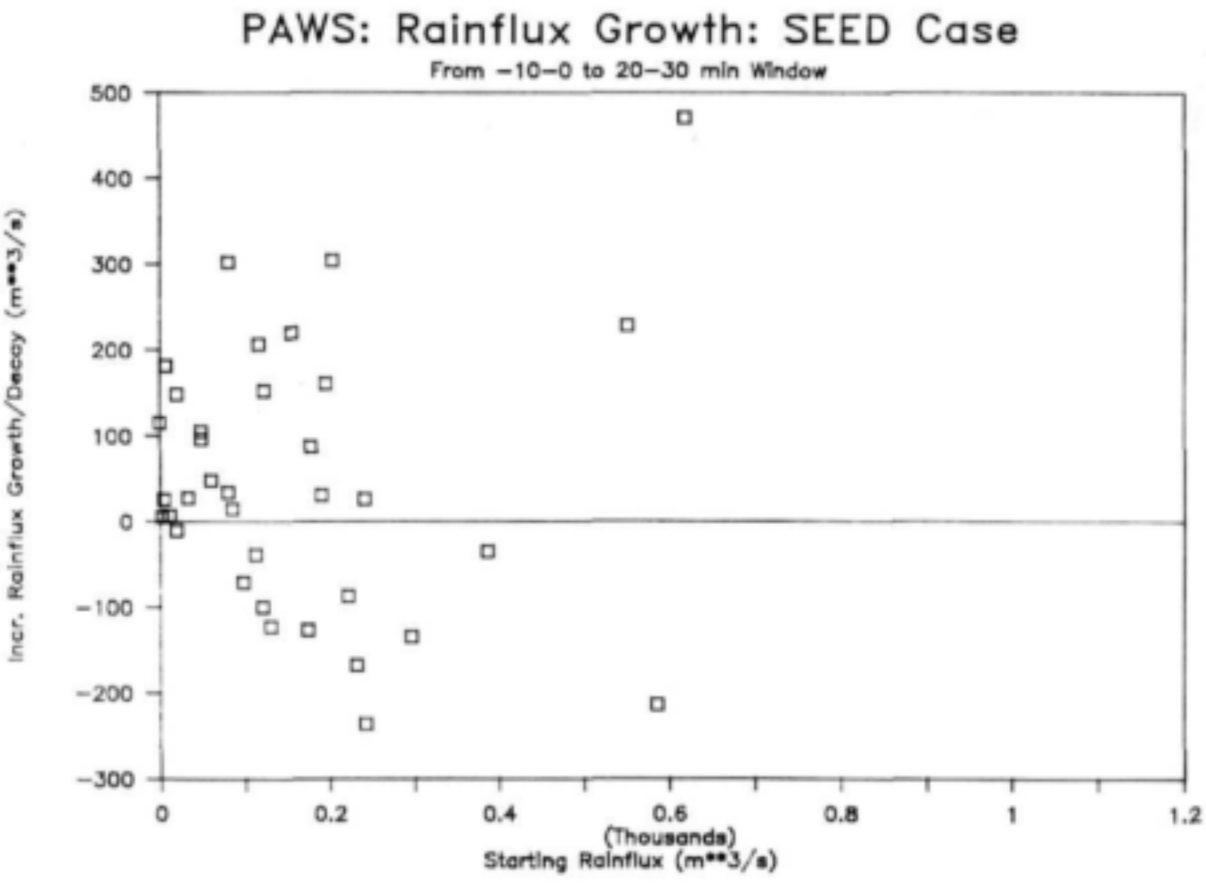
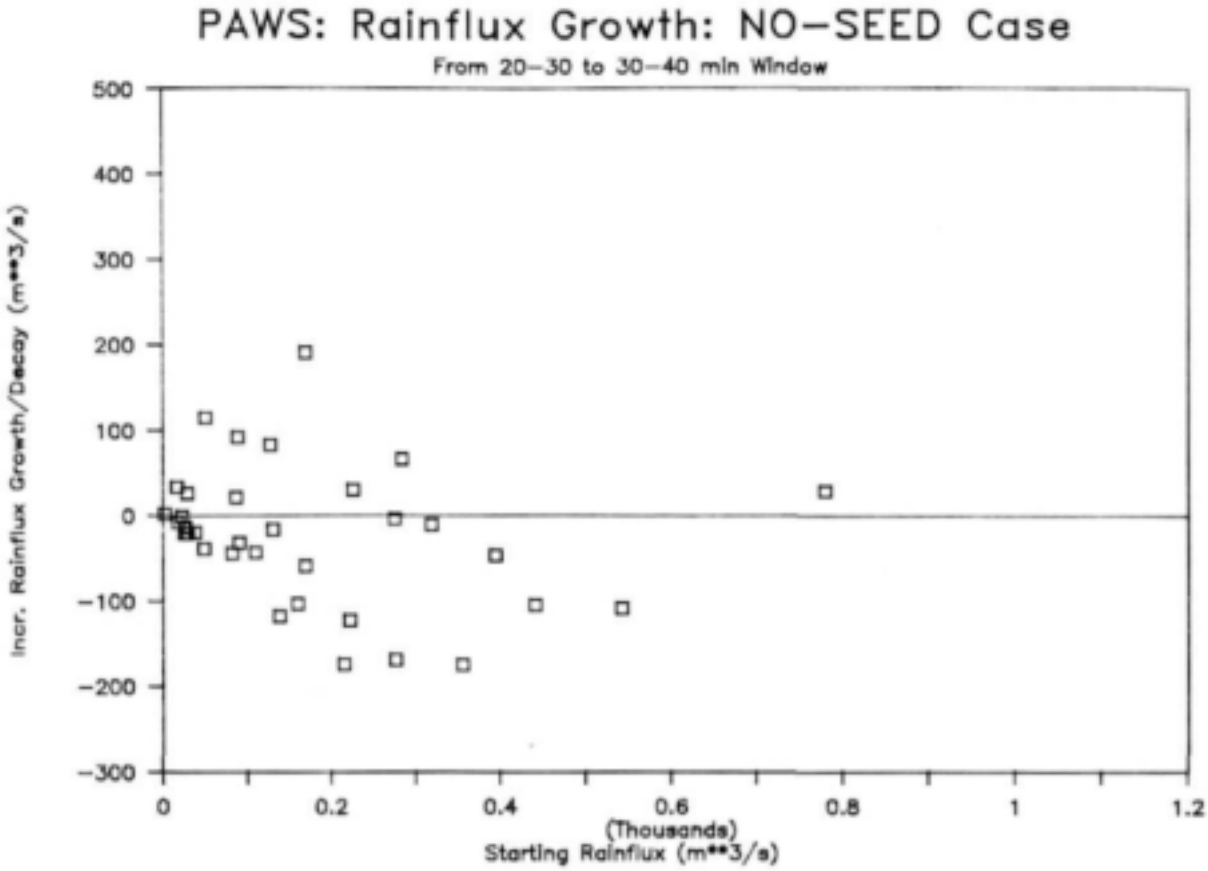

PAWS: Rainflux Growth: SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

FIGURE 5.16 A


PAWS: Rainflux Growth: NO-SEED Case
From 20-30 to 30-40 min Window
500
400
300
200
100
0
-100
-200
-300
Incr. Rainflux Growth/Decay (m**3/s)
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

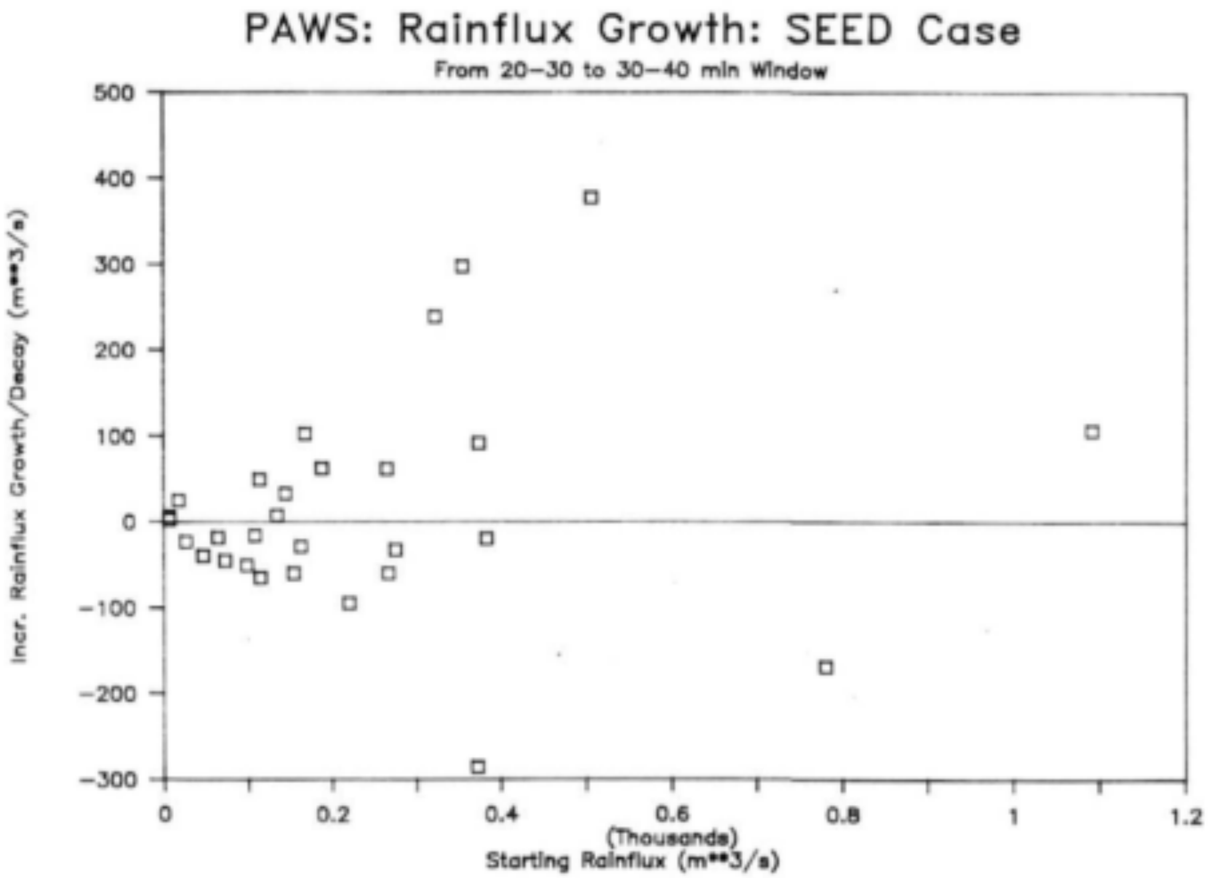
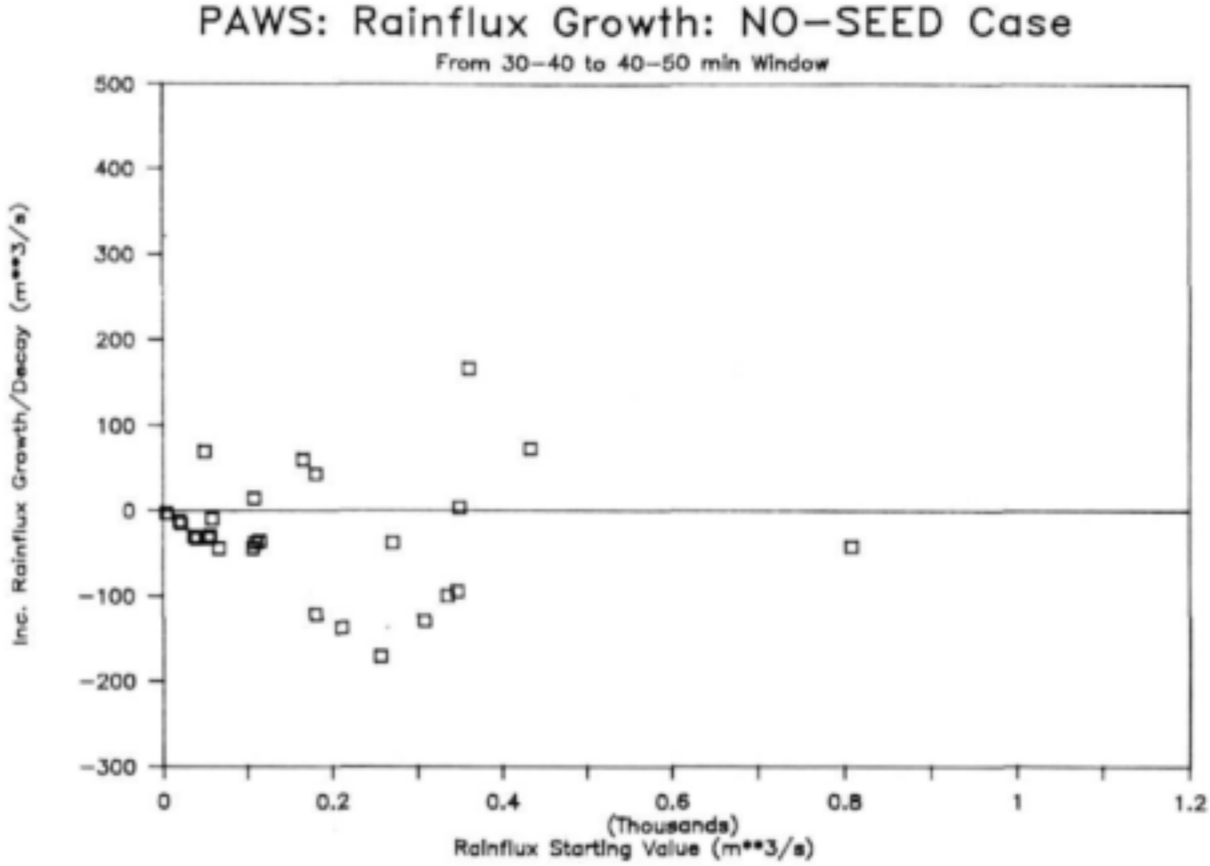

PAWS: Rainflux Growth: SEED Case
From 20-30 to 30-40 min Window
500
400
300
200
100
0
-100
-200
-300
Incr. Rainflux Growth/Decay (m**3/s)
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

FIGURE 5.16B


PAWS: Rainflux Growth: NO-SEED Case
From 30-40 to 40-50 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

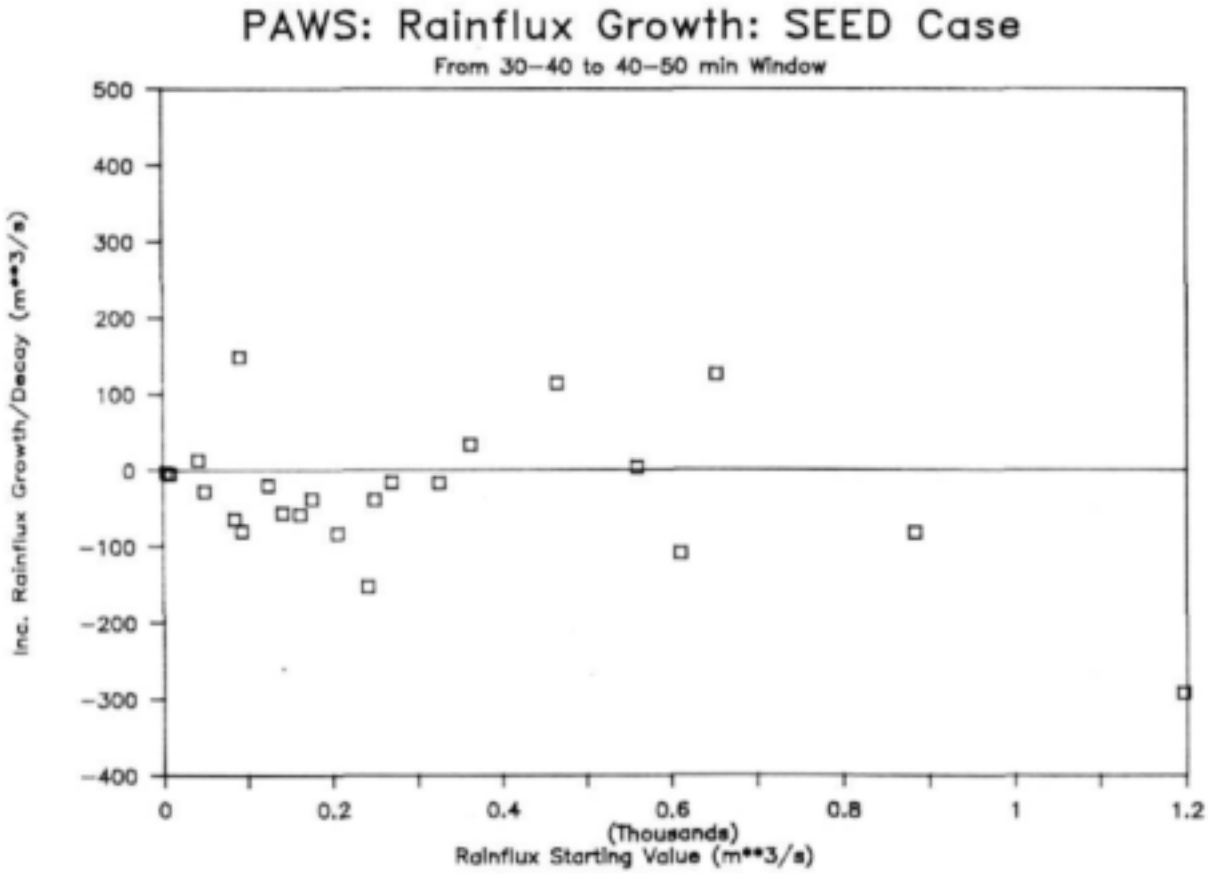
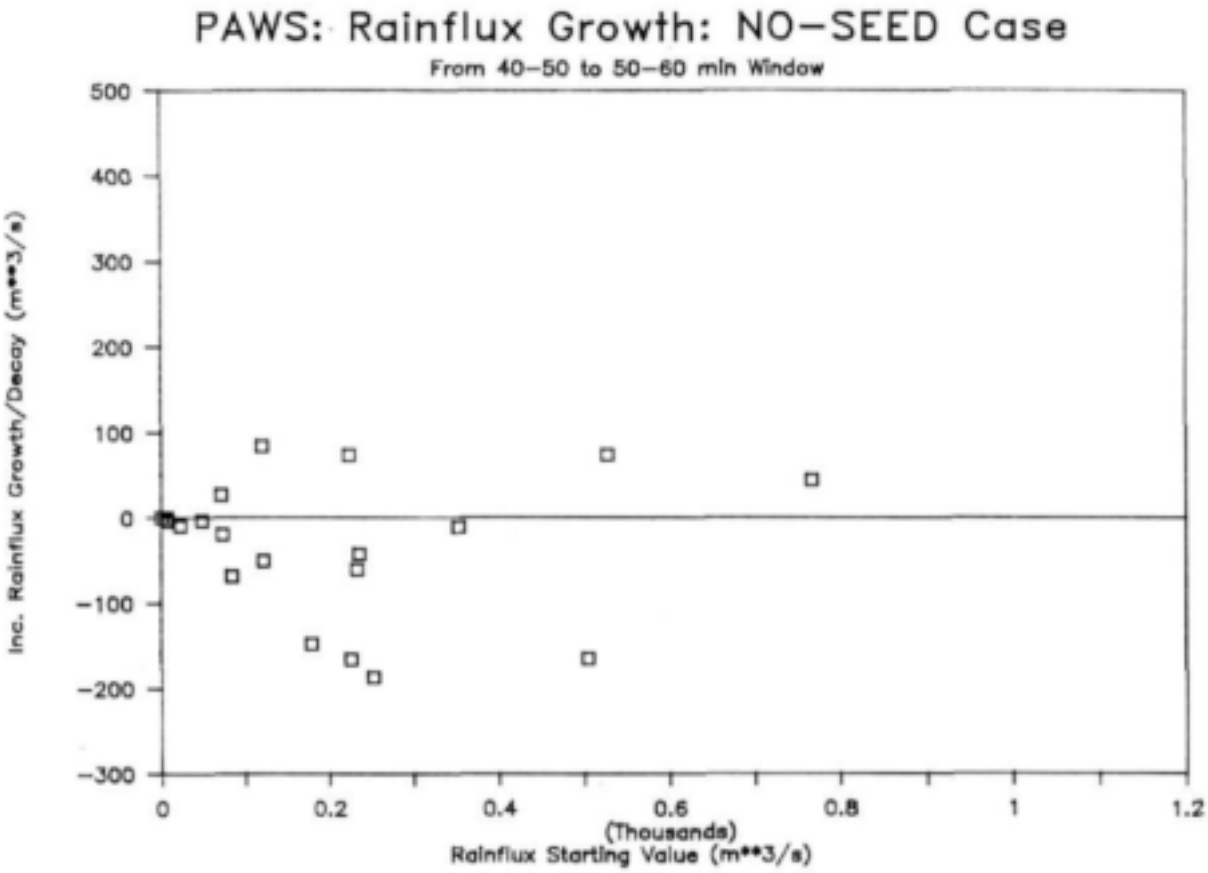

PAWS: Rainflux Growth: SEED Case
From 30-40 to 40-50 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
-400
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

FIGURE 5.16 C


PAWS: Rainflux Growth: NO-SEED Case
From 40-50 to 50-60 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

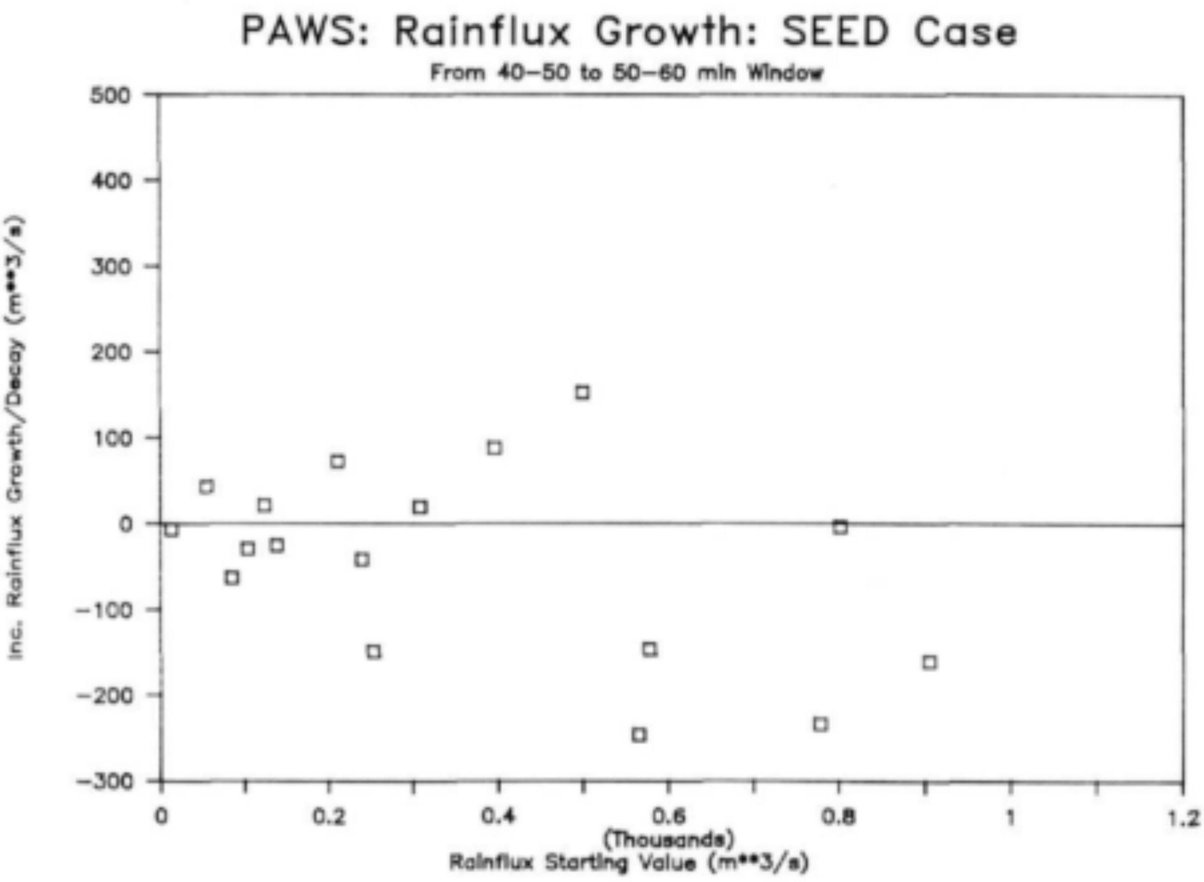
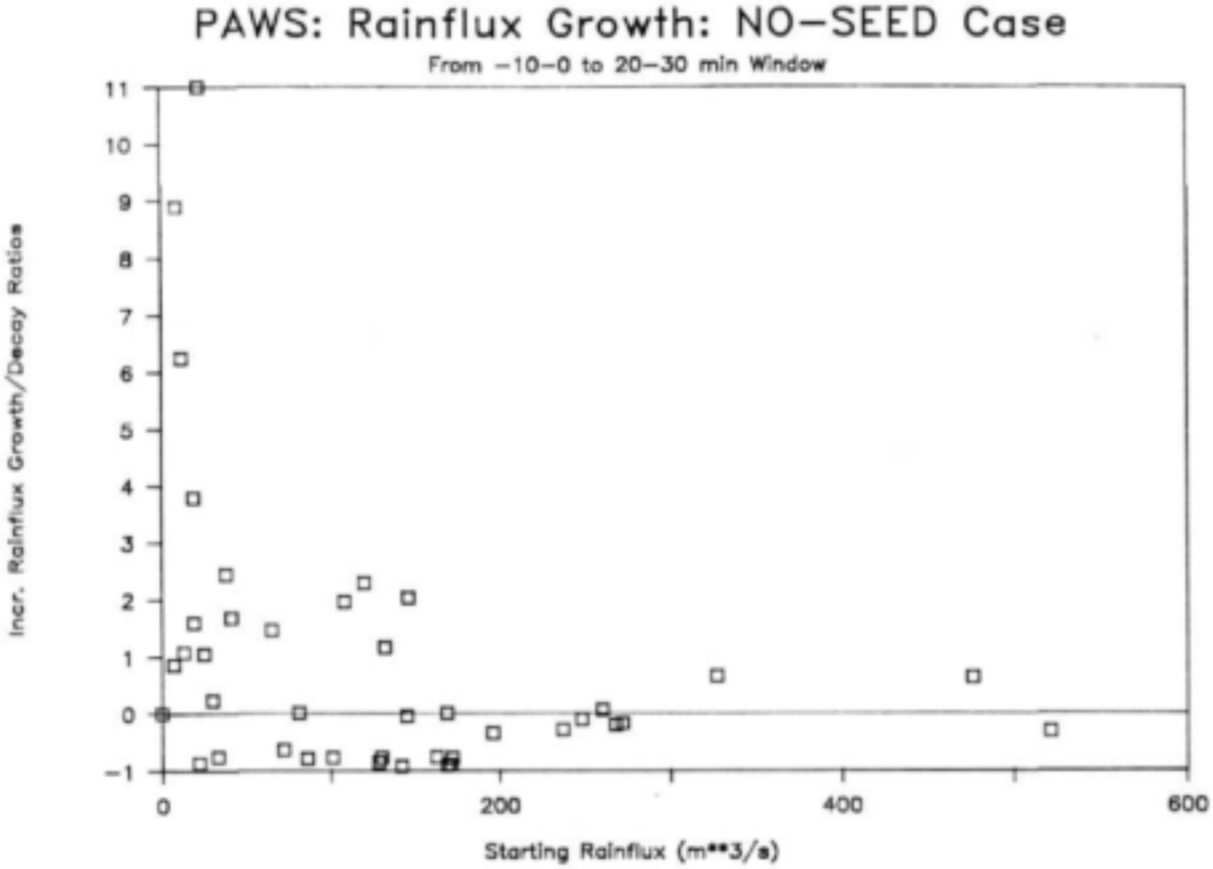

PAWS: Rainflux Growth: SEED Case
From 40-50 to 50-60 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

FIGURE 5.16D


PAWS: Rainflux Growth: NO-SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay Ratios
Starting Rainflux (m**3/s)
11
10
9
8
7
6
5
4
3
2
1
0
-1
0
200
400
600

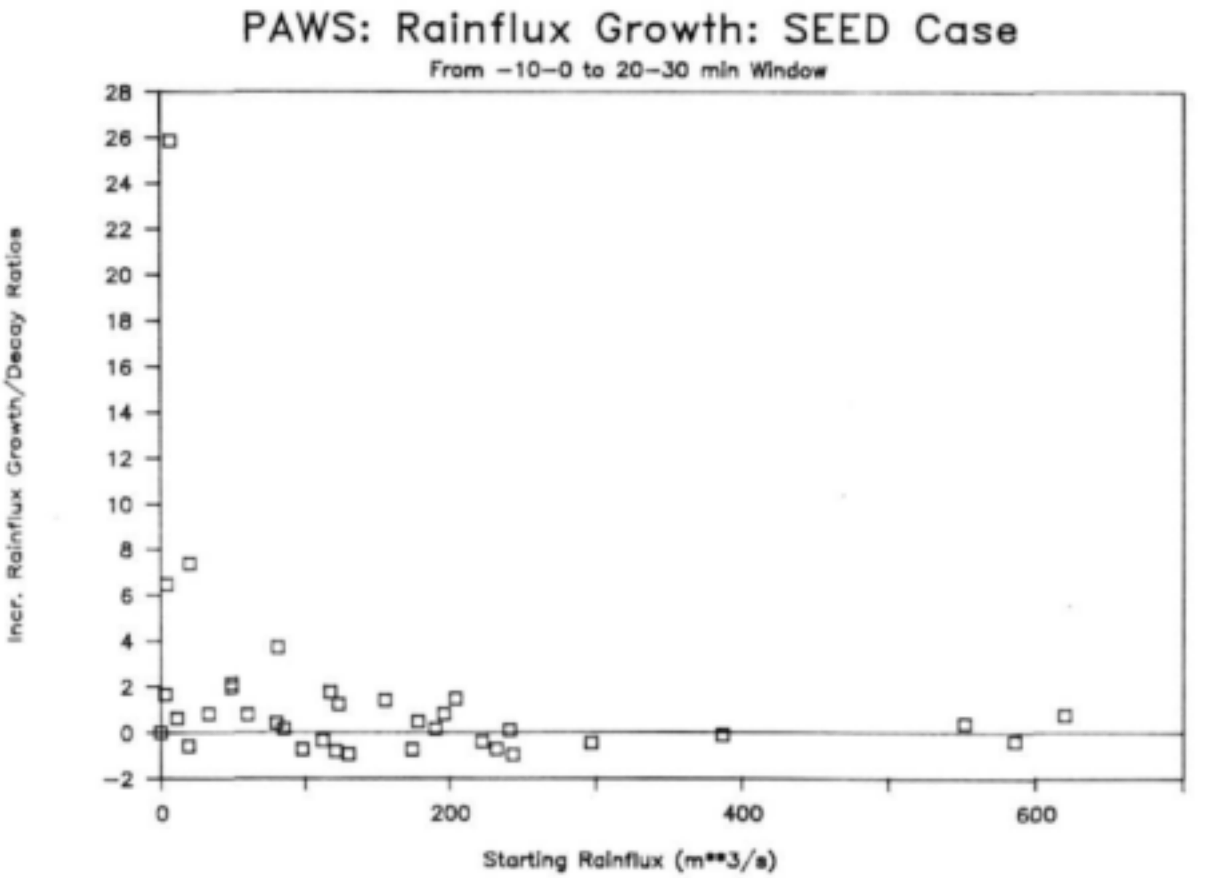
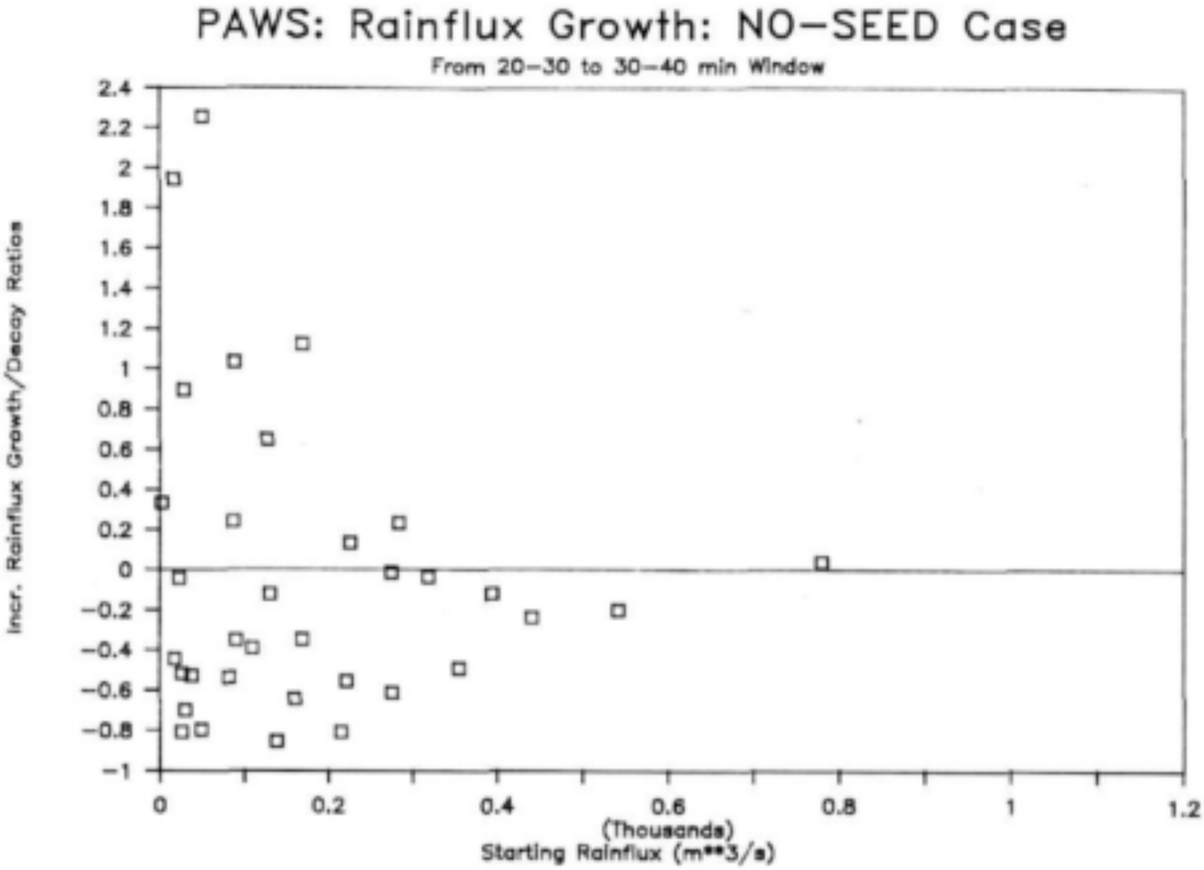

PAWS: Rainflux Growth: SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay Ratios
Starting Rainflux (m**3/s)
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
0
200
400
600

FIGURE 5.17A


PAWS: Rainflux Growth: NO—SEED Case
From 20—30 to 30—40 min Window
Incr. Rainflux Growth/Decay Ratios
(Thousands)
Starting Rainflux (m**3/s)

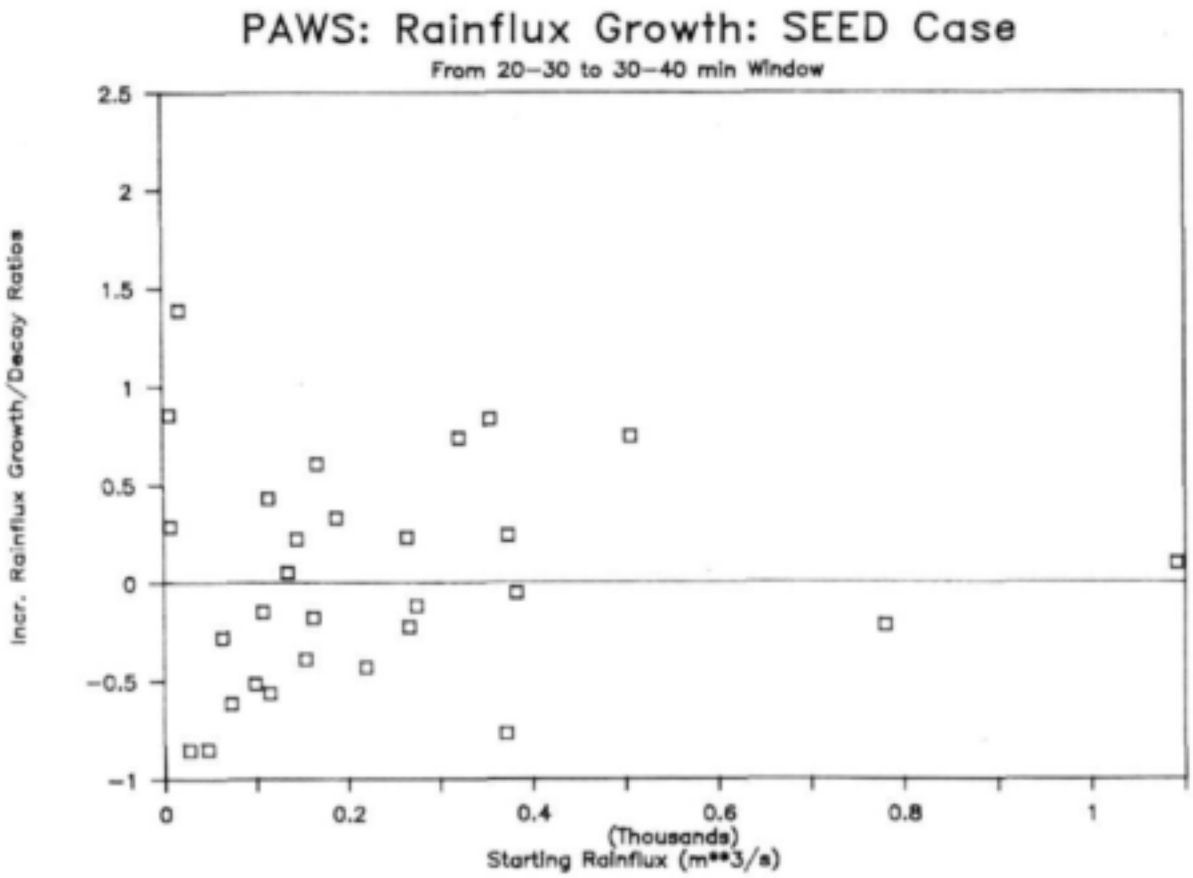
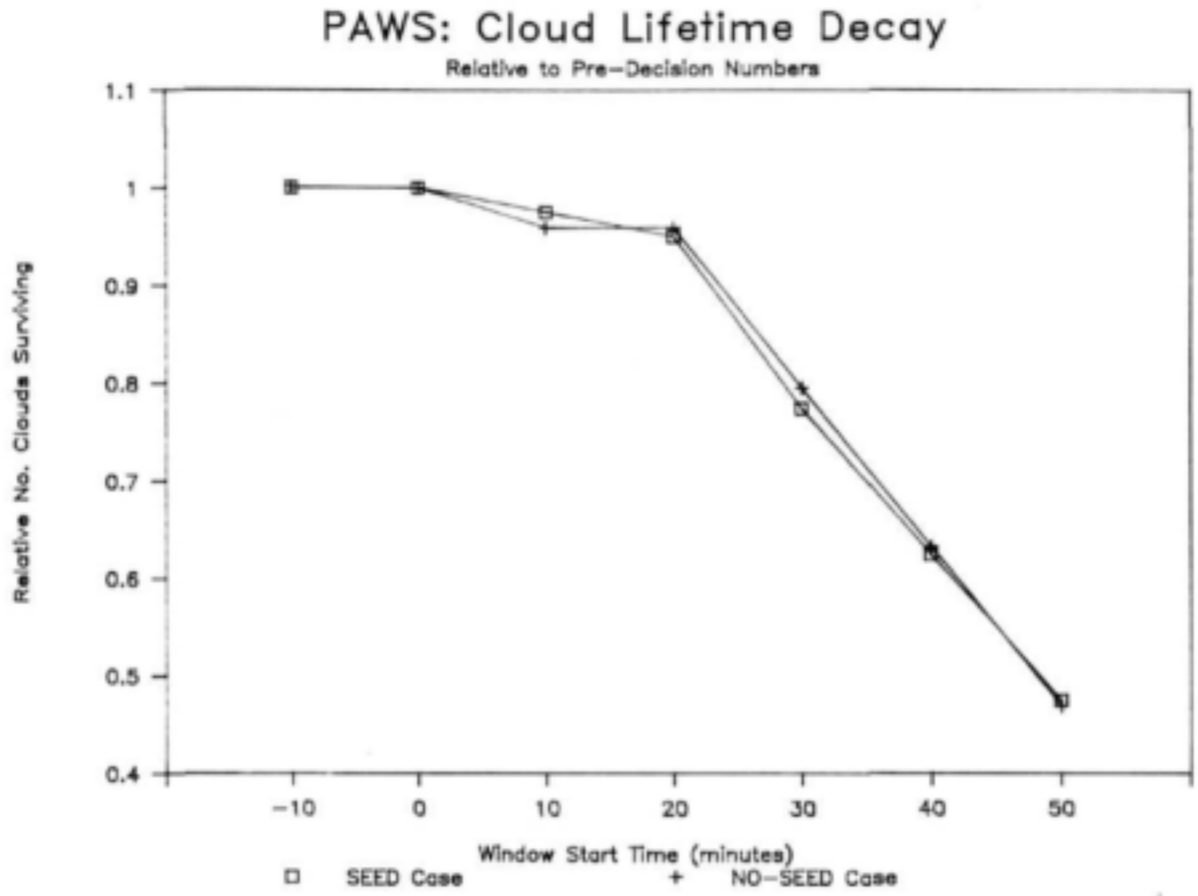

PAWS: Rainflux Growth: SEED Case
From 20—30 to 30—40 min Window
Incr. Rainflux Growth/Decay Ratios
(Thousands)
Starting Rainflux (m**3/s)

FIGURE 5.17B


PAWS: Cloud Lifetime Decay
Relative to Pre-Decision Numbers
Relative No. Clouds Surviving
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
-10
0
10
20
30
40
50
Window Start Time (minutes)
SEED Case
NO-SEED Case

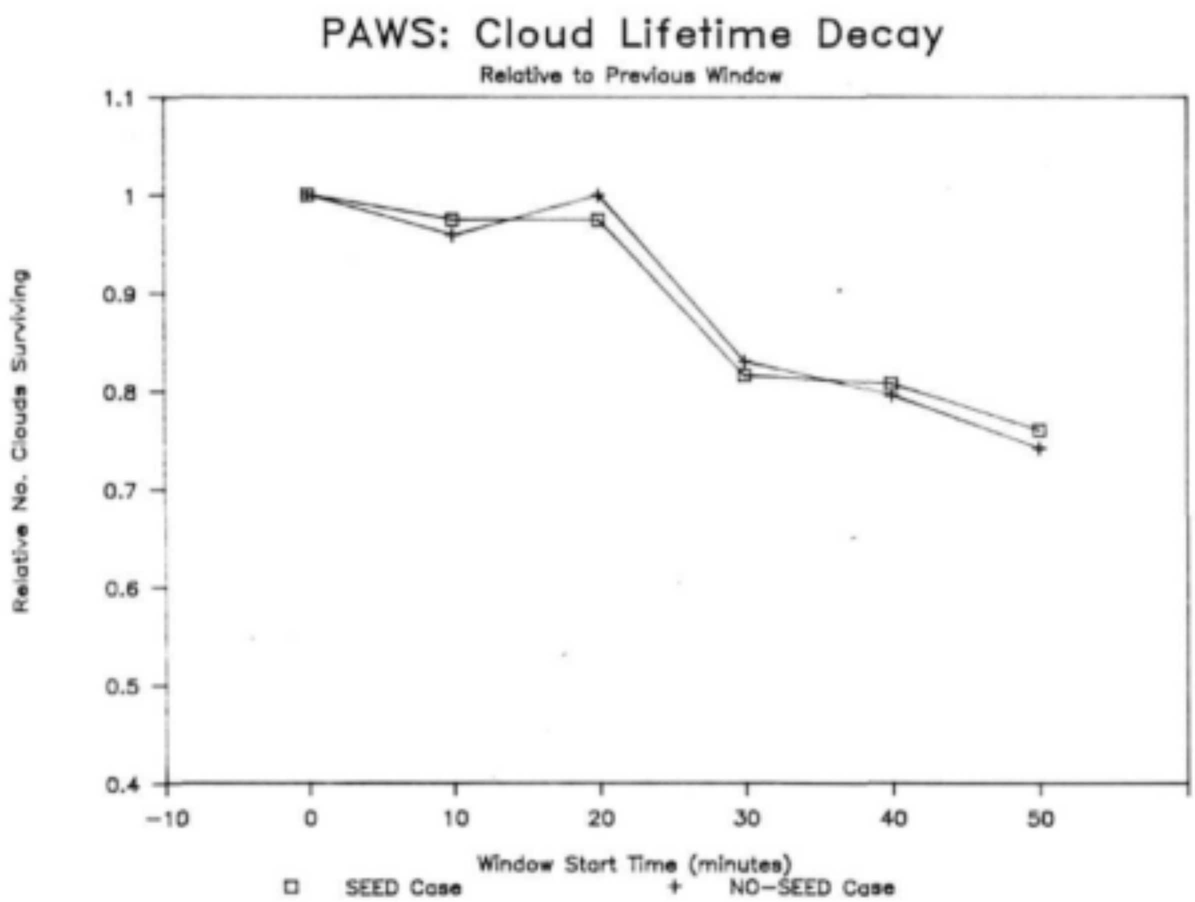

PAWS: Cloud Lifetime Decay
Relative to Previous Window
Relative No. Clouds Surviving
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
-10
0
10
20
30
40
50
Window Start Time (minutes)
SEED Case
NO-SEED Case

FIGURE 5.18

5.8 The route to a credible augmented rainfall time series

In this last section of this chapter we present a brief summary of our findings so far so as to set the scene for our proposal of a feasible route for the development of credible augmented rainfall time series. So far we have

* quantified positive mean seeding effects achievable in convective clouds during each of four ten-minute time windows spanning cloud lifetimes 20 to 60 minutes after decision time (Table 5.6);
* found that "outlier" storms do not dictate the finding of a positive seeding effect;
* shown that inter-storm seeding effects seem extremely variable and do not show any relationship with storm size as measured by mean rainflux;
* found indications that incremental rainflux growth in seeded storms remain dominant until 40 minutes after decision time, whereas, for no-seed cases, decay becomes dominant 10 minutes earlier;
* shown that the variability of rainflux growth of seeded storms is very similar to that of unseeded storms beyond 40 minutes after decision time, but is substantially different before that point;
* found that seeded and unseeded storms have nearly identical survival/decay rates;
* defined five crucial areas of data variability and statistical dispersion (section 5.6.3) that should form part of any attempt to develop credible modified rainfall time series:
    - individual storm seeding responses,
    - occurrence of seedable clouds on each day,
    - total daily seeding response at a point,
    - sub-areas "swept" out by seeded storms each day,
    - areal distribution of rainfall inputs into a catchment.

While designing a base-line methodology required for the reconstruction of time series in terms of seeding effects, we attempted to keep the five crucial areas of data variability in focus. The following sub-sections first relate the base-line methodology that seems feasible to us and then propose the route by which this methodology can be implemented.

5.8.1 Time series reconstruction methodology

This methodology represents a base-line approach (i.e. the least effort that we believe necessary for useful results) and could plausibly be extended as part of a comprehensive climatological assessment of long-term seeding impacts. The framework of the methodology is as follows:

(i) It is based on the full set of PAWS radar-derived storm tracks and time histories of all storm echoes that exceeded 30 dBZ on operational days during the period October 1982 to the present. Appendix B summarises the full PAWS data set and gives a useful overview of the total member of storm tracks on record.

(ii) It requires the selection of "target" sectors of the PAWS radar annulus which could serve as the focus areas of various cloud-seeding impact studies.

(iii) It requires the establishment, by appropriate methods (geostatistical interpolation techniques, surface-fitting methods), of daily rainfall time series for the above period of seven years, on a grid basis, for the selected "target" sectors of the PAWS radar annulus. For each day the daylight component of the rain needs to be estimated.

(iv) It requires the selection, by pre-screening, of the storm tracks of all "seedable" storms that overlap with the target sectors for the greatest part of their lifetimes - for each operational day, i, this storm number is denoted by N_i.

(v) It assumes that rainflux, as the integrator of both areal and intensity seeding effects, is an appropriate link with areal rainfall interpolated from point observations, and, along with (iv) above, accommodates the need to account for the statistical dispersion of areal rainfall distribution.

(vi) It attaches importance to the variation of mean seeding effects by 10 minute time windows during the life of seedable storm tracks.

(vii) It arbitrarily locates a "decision time" at 10 minutes after the first exceedence of 30 dBZ reflectivity.

(viii) It does not recognise any seeding effects during the first 20 minutes after decision time or beyond 60 minutes after decision time.

(ix) It accepts the coefficients of variation of incremental rainflux growth/decay for seed storms reported in Table 5.8, as well as the maximum and minima shown in Figs 5.15(a) to (d), as essential target parameters for the superposition of seeding effects as per Table 5.6.

(x) It assumes that seeding does not meaningfully increase total storm durations.

The following steps constitute the proposed methodology:

Step 1 : Remove all days with actual seeding operations from the total sample so that an "uncontaminated" no-seed sample ensues.

Step 2 : For each operational day of the remaining sample, remove all storms, n, with post-30 dBZ lifetimes shorter than 30 min, leaving a sample of $(N_i - n_i)$.

Step 3 : For each day, divide the $N_i - n_i$ storms into 10 minute windows and calculate the mean rainflux of each window. Divide the windows into pairs as shown in Table 5.8.

Step 4 : For each day, increase the mean rainflux of all the 20 - 30 minute windows by 15% and determine each incremental rainflux growth/decay relative to the relevant -10 - 0 minute window values.

Step 5 : Calculate for the total number of days in the sample the overall mean incremental rainflux growth/decay for the -10 - 0/20 - 30 min window pair and multiply by the C_v value of 3,0 (Table 5.8) to obtain an appropriate standard deviation.

Step 6 : By random sampling from a truncated Normal distribution with the above mean and standard deviation and truncated near the maximum growth and decay values shown in Figure 5.15(a), a new (and random) growth/decay value is generated for every -10 - 0/20 - 30 min window pair for every day i. If a random incremental decay larger than the initial mean rainflux is generated, then that value is suppressed and sampling repeated until a small enough value is generated. This generated value is now added to the -10 - 0 rainflux to produce a random "seeded" rainflux for the 20-30 window.

Step 7 : Repeat steps 4, 5 and 6 in turn for each of the time window pairs 20-30/30-40, 30-40/40-50, 40-50/50-60 with use of the relevant respective seeding effects 25%, 50%, 55% (Table 5.6), as well as the respective C_v values for incremental growth/decay 8,5 , (-)3,0 , (-)3,4 (Table 5.8) and the relevant truncations of the Normal distribution (Figs. 5.15(b) to (d)). For each window pair the newly derived "seeded" rainflux of the first member of the pair replaces the rainflux value derived by simple application of the percentage seeding effect referred to in Step 4.

Step 8 : For each day, sum the effective increase in total rainflux due to the imposition of random seeding effects as set out above. Express this increase as a percentage of the original total rainflux for the day, which can be called the "daily seeding effect", DSE_i , achieved on that day. In this way a large sample of daily seeding effects (as percentages) is developed.

Step 9 : On the assumption that the DSE, which is rainflux-related, would also be valid for spatially averaged rainfalls observed on the ground, an equivalent sample of daily rainfall increases in mm can be developed for the period under consideration. This is done by applying the DSE's to the daylight component of each day's spatially averaged rainfall over the sectors of interest.

Step 10 : By repeating Step 6, the relevant parts of Step 7, and Steps 8 and 9, many times over, say 100 or 1000 times, an equivalent number of quasi-independent samples of seeding-related daily rainfall increases can be developed for the period and the sectors of interest.

Step 11 : Devise a methodology by which these, say 100, samples can be used to develop 100 full daily "seeded" rainfall time-series for all feasible operational days during the period of interest. This step in our proposal we leave lacking in detail, because it requires a dedicated and in-depth research undertaking - which locates it outside the scope of our brief. The challenge here is to "fill in" the irregularly spaced days which make up the samples of seeding-related daily rainfall increases developed under step 10. This would convert these samples into daily time-series. For this step parallel historical data for the period of interest of all or some of the following types would be required:

- occurrence of treatable clouds on the days not covered by PAWS radar tracking : a satellite cloud sensus would be possible for the post - 1985 period as 30 minute meteorological satellite images are available (though not received by South Africa) from 1986 onwards,

- large-scale atmospheric systems and synoptic events,

  - daily weather type classifications similar to the approach followed by Hudak and Steyn (1978), based on upper air soundings and aircraft and automatic weather station reports.

The reader will note a complete absence of references to BPRP data in the foregoing proposals. We have not ignored the potential of BPRP in this regard, but decided to omit it at this stage because rainflux-based seeding effects have not yet been statistically proven. When BPRP reaches this point a similar methodology for rainflux time-series reconstruction should be feasible, depending on which, or whether, window concepts are used. Use of the BPRP radar cloud/storm track data set at this stage would necessitate use of surmised cloud-related seeding effects. If use of this promising storm track data set is desirable at this stage, then it seems more useful to seek a link between appropriate BPRP data and the derived PAWS daily seeding effects developed according to steps 9 and 10 above. In such a case selection of suitable "target" sectors of the BPRP radar annulus would also be required (see point (ii) above).

5.8.2 Requirements for the execution of this task

The development of modified rainfall scenarios in the form of reconstructed daily rainfall time series will require a researcher with specific skills and experience. The principal fields of interest are radar meteorology, satellite climatology and general cloud physics, while general competence in numerical modelling is a basic requirement. These requirements appear to be formidable but we believe that South Africa is currently in the fortunate position to have quite a few suitable researchers available for this task.

We estimate the duration of the execution of the base-line methodology described in section 5.8.1 as about 9 - 12 months, as a full-time undertaking. However, we believe this base-line study should be only the first stage of an extended climatological study into the long-term effects of large-scale cloud-seeding on rainfall. **The goal of this first stage is the earliest possible provision of plausible reconstructed rainfall time-series which could be used in impact modelling studies in agriculture, forestry and water resources.**

The infrastructure required for this study also deserves some attention here. Three requirements come to the fore:

* Close association without being constrained by institutional priorities, with both the PAWS and the BPRP research teams and free access to their data banks - the resources of these two projects are distributed between Pretoria, Nelspruit and Bethlehem.

* Low-cost access to powerful computing resources - a mini-mainframe or, at least, a "486" generation microcomputer running under an advanced operating system such as OS/2 or Unix with an ultra-large-screen colour monitor, large hard disk storage and tape-streaming utilities.

* Close collaboration with researchers in parallel impact studies in other disciplines, who might be based at a number of different locations.

We believe that three alternatives present themselves as possible bases for the responsible researcher:

(i) Inside the PAWS/BPRP infrastructure, which includes the CSIR.

(ii) In a university environment which meets certain specific requirements:

  * availability of general expertise in either meteorology (Dept. of Meteorology, Pretoria University) or climatology and related modelling (Climatology Research Group, Wits University), or expertise in statistical modelling of

meteorological and climatological processes (Prof W Zucchini, Dept. of Mathematical Statistics, University of Cape Town).

* parallel impact studies in other disciplines planned or in progress - recognising the risk of pre-judging this issue (which we deal with later in this report), we believe these might include the University of Natal (Pietermaritzburg) and the University of the Orange Free State, Potchefstroom University and, again, Pretoria University.

(iii) Secondment to a consultant's office which is favourably positioned in terms of the three infrastructural requirements mentioned in the previous paragraph and where in-house expertise in numerical modelling already exists. Our own firm offers such an environment.

Each of the above three alternatives holds certain advantages and disadvantages, which are also affected by whether this task is viewed in terms of only the base-line methodology set out in 5.8.2 or whether it is viewed in terms of a larger climatological study.

6. POTENTIAL END-USER IMPACTS AND RELATED RESEARCH ISSUES

6.1 Identity of potential end-users and impact fields

Water resources, agriculture and forestry are recognised as direct potential beneficiaries of augmented rainfall and are therefore described as end-users of the rainfall stimulation research results. The disciplines of meteorology, cloud physics and climatology are obviously also beneficiaries of the research, albeit mostly in the sense of research spinoffs in the areas of forecasting, instrumentation, training and general scientific advancement. The environment falls squarely in the impact category, but in the socio-political field impact seems less important than attitudes. Increased rainfall could furthermore have a meaningful socio-economic impact. And in the legal/administrative field the main impacts relate to potential exposure of desired improvements in the existing legislation in the areas of statutory control, indemnification and water rights.

Detailed impacts and related research issues in the end-user and environmental fields are explored in the following sub-sections in the context of the nature and magnitude of the attainable seeding effects discussed in Chapter 5 above. We recall the following salient points :

* only a proportion of all convective clouds are seedable
* very large (synoptic) storm systems are not seedable
* only cloud clusters/complexes are worth seeding
* average seeding effects are positive
* greatly variable responses from individual clouds
* rainfall increases more the result of increased storm areas than of rainfall intensity increases
* average seeding effects on daily rainfall a fraction of that attainable on individual clouds
* most likely target area is the eastern and south - eastern Highveld and the neighbouring Escarpment.

6.2 Water resources

The principal potential impacts in the water resources field that can reasonably be foreseen are as follows :

- increased reliability of yields of impoundments
- increased groundwater recharge
- increased base flow in rivers
- increased flood peaks in the small to medium range
- decreased variability of daily flows
- decrease in length of deficient flow periods
- increase in soil erosion/sediment yield if rainfall intensities are increased
- decrease in soil erosion/sediment yield if catchment vegetation is improved
- improved mineral quality of water in rivers and impoundments
- reduced supplemental irrigation requirements.

Potential impacts of somewhat lesser importance include the following :

- changed in-channel conditions, eg., riverine vegetation, channel losses, riverine biota, and channel morphology
- effects on runoff from neighbouring catchments
- changed groundwater chemistry.

During the course of our study we gained the impression that the potential impact of cloud-seeding on water resources was the most contentious of the three end-users. During the early years of South African cloud-seeding research, benefits to water resources were a foremost consideration. "Filling of dams", "increased reservoir yields", were popular concepts employed in the motivation of the research. More recently the realisation has dawned that these expectations were too ambitious. Analyses of rainfall patterns indicate that large dams are filled by macro-synoptic storms with high rainfall efficiencies - a scale of event not attainable (or desirable) through cloud-seeding. On the other hand, reservoir yields are determined by drought flow sequences and therefore relate to periods when a paucity of suitable clouds is likely.

Only cloud clusters/complexes appear suitable for seeding and, for such seeding to have maximum runoff generation effect, should follow in the wake of a large synoptic system when the catchment moisture conditions could be expected to be favourable for runoff generation. This might increase risks of flood damage during an already flood prone season, while during drier seasons the paucity of large-scale rainfall events might undermine this seeding tactic. A further uncertainty which awaits quantification is whether rainfall enhancement based on cloud clusters and complexes only can lead to sufficient recharge of groundwater at the regional scale so that base flow levels during droughts are sufficiently increased to register an improvement in the yield of a river system. Currently, potential water resources benefits are expected to be of a more marginal nature and the proposed impact studies should recognise this, as well as the forementioned set of issues.

6.3 Agriculture

Agriculture-related potential impacts include the following:

- increased dryland grain production
- reduced dryland grain production risks
- improved natural pasture (within fixed ecological domains)
- changes in natural pasture species composition
- increased fodder production
- increased grazing animal production
- improved availability of red meat
- improved dairy production
- reduced energy costs associated with supplemental irrigation
- changes in pest species composition
- increased soil erosion if increased intensities turn out to be a more dominant effect than is expected.

The benefits of augmented rainfall to dryland crop and pasture production stem mainly from the expected resulting reduction in frequency of incidences of plant stress related to deficient soil moisture. A crucial determinant of monocultural (eg. grain) crop yield is the exact timing of the moisture stress - for instance, it is well-known that maize production is highly sensitive to moisture stress at anthesis. Consequently, the impact of augmented rainfall will be much more pronounced if its timing coincides with anthesis, or preceeds it by a limited number of days. A further crucial consideration is that monoculture does not exist at macro-scale in the relevant target area and that crop diversity enforces conflicting tactical requirements in terms of the timing of augmented rainfall for maximum impact on yields. In brief, a grain farmer might welcome seeding-related rainfall in January while a neighbouring potato farmer might regard rain at that time as potentially damaging. Impact studies will have to take cognisance of such conflicting spatial needs.

At the micro-scale, however, the potential benefit to, say, grain production is undeniable. De Jager (1989), employing the PUTU growth model with a daily meteorological time series for Bethlehem, demonstrates that a blanket 20% increase in daily rainfalls would result in a long-term wheat yield increase of 30% . The corresponding increase in maize yield is 35% . When considering these figures one should allow for the fact that De Jager's assumed modified rainfall scenario is too optimistic. In Chapter 5 we show that the attainable mean seasonal areal seeding effect is not likely to exceed 10% . On the other hand, we also show that individual seeding responses sometimes far exceed the mean, which might, in cases of fortuitous timing, have an extraordinary effect on yields - an effect which the De Jager study does not emulate successfully. This discussion, despite its brevity, underlines that additional to the spatial considerations we touched on in the previous paragraph, there exist point or micro-scale considerations for dryland crop yield responses which warrant careful research probing in impact studies.

The potential benefit of natural pasture production improvement is ultimately manifested in the production benefit for the grazing animal. Quantification of this benefit is somewhat less straightforward than for a monocultural crop, for the following reasons (Booysen,1990):

* changes in rainfall would trigger changes to the composition of the species in a natural system - these changes would determine the quantity and quality of plant production and thus animal production

* the growth period and phenological triggers for any given species vary considerably depending on its environment and its ecological status in that environment

* production estimates are not very meaningful unless the time of availability, and the nutritional value of the produced phytomass at that stage are analysed

* historical deterioration of veld condition and of the associated species composition results in permanent modification of the habitat of the pasture - these modifications limit veld condition improvements attainable under more favourable regimes such as might result from augmented rainfall.

These considerations dictate that impact studies on natural pastures and grazing animal production should follow a systems approach, progressing from habitat and species identification studies in the target zone, through veld condition assessments to, first, phytomass production and, then, animal production.

6.4 Forestry

The potential impacts in the forestry field are :

- increased timber production in recognised prime areas in the relevant target corridor
- reclassification of much marginal land to prime forestry land, leading in turn to increased timber production
- increased timber production from marginal land
- changes in tree species composition in the target zones
- accelerated conversion of "agricultural" land to forestry
- changes in pest species composition.

Timber production in prime areas (mean annual rainfall greater than 950 mm) is much less sensitive to the timing of moisture stress (or its alleviation) than is the case for agricultural yields. Consequently, tactical seeding in these prime areas is expected to be less of a consideration from a forestry perspective. Also, different species that are in close proximity do not present the same dilemma in terms of conflicting soil moisture replenishment requirements. However, in marginal areas timber yield is sensitive to soil moisture deficits. Augmentation of rainfall could therefore increase the timber production in two ways: increase the amount of land that could be regarded as having afforestation potential and increase the yield of existing plantations.

In general, it appears that forestry is one of the most promising end-users of cloud-seeding technology, given the robust nature of its soil moisture replenishment requirements and its perennial growth cycle. Roberts (1989), using simple growth models, illustrates this fact by showing that a 10% increase in mean annual rainfall translates into an increase in yield from existing plantations of R153 million per annum (standing timber). Similarly, he estimates an increase in area potentially suitable for afforestation of one million hectares. Even if we allow for the fact that Roberts includes many plantations and marginal areas that lie outside the target corridor, his figures suggest a potential benefit to the country that deserves close research scrutiny.

6.5 Environment

The long-term structure of the dynamic equilibrium that characterises healthy ecosystems is a response to average climatic conditions. Consequently, the small magnitude of the mean rainfall increases attainable by cloud-seeding suggests that environmental impacts on individual entities could be expected to be small and quite subtle.

Two categories of environmental effects are possible: direct and indirect. Direct effects result from the addition of chemicals such as silver iodide to the environment in the seeding program. It is likely, in the light of the PAWS results achieved with dry ice, as well as the lack of evidence in the BPRP of any superiority of silver iodide over dry ice, that silver iodide will not be used at the operational scale in the target area. Nevertheless, studies elsewhere (Montana State University, 1973) have indicated that neither absorption nor reduction in growth could be shown for crop plants growing in soils enriched with up to 10 000 ppm of silver iodide. The absence of absorption suggests that there is little possibility of concentration of silver up the food chain. A check that silver deposited in seeding might not somehow be transformed by physical or biological processes to a more soluble, and more dangerous form, was done by repeating the forementioned study with silver nitrate - which is 4×10^{10} times more soluble than silver iodide. Transformation rates this extreme are highly unlikely, but even so it was found to be unlikely that silver effects would be detectable after 1000 years of seeding. If silver iodide should remain in contention as a seeding agent, the forementioned study should be extended to include aquatic ecosystems and higher terrestrial organisms.

Indirect environmental effects of cloud-seeding are those that result from biological responses to the change in climate produced by the seeding operation - popularly referred to as the "bio-feedback loop". A considerable volume of literature exists on the relationship of biological sub-systems to weather, some specifically aimed at the weather modification community - most of the latter highly speculative, due to an almost nonexistent data base. For our orientation we found a summary report from Kansas State University (1978) particularly enlightening.

Ecological effects of successful cloud-seeding would be the result of moderate shifts in rates of reproduction, growth, and mortality of weather-sensitive species of plants and animals. These shifts would not be sudden, as plant and animal communities change rather slowly in response to moderate changes in climate. The cumulative effect of slow year-to-year changes in species abundance could be a rather extensive alteration of the original condition, but the change could take place almost unnoticed by the public. The combined effect of such stresses as air pollution, pesticide application, and other environmental changes might interact with rainfall stimulation in such a way that the total effect will be substantially greater than the sum of the individual relatively small alterations.

The prospect of complex ecological interactions is one of the most important considerations in assessing the probable consequences of environmental change due to rainfall stimulation. We have already intimated this point (in section 6.3 above) in the context of natural pasture responses to augmented rainfall. It now seems logical that cloud-seeding impact studies relating to natural pasture production should perhaps be seen **as a prime base-line task in a wider ecosystem response appraisal.**

Such an appraisal would have to contend with the reality that rainfall augmentation would be a perturbation imposed on an already variable climate, which would make quick detection of effects quite unlikely. This problem would be accentuated by the natural fluctuations in species populations of plants and animals in a variety of habitats. The impact of rainfall stimulation would be superimposed on these. Clearly, these issues make base-line ecosystem data gathering exercises in the target area a mandatory prerequisite before any field studies supporting such an ecosystem response appraisal could be planned. These base-line situation assessments would have to be conducted along transects in a regional context and would have to cover several phases of the environment, emphasising those phases relating to natural pasture, agricultural pests, erosion-controlling natural vegetation, certain aquatic sub-systems and conserved wildlife. It is perhaps comforting to note that a South African endeavour along such ambitious lines would not have to start from scratch. Several volumes in the South African Scientific Programmes Report Series sponsored by the CSIR's Foundation for Research Development are promising initiating documents. Specifically notable are the famous Red Book Series and various syntheses on South African Grasslands, Savannah and Inland Water Ecosystems (Macdonald and Crawford, 1988).

In the course of our investigation we have gained the impression that small-scale studies of the environmental impacts of rainfall stimulation would provide answers so slowly and piece-meal that we have to question their value. On the other hand, we feel somewhat pessimistic about obtaining even just the base-line data base at a reasonable cost in Rands and scientific man-years. Additionally, it seems that amongst the identifiable potential environmental impacts, the only distinctly negative one is a potential increase in agricultural pest populations. All other potential ecological impacts seem either neutral or beneficial. This set of considerations leads us to conclude that only two categories of environment-related studies warrant consideration in the target area:

* natural pasture response studies in an ecosystem context as suggested earlier
* agricultural pest response studies.

6.6 The three end-user impact study routes

At the start of Chapter 5 we introduced the **three routes** by which rainfall stimulation impact studies in the **end-user** fields could occur. Here we would like to flesh these concepts out further and link them to priorities and to the state-of-the-art in each field.

Figures 6.1 and 6.2 provide an overview of these concepts and their inter-relationships.

Route (i) field experiments under conditions of operational cloud-seeding relate to direct forms of measurement of the effects of cloud-seeding on runoff, crop, pasture/animal and timber production in well-instrumented catchment areas inside the target zone. Such experiments would require forms of control such as paired catchments without cloud-seeding or historical pre-seeding observations in the same catchments. A further complication is the conflict inherent to the mandatory hydrological interest of "stable" land-use as opposed to the fluctuations imposed by large-scale crop cultivation and harvesting. This conflict would be much less prevalent in afforested catchments.

Having noted the consensus in the South African cloud-seeding community that there still exists an obligation for vastly improved understanding of local microphysical and meso-scale cloud processes before operational rainfall stimulation can take off, we believe that Route (i) experiments will only be feasible quite far in the future - probably more than five years from now. However, if the Route (i) field experiments necessitate the development of pre-seeding time series of rainfall, runoff, crop yields, etc., as control data, then Route (i) research could need to be initiated without much delay so that such control data might be adequately assembled by the time cloud-seeding is expected to become feasible at the catchment scale. Route (i) field experiments might further be highly dependent on successful preceding research into measurement problems relating to ground-level **rainfall observations by radar**, research into problems relating to **geostatistical interpolation** of point rainfalls and research into increased **accuracy of river flow measurement.** Such supporting research might be mandatory for the successful interpretation of results in Route (i) field experiments.

Route (ii) experiments consist of simulating cloud-seeding effects by some form of supplemental irrigation. This would only be a plausible approach for crop yield studies at the plot or lysimeter

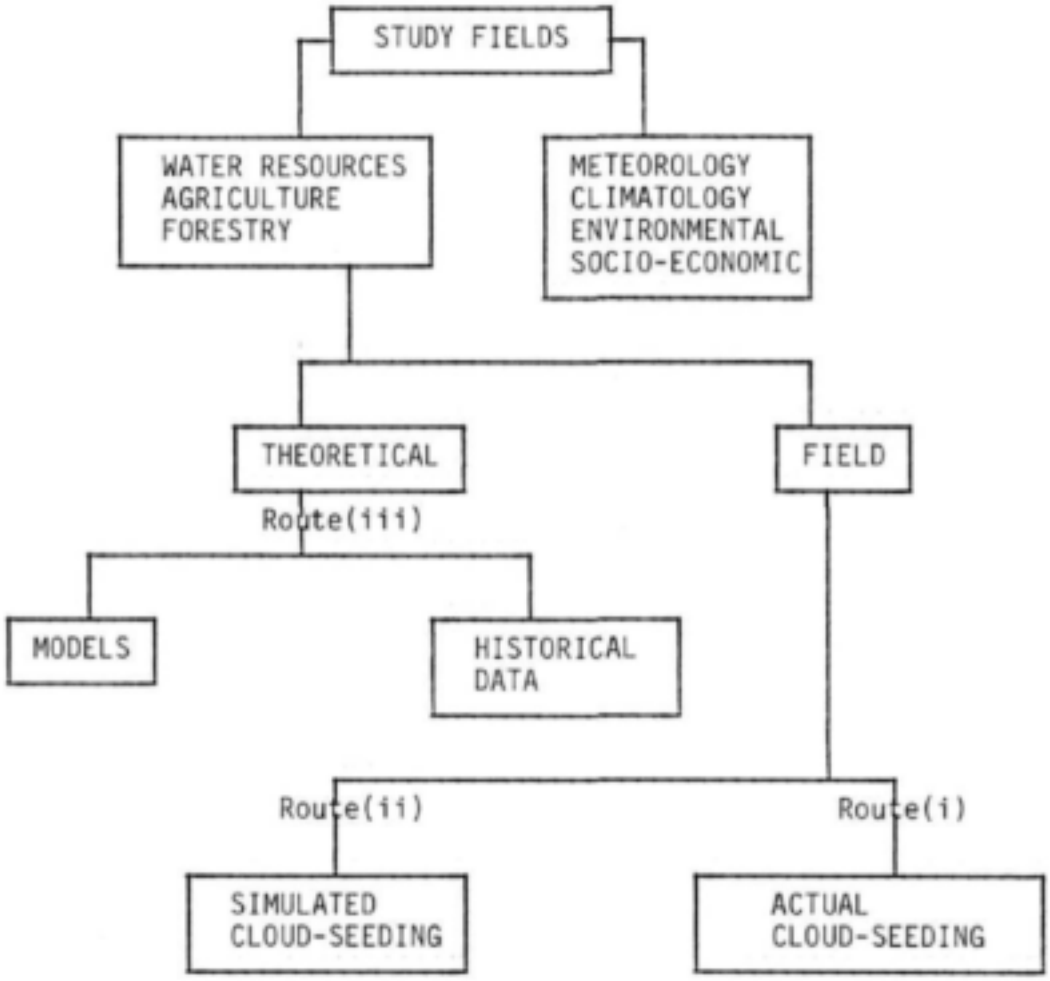


FIG 6.1 : **FLOW DIAGRAM OF PROPOSED IMPACT STUDY ROUTES**

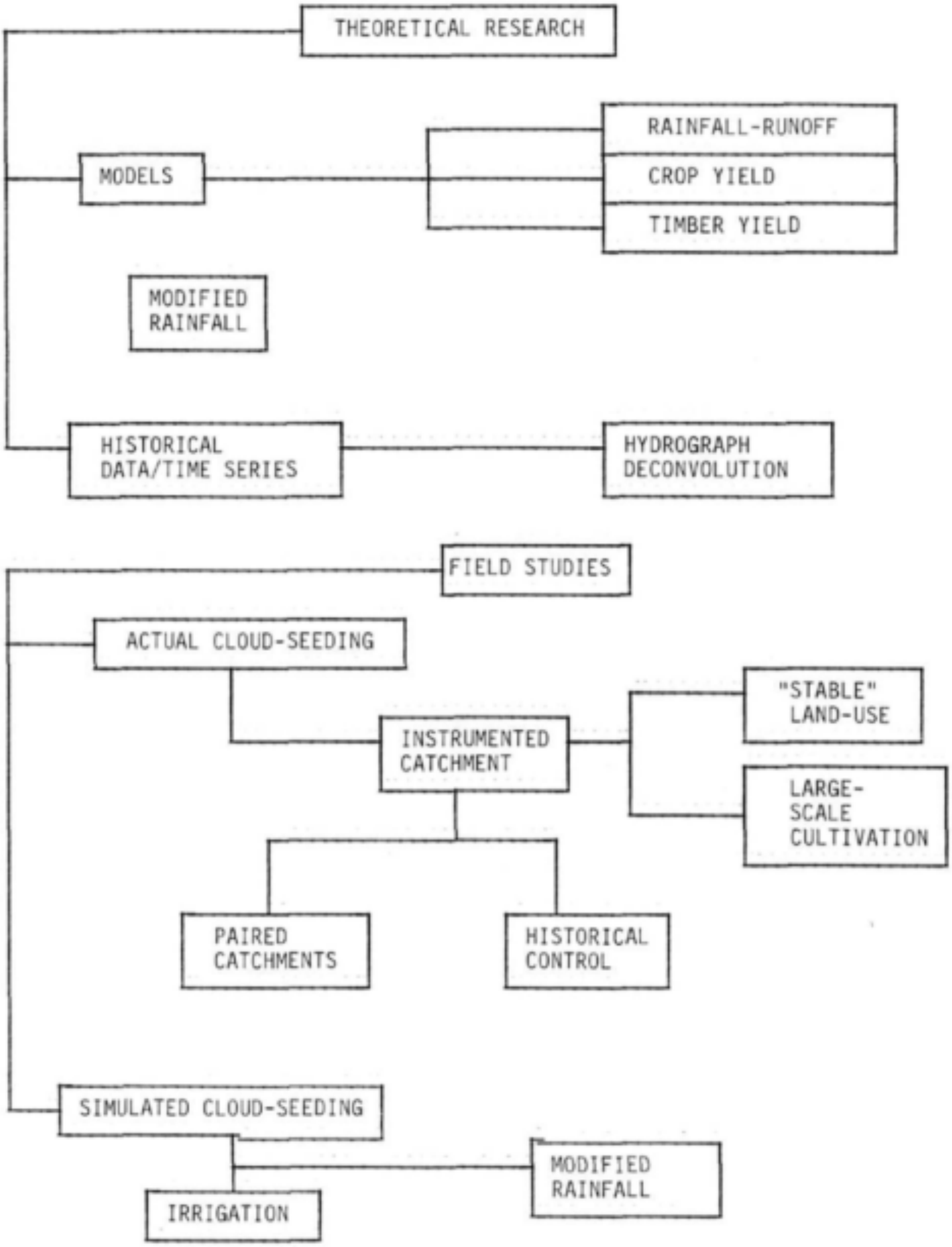


FIG 6.2 : **FLOW DIAGRAMS OF THEORETICAL IMPACT STUDIES AND OF FIELD STUDIES UNDER ACTUAL CLOUD-SEEDING CONDITIONS**

scale. The supplemental irrigation pattern would be based on plausible seeding effects related to the actual occurrence of storms in the vicinity. Clearly, very close monitoring of the micro-physical suitability for hypothetical seeding of the prevailing clouds would be required. Needless to say, controls that do not receive supplemental irrigation would be essential to make sense of the experiment. Such Route (ii) experiments could be planned for immediate initiation, given that credible rainfall modification scenarios could be formulated. We doubt that these experiments would provide more reliable results than what can be achieved with crop growth models - especially when we consider that they are mere point estimates and do not enlighten us as to the spatial impacts of cloud-seeding on crop production.

Route (iii) experiments are based on theoretical or desk-top assessments of the effects of enhanced rainfall on end-user yields. As the state-of-the-art of the various numerical models applicable to Route (iii) appears to be suitably advanced for this research, these experiments could be planned for immediate initiation. It should be noted that Route (iii) experiments might require various levels of field investigations, ranging from mere field measurements of crucial input data for the models, to yield/growth observations appropriate for model (and impact) verification. We believe that Route (iii) studies are essential to confirm or disprove the potential benefit of rainfall stimulation in the various end-user fields at a moderate research investment. Given the high-risk nature and the magnitude of the investment required to launch a quasi-operational cloud-seeding venture for Route (i) field experiments, it seems more than prudent to follow the desk-study route first. The sub-section below is dedicated to yield/growth modelling expertise in South Africa in the various end-user fields as a confirmation of its importance to this planning study.

6.7 Yield/growth modelling expertise in South Africa

The following discussion is based on the supposition that development of credibly modified rainfall time series that reflect cloud-seeding effects would be feasible and available to the end-user modellers.

6.7.1 Water Resources

Referring to 6.2 above we short-list three primary impacts relevant to the water resources field:

* increased reliability of firm yield of large impoundments (multi-year critical periods)
* increased yields of farm dams (critical periods less than one year)
* increased groundwater recharge.

We are optimistic that theoretical quantification of the two primary impacts on surface resources could proceed quite smoothly, but groundwater recharge impacts would present severe problems in this regard. Although foremost expertise in groundwater modelling is resident at the Institute of Groundwater Studies of the University of the O.F.S. and in the Directorate of Geohydrology of the Department of Water Affairs, such a study would be faced by three severe handicaps:

- the scale of the potential recharge impacts: In the target zone groundwater recharge encompasses a few percent of total mean annual rainfall. With the average seeding effect expected to be less than 10% on mean annual rainfall, it is clear that the eventual impact on groundwater recharge is likely to be so small as to lie inside the accuracy limits of even the best quantification approaches.

- the fact that groundwater in the area mainly resides in fractured rock aquifers, the spatial characteristics of which are ill-quantified and spatially highly variable

- the scarcity of time-series data on groundwater levels and yields in the target area.

We consequently do not consider impact studies on groundwater recharge as deserving of a high priority.

It is our view that there are essentially two routes by which impacts on streamflow (and therefore on dam yields) could be investigated through desk-studies:

* distributed rainfall-runoff modelling
* recursive analysis and "seeding" of historical streamflow data series.

(i) **Rainfall-runoff models** suitable for use in impact studies would need the following primary characteristics:

- daily time series input requirements, to match the resolution of the seeding-related modified rainfall; a monthly resolution would not do justice to a high frequency of small daily seeding effects
- physically-based structure so that calibration requirements are minimal, enabling a spatially distributed discretisation of catchments
- continuous moisture budgeting, sensitive to land-use.

Rainfall-runoff modelling expertise is well-grounded and distributed in South Africa in the academic, research, public and consulting sectors. Conceptual lumped modelling, usually at a resolution of one month, is the preferred approach for yield studies in the public and consulting sectors because of modest data requirements and value-for-money benefits. The well-known Pitman catchment model (1973, 1976) and its derivatives are arguably the foremost exponents of this approach in general use. We doubt that the Pitman model, even in daily mode, would be an adequate vehicle for streamflow impact studies because its structure and controlling parameters, though conceptual, are not physically-based in a way that allows *a priori* choices of parameter values without calibration. Consequently, its use in a distributed mode is not feasible.

There is, however, a way in which the Pitman daily model might be considered : if the requirement for minimal calibration is cancelled. This might be a plausible approach in the case of a recconaisance study of seeding-related impacts on large reservoir yield, to determine fairly quickly if a more intense investigation is warranted.

Maaren (1984) reports use of ALDO, a simple, but imaginative conceptual daily model with emphasis on the infiltration and plant water use components - developed at the Hydrological Research Institute - which accommodates spatial variability of catchments on a grid basis. Refinement of this model was unfortunately ceased and it is therefore not in contention.

The only continuous rainfall-runoff model in South Africa that approximately meets the three criteria mentioned earlier, is the quasi-physically-based ACRU model, developed by Schulze (1985). This model has daily layered soil-moisture budgeting that recognises the soil form/texture class as controlling, calculates storm runoff on a SCS Curve Number basis, recognises land-use, and can be configured in a quasi-GIS mode to implement spatial variability in physical, land-use and rainfall characteristics. Furthermore, it complements the runoff simulation with various crop yield and timber growth modules. Its principal weakness is a rather primitive treatment of the delivery of deep percolation from beyond the root zone to the stream channel.

We believe that the ACRU model holds promise as a tool for desk-studies of cloud-seeding impacts on streamflow and, by extension, on both farm dam and large reservoir yields. To this might be added its versatility relating to crop and timber production, as well. A relevant consideration is where expertise with the ACRU model currently resides. We have drawn up a short-list of organisations in order of priority where this is the case:

- Department of Agricultural Engineering, University of Natal (Pietermaritzburg) : Prof R. Schulze and staff

- Ninham Shand, Randburg : Ms W. George

- Hill, Kaplan, Scott, Pietermaritzburg : Mr E Schmidt

- Computer Centre For Water Research, University of Natal (Pietermaritzburg) : Dr M. Dent

- Steffen, Robertson and Kirsten, Johannesburg : Mr C. Schultz

(ii) **Recursive historical streamflow** time series analysis presents a promising approach for impact studies. The available streamflow series in gauged catchments in the target area is divided into discrete runoff events by hydrograph separation methods - the deconvolution methods proposed by Cousens (1980) and Pegram (1984) are particularly appropriate. Each discrete hydrograph is linked to a causative rainfall day for which a net cloud-seeding-related rainfall increase has been generated as part of the modified rainfall scenario development. The linking of this rainfall increase to the corresponding hydrograph will be a key research thrust in this approach. The expertise for this work resides in three locations:

  - Department of Civil Engineering, University of Natal (Durban) : Prof G. Pegram

  - Department of Mathematical Statistics, University of Cape Town : Prof W. Zucchini

  - Department of Civil Engineering, University of Pretoria: Prof W. Alexander.

6.7.2 Dryland grain crops

Grain crop growth simulation models suitable for use in impact studies would need to conform to at least two primary criteria:

- daily time series input requirements, to match the resolution of the modified rainfall scenario; a particular data requirement is that of daily sunshine duration rather than daily global radiation inputs as the former is much more commonly observed in South Africa

- quasi-mechanistic, physiology/genetics-based representations of processes so that empiricism does not impede the implementation of the model in varying environments; this obviously also excludes calibration requirements.

Three grain crop growth models in use in South Africa in recent years meet these two criteria to varying degrees:

(i) **PUTU** - a local model under continuous development at the University of the O.F.S. since the 1970's (see eg. De Jager, Van Zyl, Kelbe and Singels, 1987), verified for both wheat and maize with daily and hourly input resolution/soil moisture budgeting, and operational with the following daily data inputs:

total sunshine duration
total rainfall
maximum temperature
minimum temperature.

Growing conditions must be initialised; details required for maize are:

cultivar
heat unit requirement: planting to 50% silking

planting date
plant density .

Soil properties are defined by :

soil moisture extraction curve of the given soil
effective maximum rooting depth
permeability of water impermeable layer
depth of root impermeable layer
soil moisture content on Jan.1 or March 1 of planting year.

Eight growth stages are simulated: pre-rest period, rest period, tillering, stem extension, booting, anthesis, grain-filling and ripening.

(ii) **CERES-MAIZE** - a Texan maize growth model by Jones and Kiniry (1986), tested and improved in Australia and now being improved and validated by the Grain Crops Research Institute at Cedara (Houston, Mallett and Fleischer, 1989), with daily input and soil moisture budgeting resolution and with the following daily input requirements:

radiation
rainfall
minimum temperature
maximum temperature.

Genetic inputs of maize cultivars that are required:

growing degree days from seedling emergence to the end of the juvenile phase
photoperiod sensitivity
growing degree days from silking to physiological maturity
potential number of kernels per plant
potential kernel growth rate.

planting date
plant density .

Soil properties are defined by :

soil moisture extraction curve of the given soil
effective maximum rooting depth
permeability of water impermeable layer
depth of root impermeable layer
soil moisture content on Jan.1 or March 1 of planting year.

Eight growth stages are simulated: pre-rest period, rest period, tillering, stem extension, booting, anthesis, grain-filling and ripening.

(ii) **CERES-MAIZE** - a Texan maize growth model by Jones and Kiniry (1986), tested and improved in Australia and now being improved and validated by the Grain Crops Research Institute at Cedara (Houston, Mallett and Fleischer, 1989), with daily input and soil moisture budgeting resolution and with the following daily input requirements:

radiation
rainfall
minimum temperature
maximum temperature.

Genetic inputs of maize cultivars that are required:

growing degree days from seedling emergence to the end of the juvenile phase
photoperiod sensitivity
growing degree days from silking to physiological maturity
potential number of kernels per plant
potential kernel growth rate.

Soil conditions are defined by:

drained lower limit
drained upper limit
saturated water content
effective rooting depth.

Four sets of growth processes are simulated:

phenological development
extension growth of leaves, stems, and roots
biomass accumulation
partitioning.

(iii) ACRU - the agro-hydrological model mentioned in 6.7.1 possesses crop yield functions for winter wheat and grain. ACRU has a daily input and soil moisture budgeting resolution and the following daily input requirements:

rainfall
mean temperature
A-pan evaporation.

The generic phenologically-based grain sub-model is driven by growing degree days and is a function of accumulated potential evapotranspiration from the top- and subsoil horizons for the duration of the active growing season. Specific growth controlling inputs for maize are:

growing degree days from emergence to flower initiation
growing degree days for flowering stage
growing degree days from end of flowering to maturity
crop coefficients for the full growth cycle
planting date.

Soil conditions are defined per layer, where applicable:

effective rooting depth and depth distribution
porosity, field capacity, wilting point, stress ratio
drainage factors for field capacity excess and groundwater outflow.

Three growth stages are recognised:

emergence to flower initiation
flowering stage
end of flowering to maturity.

The phenologically-based winter wheat sub-model has an identical form to that for maize but is driven by the number of days since planting, instead of by growing degree days. The three growth stages recognised are:

emergence to jointing
jointing to soft dough
soft dough to maturity.

The main thrust of rainfall stimulation impact research through implementation of any of these three models would be in taking account of the **spatial variability** of dryland grain crop growth resulting from the spatial variability of soil conditions, rainfall inputs and general meteorological variables. Here the ACRU model holds an advantage in that it is specifically configured to suit the quasi-GIS-type of approach implied by the foregoing statement. A crucial source of spatial information of that section of the target zone that falls inside the Highveld Region of the Department of Agriculture, is the landmark description of the dryland agricultural potential of this region by Scheepers, Smit, and Ludick (1984). They divide, map and characterise the 219 land types in the region into 57 reasonably homogeneous farming areas ("**RHFA's**") and a large number of ecotopes.

Additionally, they report the potential yield of these resource units for maize, wheat, grain sorghum, sunflowers, dry beans, potatoes, and groundnuts. Unfortunately, no such synthesis has yet been done for the Transvaal Region, to which a large part of the target area belongs.

Expertise in each of the grain growth models described above resides as follows:

- PUTU : Department of Agrometeorology, University of the O.F.S. : Prof J. De Jager and his research staff
- CERES : Grain Crops Research Institute, Cedara : Dr J. Mallett and his research staff
- ACRU : Department of Agricultural Engineering, University of Natal, Pietermaritzburg : Prof R. Schulze and his research staff
- ACRU : Ninham Shand, Randburg : Ms W. George.

6.7.3 Dryland Pasture

Dryland pasture growth simulation models would be subject to the same two requirements identified in 6.7.2 above for dryland grain growth models. Two models in use in South Africa in recent years meet these two requirements to varying degrees: PUTU (Booysen, 1983) and PUK/EI (a suite of grass veld production models developed at Potchefstroom University; Bosch, 1988; Smuts, 1989; Naude, 1990). However, a third criterion must be applied in the case of pasture growth simulation:

- the modelling approach must allow for the dependence of the growth periods and phenological triggers of a diversity of species on the degradation level of the environment and on their ecological status in that environment.

No single model meets this third criterion convincingly, though the PUK/EI approach seems, through a process of continual refinement, to be on course to this goal. It is likely that rainfall stimulation impact modelling on pasture will require a hybrid modelling approach in which the best features of existing models become integrated. We refer to our assessment of the requirements for potential impact studies in the pasture section of section 6.3 above and would like to stress the need for a wide-angled modelling/field survey approach to deal with the complexities of species compositions, environmental/grazing degradation gradients and phytomass loss components.

It seems that the right mix of multi-disciplinary expertise appropriate to this undertaking resides only at one location:

- Department of Plant Sciences, Potchefstroom University : Prof O. Bosch and Dr J. Booysen

6.7.4 Timber

Dynamic timber growth simulation is at present less systematised than modelling in the other end-user fields and some development work to this end would be necessary for rainfall stimulation impact assessment in this field. Fortunately, field studies of the relationship between growth and site factors/consumptive water use for a number of tree species have pointed the way and await synthesis with a dynamic soil-moisture budgeting type of model. The first such steps have been taken with the ACRU model along two routes.

In the first of these, Schulze and George (1986) investigated afforestation (Pinus Patula) effects on water yield. The dynamic nature of land use change by the growth of forest is expressed by temporal changes in leaf area index (LAI), the ratio of actual to potential evaporation, interception loss and the proportion of roots in the A-horizon. These values were input as monthly data in a so-called dynamic land-use file which spans the full lifetime of the trees in question (18 years in this case). Although successful in terms of its own goals, this attempt did not provide a link with timber production as such.

The link with timber yield (as utilisable volume) was made by Boden (1987) when he showed that cumulative actual evapotranspiration (AET) for Eucalyptus grandis as calculated by ACRU could be shown to be firmly correlated with utilisable volume as measured at seven sample plots within the seven main areas where this species is grown, covering a range of soil depths and mean annual rainfalls. The growth periods modelled varied from 8 to 12 years. An important deficiency in ACRU is the inability to account for water taken up from the groundwater store (eg. Eucalyptus grandis is known to tap groundwater over 7m deep). Also, simulation of the effects of litter interception should improve model verification success.

In summary, it is clear that for the time being timber growth components of models like ACRU would not be physiologically based, but might rather be fairly empirical.

Expertise in this form of timber growth modelling seems currently to be tied to expertise in ACRU applications in this field or to forestry researchers with an interest in consumptive use by trees. These are:

- Department of Agricultural Engineering, University of Natal (Pietermaritzburg) : Prof R. Schulze

- Ninham Shand, Randburg : Ms W. George

- Division of Forest Technology, CSIR, Stellenbosch : Mr J. Bosch

- Commercial Forestry Research Institute, University of Natal (Pietermaritzburg) : Prof P. Roberts and his research staff.

6.8 The need for common goals in end-user impact research

The design of the different end-user impact modelling (route (iii)) studies must not be allowed to lose touch with their common ultimate goal :

to calculate the total net economic benefit of rainfall stimulation for the whole or identical parts of the target area for a representative set of primary end-users.

Assurance of commonality can be achieved only if four conditions are met:

* the desk-studies in the three end-user fields must share identical sub-catchment boundaries even though each may address a different land surface inside each sub-catchment

* each desk-study must produce results that are areally integrated for each sub-catchment, i.e. point impact results are not adequate

* conflicting claims between end-user fields for new land for expansion, eg. between plantations and pastures, must be resolved for each sub-catchment before desk-studies reach an advanced stage

* conflicting requirements for soil moisture replenishment between different components of the same end-user group, eg. agricultural crops, pit one component against another in the same group and must also be resolved at an early stage.

The total net benefit is of course the necessary first part of a "first approximation" benefit-cost analysis of operational cloud-seeding over the target area - a crucially important decision-making moment in rainfall stimulation research planning in South Africa.

We surmise that the best route for the integration of the individual end-user desk-study results, the subsequent conversion to monetary value, the cost analysis of operational cloud-seeding in the target area and, most importantly, deductions about optimised operational cloud-seeding in the target area would be via a two-day workshop attended by a small group of end-user researchers, representatives of the cloud-seeding community, planners in end-user state departments and the relevant WRC staff. To ensure conclusive cost-benefit decision-making by the workshop, it should be preceded by careful collation of the model findings on end-user yield impacts, a review of marginal cost structures in the four end-user fields and a thorough assessment of operational cloud-seeding costs - preferably by an ad hoc one- or two-man "expert" consultancy.

Hitherto we have referred to the "target area" in a rather poorly defined fashion. Clearly, the last task outstanding in this chapter is the systematic consideration of a plausible target area for operational cloud-seeding and, in context, for the end-user impact modelling studies we examined earlier in this chapter.

6.9 A plausible target area

In the course of our investigation we asked a wide range of scientists, research coordinators and planners/ administrators in the cloud-seeding and the end-user fields to define what they regard as a plausible target area for operational cloud-seeding. We were struck by the high degree of consensus that an extended corridor about 500 km long running through Nelspruit and Bethlehem (and beyond at either end), would be a rational choice for this purpose. In some instances the respondents might have been merely latching onto the historical fact of the respective locations of the existing cloud-seeding research projects at Nelspruit and Bethlehem. However, upon further probing, we found that examination of the grounds for choosing this corridor as target required recognition of fifteen individual considerations:

- Seedability of clouds/applicability of PAWS/BPRP findings

- Seeding opportunity/frequency of seedable clouds
- Topography and favourable forcing at meso- and synoptic scale
- Atmospheric moisture abundance
- Headwaters of major river systems
- Significant existing timber plantations
- Significant areas of "good" and "marginal" land suitable for timber expansion
- Dryland crop potential
- Meteorological monitoring infrastructure
- Streamflow monitoring infrastructure
- Radar coverage
- Socio-economic attractions/inhibitors
- No-go and international territories
- Airport facilities.

The target zone under discussion is depicted in Fig. 6.3, showing magisterial and main river catchment boundaries. It can be seen that the northern and north-eastern parts of the target corridor includes the escarpment while the southern parts are pure Highveld.

An obvious starting point for this exercise is to consider if the clouds in the target corridor can be expected to show **a seeding response of increased rainfall.** We accept that the PAWS results indicate a positive mean seeding effect on rainflux (areal rainfall) from convective clouds for a large part of the northern half of the corridor. In the southern half the BPRP has not yet reached any conclusions about seeding effects on rainfall, but proof was obtained that the micro-physics of target convective clouds shows promising changes after seeding. It is not clear yet whether the dominant rainfall-producing mechanisms can be regarded as similar in either half. If so, then the PAWS success indicates that a positive seeding effect would also be likely for BPRP.

The **frequency of occurrence of daytime convective clouds** inside the target zone is the next consideration of importance. The average number per operational day in the BPRP is about 100 (Steyn, 1989) and in PAWS it is about 90 (SWA and CIC, 1986b). Of more relevance

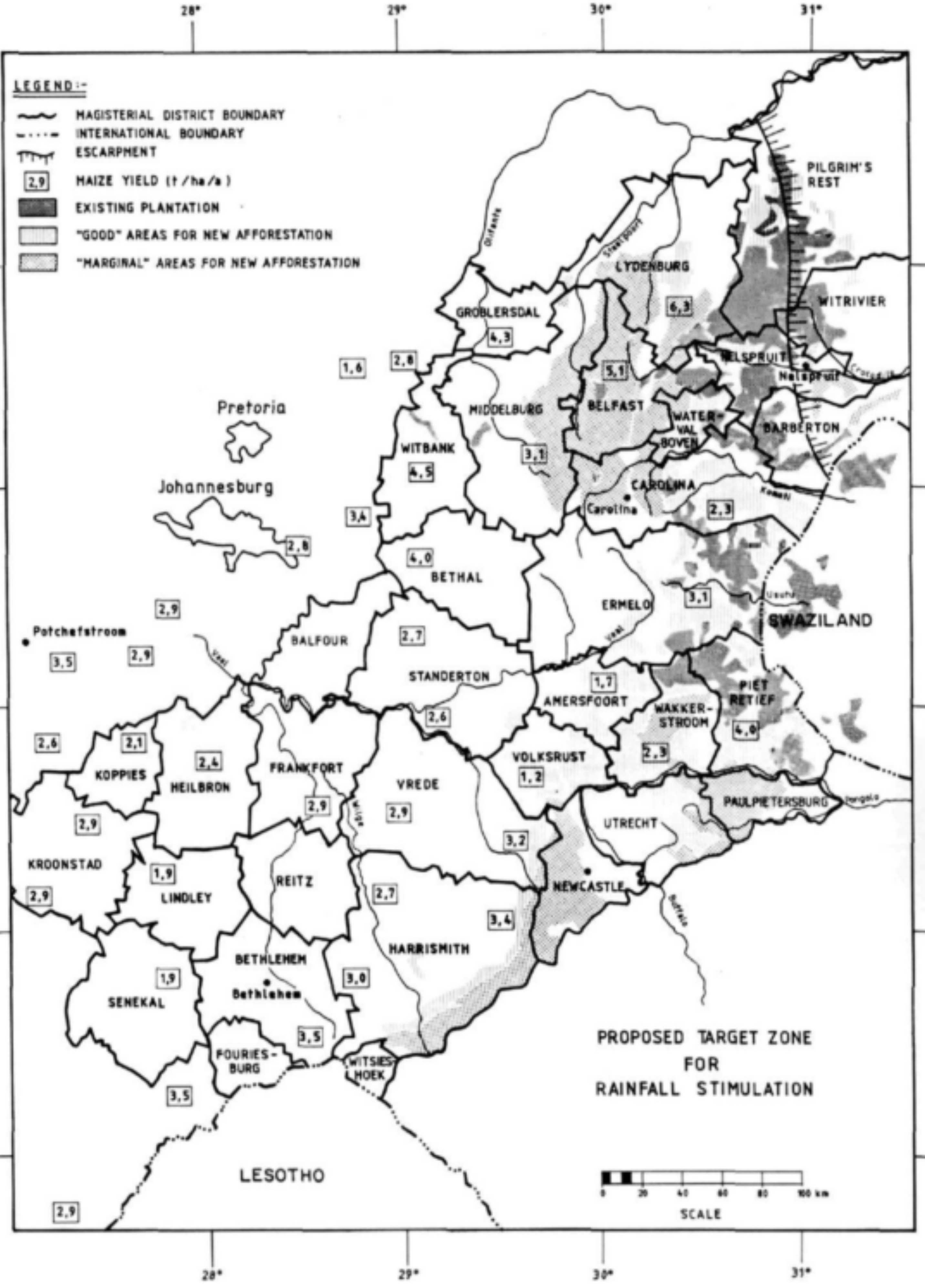
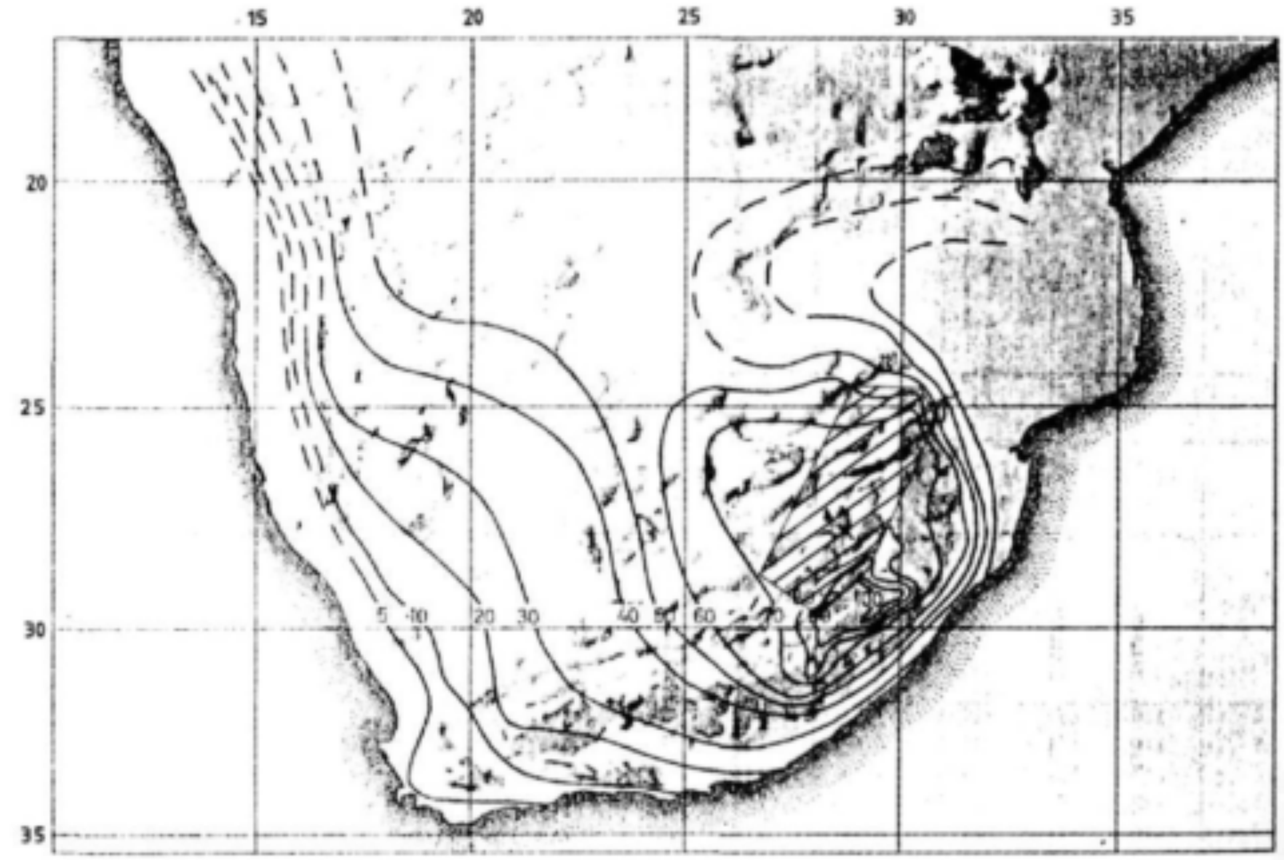

LEGEND:-
MAGISTERIAL DISTRICT BOUNDARY
INTERNATIONAL BOUNDARY
ESCARPMENT
MAIZE YIELD (t/ha/a)
EXISTING PLANTATION
"GOOD" AREAS FOR NEW AFFORESTATION
"MARGINAL" AREAS FOR NEW AFFORESTATION
PROPOSED TARGET ZONE
FOR
RAINFALL STIMULATION
Pretoria
Johannesburg
Potchefstroom
PILGRIM'S REST
LYDENBURG
WITRIVIER
GROBLERSDAL
NELSPRUIT
MIDDELBURG
BELFAST
WATERVAL BOVEN
BARBERTON
WITBANK
CAROLINA
BETHAL
ERMELO
SWAZILAND
BALFOUR
STANDERTON
AMERSFOORT
WAKKERSTROOM
PIET RETIEF
VOLKSRUST
KOPPIES
HEILBRON
FRANKFORT
VREDE
PAULPIETERSBURG
UTRECHT
KROONSTAD
LINDLEY
REITZ
NEWCASTLE
HARRISMITH
BETHLEHEM
SENEKAL
FOURIESBURG
WITSIESHOEK
LESOTHO
SCALE
0 20 40 60 80 100 km
28° 29° 30° 31°
25° 26° 27° 28° 29°

FIGURE 6.3

is how these numbers compare with other regions where convective rain is dominant. Such data for other regions are scarce, but Figure 6.4 may cast some light on this aspect. It is clear that the target corridor lies in that part of the country with the highest average number of days per annum on which thunder is heard. As thunder is much more associated with convective than other forms of rainfall, then this map indicates that the chosen target zone might be optimal in terms of this one criterion.

Topography influences **forcing at meso- and synoptic scales** quite favourably for rain production (SWA and CIC, 1986b, and Estie and Steyn, 1988). Much of the convective development occurs in synoptic-scale systems which move over the target area from the west and north-west. These systems experience orographic lifting which induce vertical velocities between 2 and 10 cm/s and which enhances convection considerably. Further, under certain conditions,the presence of the mountain barrier and the escarpment tend to favour the generation of low level convergence fields which induce mesoscale convection leading to clusters and line-storms. Along the escarpment scattered storms result in mid-summer from a cool, moist, low-level, mesoscale easterly wind from the Lowveld that supplies moisture to the high terrain west of Nelspruit where convective development has been triggered.

After finding, as shown in the previous paragraph, an integrated meteorological origin for the high incidence of convective storms over the target corridor, we wondered if this also implied greater **abundance of atmospheric moisture.** Figure 6.5, from a study by McGee (1982) on the distribution of the total water vapour content of the atmosphere, shows that the mean daily precipitable water content in summer varies from 25 mm in the south of the target zone to 35 mm in the north. The former value is fairly steady over the central and western parts of the country. However, Figure 6.6 reveals that over the target zone this vapour is transformed more sucessfully into rain than the latter parts of the country, which might signify greater marginal benefits from rainfall stimulation for the target zone.

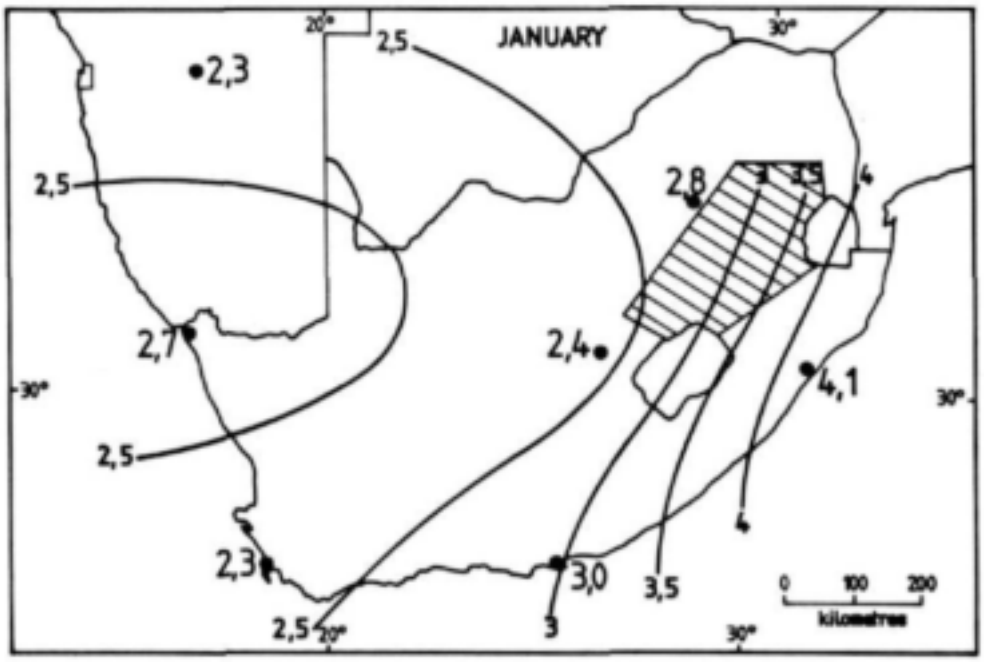


AVERAGE NUMBER OF DAYS PER ANNUM WITH THUNDER

(WEATHER BUREAU, 1986)

TARGET ZONE

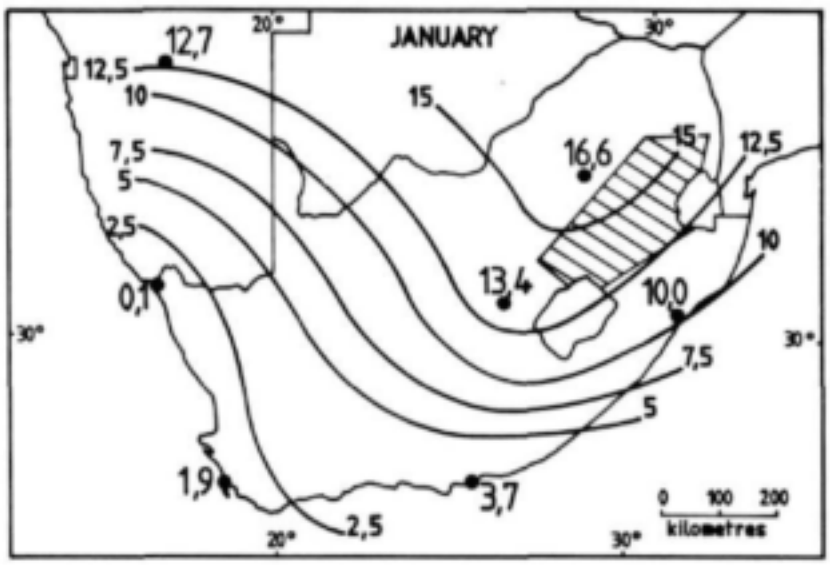
FIGURE 6.4



MEAN PRECIPITABLE DAILY WATER VAPOUR (cm): JANUARY VALUES
(AFTER McGEE, 1982)

TARGET ZONE

FIGURE 6.5



FRACTION (%) OF MEAN PRECIPITABLE DAILY WATER VAPOUR
ACTUALLY BECOMING RAIN
(AFTER McGEE, 1982)

TARGET ZONE

FIGURE 6.6

The target zone straddles the **headwaters of west- and east- flowing river systems** of major importance, as Figure 6.3 shows. These are, from south to north, the Wilge, Vaal, Buffalo, Pongolo, Usutu, Komati, Steelpoort, Crocodile, and Sabie Rivers. Some of these catchments are close to full utilisation and additional development necessitates water transfers from neighbouring catchments. If water resources could be shown to be a complementary beneficiary of rainfall stimulation, then this is a strong plus factor in the chosen location of the target area.

Figure 6.3 shows the presence of large **existing timber plantations** in the target corridor. More importantly, it reveals the existence of vast land areas identified (by Van der Zel, 1989) as **"good" and "marginal" for additional afforestation.** As we reported in section 6.4 above, timber production benefits of cloud-seeding would ensue not only from greater existing yields but also from converting marginal land to suitable land.

Maize and wheat are the only **dryland crops** for which we considered the **production potential** in the target zone, because of their overwhelming economic importance. (For the record, the other crops of importance to the zone are grain sorghum, sunflowers, dry beans and potatoes. In individual sub-regions any of these might be of equal importance.) Figure 6.3 indicates average expected annual maize yields. For the Transvaal Region of the Department of Agriculture these values were only available (from the Regional Headquarters) as averages per magisterial districts. In the Highveld Region we could utilise the excellent mapping of RHFA's from the report by Scheepers, et al, (1984), referred to earlier. The yield figures shown therefore vary in resolution over the target, but it does seem as if there is considerable variation from low- to high-yielding sub-regions, and that the average is not noticably higher than the drier regions to the west of the target. However, Dreyer (1989) has pointed out that the reliability of yields is much higher in the eastern areas than to the west. Consequently, the marginal benefit that rainfall stimulation might hold for maize production should be higher over the target area than over the western regions. As far as wheat is concerned, very high potential has been identified by Scheepers, et al, (1984), for some parts of the southern sector of the target area, ranging from 3,5 - 4,3 t/ha.

Potential dryland grazing capacities are higher inside the target zone compared with areas to the west. Non-arable dryland grazing capacities vary between 3 and 6 ha/large stock unit (LSU) inside the target while the equivalent range is between 4 and 8 ha/LSU further to the west. Also for cultivated improved dryland grazing is there, on average, an advantage inside the target area, namely 1 - 1,5 ha/LSU as against 1,5 - 2 ha/LSU (Scheepers, et al, 1984). As with grain, the general expectation is that the marginal benefit of rainfall stimulation in the higher yielding areas should be greater than in other areas. We make this statement conditionally, given the discussion in section 6.4 above regarding the limitations imposed on pasture improvements by historical veld degradation.

The meteorological monitoring infrastructure is an important consideration for two reasons:

* provision of a database for pre-seeding impact desk-studies of the type discussed earlier in this chapter

* monitoring of progress of operational cloud-seeding programme.

Apart from a number of "duty" weather stations as well as a large number of daily rainfall stations run by the Weather Bureau (250 and 80 respectively in the BPRP and the PAWS areas alone), each cloud-seeding research project also maintains a large number of automatic recording weather stations. We are confident that this network will provide a suitable database for desk-studies, but that operational monitoring might require an extensive redesign of the network.

The streamflow monitoring infrastructure is an important consideration for the same two reasons as above. The Department of Water Affairs maintain a large number streamflow gauging stations in the target corridor. We are confident that a suitable database for desk-studies will ensue from this network. Unfortunately, the calibration accuracy of the individual stations is quite variable, while most station records will display the effects of land-use change over time. Monitoring of operational cloud-seeding effects will almost definitely require a specially designed streamflow gauging network. Such a network of 9 catchments, some of which are nested, on the Wilge River was designed in the late 1970's for the BRAR (Bethlehem Runoff Augmentation Research) Project - a supporting hydrological modelling research project for the precursor to the BPRP. The BRAR Project has been terminated, but its streamflow gauging network is still maintained and could serve as a starting point for new studies.

Radar coverage of the whole target zone is not feasible, but an excellent data base of historical cloud coverages of all operational days since 1983 has been built up by both PAWS and BPRP. In Chapter 5 we indicate how this data base could be implemented to provide modified rainfall scenarios for desk-studies. For operational cloud-seeding this radar coverage would need to be expanded to help focus operations on specific experimental or monitoring areas on the ground.

Socio-economic considerations can either be inhibiting or attracting. For instance, the Grain Crops Research Institute staff in Potchefstroom pointed out to us that rainfall stimulation could in theory help to stabilise marginal grain crop farming in the more arid region west of a line through Bloemfontein and Potchehfstroom and help counteract the depopulation of the platteland in this region. However, the modest scale of mean seasonal areal rainfall increases that we project from PAWS results in Chapter 5, forces one to try and maximise what are really only marginal benefits - to ensure this the target area would need to be in the higher rainfall zones of the eastern Highveld.

No-go and international territories have to be considered in the delineation of the target zone. The target zone shown in Figure 6.3 has Lesotho and Swaziland excised. Semi-autonimous areas such as "homelands" might also need to be excluded. Cloud-seeding over urban areas would not be prudent from a risk management perspective, while the only beneficial impact, additional runoff, if any, would instantly degrade due to urban pollution. Consequently, the large built-up areas of the Rand have also been excised from the target zone.

Airport facilities are of course crucial to a cloud-seeding programme. Ideal requirements are hard-surface landing strips, air traffic controlling, radar and bad weather navigational communications. The target corridor under discussion is served by a number of reasonable airports - some of which come close to satisfying all the ideal requirements.

In Chapter 9 below we return to the subject of the target zone, but then we specifically address the need to identify individual sub-catchments inside the target zone on which the rainfall stimulation impact desk-studies should focus. But first, we need to address the social, socio-economic, and legal/administrative aspects of rainfall stimulation; this takes place in the next chapters.

7. SOCIAL AND SOCIO-ECONOMIC CONSIDERATIONS

During our interviews with persons in planning, decision-making and management positions we asked, in one way or another, questions relating to perceptions of the likely social and socio-economic impacts of rainfall stimulation. The two sections that constitute this chapter summarise some of these responses and address the research needs in these two areas briefly.

7.1 Social considerations

A recurrent phenomenon reported in the literature about the sociology of social change is the postulated lag between technological innovations and the knowledge or means to regulate the development or control the consequences of the innovation. Artificial rainfall stimulation can be discussed within this framework. For instance, if operational cloud-seeding is introduced at a faster rate than the accumulation of knowledge or understanding of it by the majority of the people affected by it, then public resistance might threaten the full realisation of an operational programme.

We were struck by the high degree of consensus among interviewees that positive social attitudes to and public perceptions of rainfall stimulation are as important to the possible future success of research in this field as overcoming technical hurdles might be. We also were somewhat surprised by the strong opinions (negative ones seemingly in the majority) that people from all walks of life seem to have about this issue, regardless of their level of informedness. Emotionally-laden campaigns such as by the "Red-Ons-Reën" movement in the Eastern Transvaal a few years ago, feed on this natural inclination of people to hold strong opinions about weather-related research. The best defences against negative perceptions are information transfer and public "education". It would be prudent of the WRC to regard this form of social impact with seriousness and to accept that impact research should include public opinion surveys and research on suitable forms of public "education". Such aims would also be in harmony with the current mood in South Africa in favour of greater democratisation of public decision-making and planning.

We are convinced that, well in advance of consideration of operational cloud-seeding, the attitudes of whites and blacks in the target corridor with respect to artificial rainfall stimulation should systematically be determined. We gained a good impression of what this entails from Pretorius and Schnetler (1990), who in an attitude survey proposal from the Human Sciences Research Council to the WRC, suggest that a survey of 1380 people would suffice to provide a good profile of the people in the target zone.

They propose a qualitative as well as a quantitative approach. In a preliminary investigation the observations will be qualitative and will be carried out by means of in-depth interviews with a target group of 100 whites and 80 blacks. In a subsequent main investigation observations will be controlled by utilising a structured questionaire which will evolve from the preliminary interviews. The main structured survey will most probably be telephonic and will encompass various target groups of 1200 whites. As a first approach they suggest that only the qualitative survey be conducted in the black community, concentrating on opinion leaders, professionals and farmers, for the reason that they expect the level of awareness of the issues to be fairly low in the black community at this stage. The cost of the survey as proposed above is estimated at about R85 000. Figure 7.1 provides a good overview of the provisional target groups in each community.

It is furthermore essential to accept an education component as part of the social sphere of research. Studies dealing with desired educational actions aimed at the general public or specific population sectors would be a necessary part of preparation for operational programmes.

TEMPORARY TARGET GROUPS

WHITE

- **Agriculture**
  - Farmers
  - *Corporations*
  - Agricultural advisers
  - Agricultural unions
  - Landbank
  - Sentra-Oes
- **Teaching**
  - Teachers
- **Churches**
  - Ministers
- **Medicine**
  - Doctors
  - Chemists
- **Businesses and Industries**
  - Businessleaders
  - *Town Councils*
- **Forestry**
- **Local Press**
  - Editor

BLACK

- **Agriculture**
  - *Farmers*
- **Teaching**
  - Teachers
- **Churches**
  - Religious leaders
  - Sangomas
- **Medicine**
  - Doctors
- **Businesses and Industries**
  - Business leaders
  - Unions
  - Chiefs
- **Community Workers**

TARGET GROUPS FOR PROPOSED ATTITUDE SURVEY

FIGURE 7.1

Finally, educational studies and actions should be followed by further attitude surveys to determine their success and the need for additional education.

7.2 Socio-economic impacts

Determination of the direct net potential economic benefit in each end-user field should be a reasonably uncomplicated task, given successful completion of the Route (iii) studies discussed in the previous chapter. However, the problem becomes more complex if one considers

* integration of the individual end-user economic assessments over the whole target zone,
* including multiplier and secondary effects,
* competition between end-users for water,
* competition between end-users for land and labour,
* added strains on existing end-user transport, storage, and processing infrastructure,
* added strains on regional macro-infrastructure,
* effects on product markets and prices both inside the target zone and in the country as a whole,
* impacts on local land prices,
* effects on exports (food and timber),
* effects on imports (hi-tech and fuel),
* demographic changes caused by the ensuing changes in land-use,
* administrative impacts of demographic changes.

This non-exhaustive list of socio-economic considerations underlines the need for antecedent research in this field in the target zone before operational cloud-seeding should become a reality. It is our opinion that the necessary expertise for this type of research resides in the following institutions:

- Institute for Social and Economic Research, U.O.F.S., Bloemfontein

- Centre for Social and Development Studies, University of Natal, Durban.

A socio-economic research programme is the logical repository of the results of all the individual end-user impact studies. Such a programme would inter alia, see to the conversion of individual end-user benefits from product units (eg. tonnes maize) to Rands, to the appropriate costing of operational cloud-seeding programmes that would ensure a given probability of benefit to specific end-users and to effecting an integrated cost-benefit assessment for the whole target zone.

8 LEGAL CONSIDERATIONS

Scrutiny of the legal considerations relevant to the planning of rainfall stimulation programmes, regardless of whether it be in a research or an operational context, needs highly specialised inputs, which clearly fall outside our own competence. For this purpose we commissioned two legal experts of the Faculty of Law, University of Stellenbosch, Prof M A Rabie and Prof M M Loubser, with the following brief (in Afrikaans): "The formulation of a formal legal opinion on legal aspects of artificial rainfall stimulation in South Africa. The minimum number of aspects to be considered are :

(i) Liability for damages.

(ii) Water rights.

(iii) Statutory control and licensing.

(iv) The state of existing legislation in the water, forestry, agriculture and environmental fields with respect to above points (i) to (iii).

(v) The most critical directions for amendment and development for future legislation in South Africa in these different fields."

Professors Rabie and Loubser responded to our brief with an excellent report entitled "Legal aspects of weather modification". This document comprises 74 pages, including extensive foot-notes. Due to its length and because it does not have a direct bearing on the research proposals made in Chapter 9 below, we decided to include the Rabie/Loubser report as Appendix C. We regard the Rabie/Loubser report as essential preparatory reading for any planning and operational actions in this field and, also, as an important base-line for any research into desired improvements in the existing legislation.

9. PROPOSED INTEGRATED RESEARCH PROGRAMME TO ASSESS THE POTENTIAL IMPACTS OF RAINFALL STIMULATION IN PRIMARY END-USER AND IMPACT FIELDS

This ultimate chapter of our report is devoted to the proposal of an integrated, multi-disciplinary, multi-objective, medium-term research programme in the cloud-seeding target zone aimed at the following fields which our investigation identified as primary:

* **meteorology/cloud physics** - modified rainfall
* **end-users** - grain production
  pasture production
  timber production
  water resources : reservoir yields
  flow statistics
* **social impacts** - socio-economic
  social attitudes

We do not recommend any purely environmental research projects in the short- to medium-term; however, we believe that the pasture production study should be seen as a base-line study for natural habitat definition in the cloud-seeding target zone which might form the seed of an environmental study, if viewed as necessary at a later stage.

9.1 Goals

The primary goals of the research programme are:

(i) obtain results in the short- to medium-term which can be used to **inform decision-makers/planners** in the public and private sectors, as well as the **general public**, of the potential benefits and drawbacks of rainfall stimulation for water resources, agriculture, forestry, and the general economy.

(ii) To obtain results in the medium-term which can be used to set rainfall stimulation programmes in an **optimal economic**

framework - striking a balance between benefits and disbenefits in each of the forementioned end-user/impact fields individually and collectively.

(iii) To develop an experimental framework for the effective **field monitoring** of the consequences of possible future operational rainfall stimulation programmes.

9.2 Research stages and time-tables

The preceding three goals identify three sequential stages in the proposed research programme:

Stage 1: End-user desk-studies and social/ socio-economic impact surveys.

Stage 2: Reconciliation and optimisation stage to derive a range of desirable rainfall stimulation programmes which would be both end-user cost-effective and socially/ legally/ environmentally acceptable.

Stage 3: Confirmatory field experimentation and monitoring in the end-user fields under operational cloud-seeding conditions - including a certain amount of iterating to tasks introduced in Stages 1 and 2.

Clearly, Stages 1 and 2 would precede the initiation of operational cloud-seeding programmes and, indeed, would determine their design. In contrast, initiation of Stage 3 would be dependent on initiation of operational rainfall stimulation - unless the field experiments require pre-seeding end-user behaviour characterisations. Table 9.1 presents a plausible time-table for Stages 1 - 3 in the form of a simple bar diagram.

In the design of the time-frames we kept in focus the strong impression gained throughout our investigations that cloud-seeding research in South Africa still needed a number of years of consolidation via micro-physical studies and cloud model explorations. Consequently, 1996 is accepted as the earliest date at

TABLE 9.1 **A PLAUSIBLE TIME-TABLE FOR THE PROPOSED RESEARCH PROGRAMME**

Stage	Impact	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
1 Desk-Study	Modified rainfall	X									
	Climatological		X	X							
	Crop yield	X	X	X							
	Water resources	X	X								
	Timber yield	X	X								
	Pasture yield	X	X	X							
	Socio-economic		X	X	X						
	Social attitudes		X				X				
	Public education			X	X	X					
2 Optimisation	N/A				X	X					
Field prepa- ration					X	X					
3 Field experiments	N/A						X	X	X	X	X

which operational programmes could be launched, and when Stage 3 projects could start. It should be noted that during compilation of Table 9.1 we ignored possible budgetary constraints that the WRC might experience and which could enforce a different phasing of projects over a longer total period.

Preliminary proposals for Stage 1 research projects were solicited from most of the centres of expertise mentioned in Chapters 6 and 7. These will be discussed in section 9.5 below. Unfortunately, this planning study has to stop short of making detailed proposals regarding Stage 3 projects, because a decision on optimal sub-catchment/ field experiment areas for multi-objective studies has to await the outcome of Stage 2, which in turn will depend on Stage 1 results.

9.3 Underlying premises for Stage 1 end-user research

In section 6.8 above we discuss the need for common ultimate goals in end-user impact modelling and desk-studies. Here we explore premises for this work that seem desirable to us:

(i) End-user desk-studies would focus on representative **pilot areas** inside the target zone that would reflect both the variety of end-users and the heterogeneity inherent to every end-user field. To ensure mergeability of the findings in different end-user fields, it is important that studies in the different fields share identical sub-catchment boundaries even though each may address a somewhat different land surface inside these boundaries.

(ii) Every end-user desk-study would be expected to ultimately **transfer results** and findings in an appropriate way from the pilot areas to the total target zone, yielding an **integrated assessment** of individual end-user impacts for the target zone.

(iii) End-user desk-studies might be supported by **field work to**

supplement model input data bases, but field experiments under operational cloud-seeding conditions are not included in this stage of the research programme.

(iv) An **integrated cost-benefit assessment** covering all end-users, as well as secondary economic impacts, would be implemented as part of a socio-economic study and would knit together the individual end-user desk-study results. Such a study would conclude the Stage 1 research and set the scene for Stage 2.

9.4 Pilot areas for Stage 1 end-user desk-studies

The guidelines for pilot area selection are as follows:

- representativeness of variety of end-users
- representativeness of heterogeneity of individual end-user conditions
- availability of hydrometeorological time series data, as well as physical data such as land and soil types, land use, crop and timber cultivation, natural grass species compositions, veld condition, etc.
- limitations on the number of pilot studies regarded as practicable in budgetary terms - this is an especially important consideration for the cost-efficient development of credibly modified areally distributed rainfall time series
- location within the radar coverage of either BPRP (Bethlehem) or PAWS (Carolina/Nelspruit) so that seeding response results from these two projects would be directly applicable and, also, so that, if experimental field studies under operational cloud-seeding ultimately take off, these are automatically monitorable by radar
- size limitations based on the collective spatial modelling requirements of the various end-users.

After consideration of these guidelines, we decided on a provisional short-list of three pilot areas, the boundaries of which are shown on Figure 9.1, namely

the Wilge,
Usutu/Upper Vaal and
Upper Crocodile River Areas.

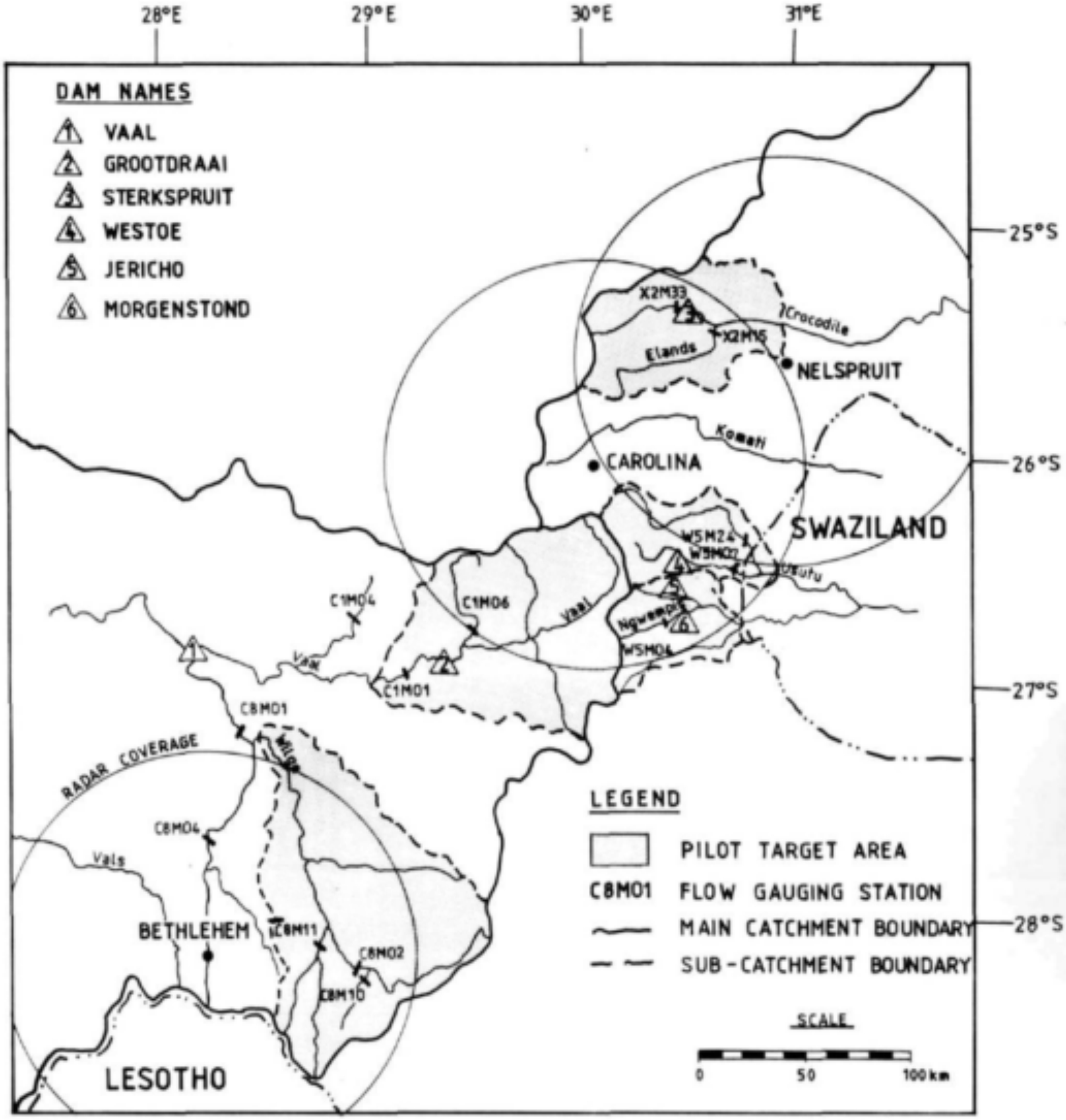
Table 9.2 (and comparison with Figure 6.3) illustrates the representation of main end-user characteristics in these pilot areas and the interrelationship of end-user interests.

9.5 Summary of proposed Stage 1 research projects

Table 9.3 summarises the preliminary proposals that we managed to solicit for Stage 1 research during the course of our investigation. After scrutiny of these preliminary proposals, we submitted them to the staff of the Water Research Commission for further processing and refinement by negotiation with their authors. After receipt of these proposals, we came to the realisation that, with 1996 as a potential target date for the start of operational cloud-seeding, 1994 should be the target date for the completion of the Stage 1 cost-benefit study - part of the socio-economic research project. This would leave one year, 1995, for completion of the Stage 2 tasks related to designing theoretically optimal operational cloud-seeding programmes. It is consequently important that all end-user desk-study programmes should include a deadline, or at least an interim deadline, at the end of 1993 by which final, or interim, results could be relayed to the researchers responsible for the integrated cost-benefit analysis.

9.6 Designing "optimal" operational cloud-seeding projects (Stage 2 research)

In section 6.8 above we expressed some preliminary thoughts on this research stage - thoughts that need further elaboration at this



PROPOSED PILOT TARGET AREAS
FOR DESK STUDIES

FIGURE 9.1

TABLE 9.2 : **SOME DESCRIPTIVE CHARACTERISTICS OF THE PROPOSED PILOT TARGET AREAS**

Characteristic	Wilge	Upper Vaal	Upper Usutu	Upper Crocodile
Area (km^2)	10675	8890	5210	4615
MAP range (mm)	700-960	700-880	830-1020	850-1240
Useful streamflow gauging sites	C8M10 C8M02 C8M11 C8M04 C8M01	C1M01 C1M06 C1M04	W5M07 W5M24 W5M04	X2M15 X2M33
Reservoirs (Capacities- 10 m^3)	-	Grootdraai (364)	Westoe(59) Jericho(59) Morgenstord(113)	Sterkspruit(167)
Forestry*:				
Existing(km^2)	None	None	1110	1140
New prime	Limited	Considerable	Extensive	Limited
New marginal	Consider-ble	None	Limited	Extensive
Grain yields	Medium to high	Medium to high	High	High
Veld types	Sour to scrubby mixed grassveld	Sour grassveld	Sour grassveld	Bushveld
Irrigation* (km^2)	20	14	11	130

*From HRU (1981) - these figures are at least 10 years out of date and the current areas under plantation are likely to be larger.

TABLE 9.3 PROPOSED PRELIMINARY RESEARCH PROJECTS IN PRIMARY END-USER AND IMPACT FIELDS

End-user/impact	Project leader(s)	Organisation(s)	Model(if any)	Field study details	Duration	Approximate budget (in R1000's) by years 1991	1992	1993	1994	1995
Modified rainfall time series	Dr A Seed	Hyd. Res. Institute Dept. Water Affairs	N/A	N/A	1 yr	130	-	-	-	-
Dryland maize and Wheat production	Prof J M de Jager	Dept. of Agrometeorology, U.O.F.S.	PUTU	Soil and crop surveys; monitor crop development using satellite data to verify model results	5 yrs	70	77	85	95	95
Dryland maize production	Dr J B Mallett	Grain Crops Research Institute, Cedara	CERES	Low budget : No field study	3-6 mths	20	-	-	-	-
				Med.budget : Soil and crop surveys	12-18 mths	50	25	-	-	-
				High budget : As for medium, but with test plots to verify model results	3 yrs	90	60	75	-	-
Dryland pasture production	Prof O J H Bosch and Dr J Booysen	Dept. of Plant Sciences, Potchefstroom University	PUK (modified)	Species composition surveys along transects; habitat definitions; degradation gradient quantification; surveys to verify model results; target area divided into 3 zones	3 yrs(Zone I) or 4 yrs(I+II+III)	17 29 49	29 84 147	32 92 160	- 65 160	(Zone I) (I, II) (I, II,III)
Reservoir system yield (preliminary assessment)	Prof W J R Alexander	University of Pretoria and Sigma Beta	Pitman +1 reservoir system model	No field work	6 mths	50	-	-	-	-
Water resources and timber production	Dr A Görgens Prof R Schulze Dr J Bosch	Ninham Shand, University of Natal, Foresttek, CSIR	ACRU	No field work	24 mths	110	175	-	-	-
Socio-Economic	Prof M F Viljoen	Dept. Agr. Econ. U.O.F.S.	N/A	Interviews with relevant persons and institutions	3 yrs	-	50	90	90	-
Social attitudes	Ms M Pretorius and Dr J Schnetler	Human Sciences Research Council	N/A	Interviews with relevant persons; two alternative proposals	6-12 mths	-	95(personal:180;telephonic; 1200 people)			
						-	160(personal:1380; no telephonic)			

point: We believe that this task should be entrusted to a one- or two-man expert consultancy who would seek formulation of appropriate guidelines for their task via at least **two workshops** - the first focussing on **optimising end-user interests**, and the second dealing with **operational cloud-seeding details.** By prudent selection of membership of the workshops, harnassing of appropriate expertise would be possible, hopefully yielding near-optimal advice.

Stage 3 **field experiments** (see 9.7 below) might be highly dependent on successful **preceding** research into measurement problems relating to ground-level **rainfall observations by radar**, research into problems relating to **geostatistical interpolation** of point rainfalls and research into **increased accuracy of river flow measurement.** Such supporting research **might** be mandatory for the successful interpretation of results in stage 3 field experiments.

If so, then such "preparatory" research should be initiated as part of Stage 2 so that suitable findings would be on the table by the start of stage 3.

9.7 The future role of field studies under operational cloud-seeding conditions (Stage 3 research)

Hitherto, all findings of the research programme relating to impacts would be theoretical. It follows that the launching of operational cloud-seeding should also herald the start of **confirmatory field experiments** in target areas, enabling practical and physical assessment of impacts, i.e. the so-called Route (i) experiments discussed in section 6.6 above. These experimental areas would consist of river sub-catchments instrumented for appropriate hydrometeorological monitoring and in which experimental crop/timber/pasture "plots" have been established - depending on what optimal "mix" of end-users the Stage 1 and 2 studies identify. The aims of these field experiments would be to:

(i) establish the likelihood of desirable rainfall enhancement scenarios being realised in practice;

(ii) test and validate postulated hydrological, agricultural and forestry responses;

(iii) identify and quantify non-anticipated impacts which might have a significant bearing on overall acceptability and cost-effectiveness;

(iv) provide hard data on the basis of which Stage 1 and 2 studies could be refined to yield a new assessment of the integrated cost/benefit picture for operational cloud-seeding over the whole target zone.

At this stage it seems obvious that the representative pilot areas used in the Stage 1 research should be in contention for the establishment of these field experiments. It also seems likely that such field studies might have to run for as much as five years before definitive results could be expected. This stage of impact research would understandably be very costly and should only be launched once the interim process-oriented cloud research in PAWS and BPRP has raised confidence levels regarding the probability of successful rainfall stimulation at the operational scale. Our own attitude to this eventuality is quite positive.

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APPENDIX A

PAWS: Primary storm track data for all target storms and all time windows from -10 min to 60 min.

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 9:52:55

TIME-DEPENDENT PROPERTIES - -10.0 to .0 mins after Decision Time.

CASES:- 85

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84/11/ 1:11- 29    84/11/11:11- 39    84/11/16:11-  1    84/11/28:11- 39    84/11/29:11- 30    84/11/29:11- 58    84/12/12:11- 10
84/12/13:11- 30    84/12/13:11- 49    84/12/17:11- 16    84/12/18:11- 29    84/12/19:11- 59    84/12/19:11- 60    84/12/20:11- 67
85/ 1/ 7:11- 14    85/ 1/15:11- 13    85/ 1/15:11- 38    85/ 1/18:11- 41    85/ 1/18:11- 25    85/ 2/ 7:11- 81    85/ 2/16:11- 30
85/ 2/28:11- 82    85/ 2/28:11-143    85/ 3/ 1:11-  5    85/ 3/ 1:11- 76    85/ 3/ 1:11-124    85/ 3/12:11-  1    85/ 3/13:11- 10
85/ 3/13:11-  1    85/10/16:11-  1    85/10/29:11-  4    85/10/29:11- 35    85/11/ 2:11- 10    85/11/ 9:11- 41    85/11/26:11-  6
85/12/ 3:11- 12    85/12/14:11- 38    85/12/30:11- 68    86/ 1/ 3:11- 15    86/ 1/ 7:11-  8    86/ 1/14:11- 13    86/ 1/15:11-184
86/ 1/18:11- 37    86/ 1/29:11- 20    86/ 2/ 5:11- 13    86/ 2/ 5:11-131    86/ 2/ 7:11-  6    86/ 2/ 7:11- 37    86/ 2/13:11-125
86/ 2/22:11- 13    86/ 3/ 3:11- 10    86/ 3/ 3:11- 31    86/ 3/10:11-  7    86/ 3/10:11- 33    86/ 3/12:11- 25    86/ 3/13:11-  4
86/ 3/14:11- 54    86/ 3/14:11- 36    86/ 3/14:11- 56    86/ 3/24:11- 43    86/11/22:11- 46    86/11/24:11-  6    86/11/26:11- 27
86/11/26:11- 54    86/11/27:11- 18    86/12/ 1:11- 21    86/12/ 1:11- 94    86/12/ 2:11-  3    86/12/19:11-  5    87/ 1/13:11- 37
87/ 1/16:11-118    87/ 1/19:11- 23    87/ 1/21:11- 73    87/ 1/22:11- 26    87/ 1/23:11- 19    87/ 1/23:11- 37    87/ 2/ 3:11-  8
87/ 2/ 3:11- 15    87/ 2/ 6:11- 47    87/ 2/20:11- 11    87/ 2/20:11- 19    87/ 2/27:11- 55    87/ 3/ 5:11-  3    87/ 3/19:11- 15
87/ 3/24:11- 50
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PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	11	11	11	11	11	11	12	12	12	12	12	12
DAY	1	11	16	28	29	29	12	13	13	17	18	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	29	39	1	39	30	58	10	30	49	16	29	59
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	6	7	10	12	13	14	18	19	20	23	24	25
SEED?	Y	N	Y	Y	Y	N	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	93	626	544	89	73	27	353	41	152	160	319	57
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	23.9	134.3	85.0	19.6	20.4	7.6	67.0	13.3	48.1	46.4	32.5	4.6
67 RFLUX 3 DEG - MASS.........(KTON)	51	313	372	11	17	12	156	11	87	85	52	3
68 RFLUX 3 DEG - MEAN.........(M3/S)	85	521	620	33	49	19	260	19	145	142	86	7

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	85	85	85	85	85	85	85	85	85	85
MONTH	12	12	1	1	1	1	1	2	2	2	2	3
DAY	19	20	7	15	15	18	18	7	16	28	28	1
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	60	67	14	13	38	41	25	81	30	82	143	5
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	26	28	30	31	32	34	35	38	37	41	42	43
SEED?	Y	Y	N	N	Y	N	Y	N	N	Y	Y	N
SAMPLE?	Y	Y	Y	N	Y	N	Y	N	N	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	91	300	163	104	43	39	59	118	83	176	310	106
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN...........(KM2)	20.1	41.7	44.6	18.4	10.7	14.7	23.9	14.1	9.3	42.8	106.2	32.8
67 RFLUX 3 DEG - MASS.........(KTON)	39	104	79	39	3	5	36	25	9	133	178	65
68 RFLUX 3 DEG - MEAN.........(M3/S)	64	174	132	65	49	38	60	41	14	222	297	108

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	3	3	3	3	3	10	10	10	11	11	11	12
DAY	1	1	12	13	13	16	29	29	2	9	26	3
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	76	124	1	10	1	1	4	35	10	41	6	12
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	44	45	46	48	49	53	54	55	56	60	61	62
SEED?	Y	N	Y	N	N	Y	N	Y	Y	Y	Y	Y
SAMPLE?	Y	N	Y	N	Y	Y	N	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	188	124	148	58	207	346	290	474	172	292	89	142
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN...........(KM2)	49.5	45.7	51.0	18.6	53.0	76.9	65.8	12.3	52.9	40.7	5.9	36.5
67 RFLUX 3 DEG - MASS.........(KTON)	74	77	78	21	88	107	102	12	114	48	4	67
68 RFLUX 3 DEG - MEAN.........(M3/S)	123	128	130	35	146	178	169	20	190	81	7	112

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	86	86	86	86	86	86	86	86	86	86
MONTH	12	12	1	1	1	1	1	1	2	2	2	2
DAY	14	30	3	7	14	15	18	29	5	5	7	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	38	68	15	8	13	184	37	20	13	131	6	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	65	67	68	71	73	76	77	78	80	81	82	84
SEED?	N	N	Y	N	N	N	N	N	N	Y	N	Y
SAMPLE?	Y	N	Y	N	Y	N	Y	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	316	62	15	94	207	81	21	81	13	238	184	588
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	55.9	.0	8.1	42.1	39.7	14.3	4.6	12.2	8.6	82.4	48.5	196.2
67 RFLUX 3 DEG - MASS........(KTON)	118	0	7	60	72	20	4	13	5	93	78	331
68 RFLUX 3 DEG - MEAN........(M3/S)	196	0	11	101	120	33	6	22	12	155	130	552

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	3	3	3	3	3	3	3	3	3	3
DAY	13	22	3	3	10	10	12	13	14	14	14	24
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	125	13	10	31	7	33	25	4	54	36	56	43
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	91	93	95	96	99	100	101	102	103	104	105	106
SEED?	Y	N	Y	Y	Y	Y	N	N	N	N	Y	Y
SAMPLE?	Y	N	Y	Y	Y	Y	Y	Y	N	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	39	92	65	171	156	87	212	209	167	243	222	20
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	12.2	31.3	5.7	35.6	31.1	18.3	42.0	81.0	20.3	49.4	81.8	5.2
67 RFLUX 3 DEG - MASS........(KTON)	12	43	5	72	70	48	142	98	0	103	146	4
68 RFLUX 3 DEG - MEAN........(M3/S)	19	72	8	121	117	80	237	163	23	171	243	7

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	87	87	87
MONTH	11	11	11	11	11	12	12	12	12	1	1	1
DAY	22	24	26	26	27	1	1	2	19	13	16	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	46	6	27	54	18	21	94	3	5	37	118	23
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	113	114	117	118	119	120	121	122	125	128	130	131
SEED?	N	Y	N	N	N	N	Y	N	Y	Y	Y	N
SAMPLE?	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	200	400	444	111	491	262	452	263	507	76	20	129
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	48.3	105.1	89.4	9.8	88.7	55.2	97.6	101.3	56.3	3.5	4.1	8.6
67 RFLUX 3 DEG - MASS.........(KTON)	103	232	196	7	286	45	352	163	118	2	3	6
68 RFLUX 3 DEG - MEAN.........(M3/S)	172	387	327	13	476	268	586	272	196	3	4	9

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	87	87	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	2	2	2	2	2	2	3	3
DAY	21	22	23	23	3	3	6	20	20	27	5	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	73	26	19	37	8	15	47	11	19	55	3	15
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	133	134	135	136	144	145	151	152	153	154	156	166
SEED?	N	Y	Y	N	N	Y	Y	N	Y	N	N	N
SAMPLE?	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	43	377	483	352	457	247	60	254	477	62	286	189
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	.0	54.4	41.7	72.9	14.9	46.3	.0	28.5	66.1	12.2	64.8	48.6
67 RFLUX 3 DEG - MASS.........(KTON)	0	139	59	149	15	123	0	49	144	11	101	71
68 RFLUX 3 DEG - MEAN.........(M3/S)	0	232	98	248	25	204	0	81	241	18	169	118

	85
YEAR	87
MONTH	3
DAY	24
SEQUENCE #	11
TRACK #	50
DBZ THRESHOLD	30
TRACK PARAMETERS - MAX SPEED	90
MAX TIME INTERVAL	30
CASE # IF APPLICABLE	169
SEED?	N
SAMPLE?	Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS

28 VOLUME - MEAN...............(KM3)	62

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

52 AREA 3 DEG - MEAN..........(KM2)	19.1
67 RFLUX 3 DEG - MASS.........(KTON)	18
68 RFLUX 3 DEG - MEAN.........(M3/S)	30

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 10:35:24

TIME-DEPENDENT PROPERTIES - .0 to 10.0 mins after Decision Time.

CASES:- 89

84/11/ 1:11- 29	84/11/11:11- 39	84/11/16:11- 1	84/11/27:11-149	84/11/28:11- 39	84/11/29:11- 30	84/11/29:11- 58
84/12/12:11- 10	84/12/13:11- 30	84/12/13:11- 49	84/12/17:11- 16	84/12/18:11- 29	84/12/19:11- 59	84/12/19:11- 60
84/12/20:11- 67	85/ 1/ 7:11- 14	85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/18:11- 41	85/ 1/18:11- 25	85/ 2/ 7:11- 81
85/ 2/16:11- 30	85/ 2/23:11- 49	85/ 2/28:11- 82	85/ 2/28:11-143	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/ 1:11-124
85/ 3/12:11- 1	85/ 3/12:11- 75	85/ 3/13:11- 10	85/ 3/13:11- 1	85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35
85/11/ 2:11- 10	85/11/ 9:11- 41	85/11/26:11- 6	85/12/ 3:11- 12	85/12/14:11- 38	85/12/30:11- 68	86/ 1/ 3:11- 15
86/ 1/ 7:11- 8	86/ 1/14:11- 13	86/ 1/14:11-240	86/ 1/15:11-184	86/ 1/18:11- 37	86/ 1/29:11- 20	86/ 2/ 5:11- 13
86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11- 37	86/ 2/13:11-125	86/ 2/22:11- 13	86/ 3/ 3:11- 10	86/ 3/ 3:11- 31
86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/13:11- 4	86/ 3/14:11- 54	86/ 3/14:11- 36	86/ 3/14:11- 56
86/ 3/24:11- 43	86/11/22:11- 46	86/11/24:11- 6	86/11/26:11- 27	86/11/26:11- 54	86/11/27:11- 18	86/12/ 1:11- 21
86/12/ 1:11- 94	86/12/ 2:11- 3	86/12/19:11- 5	87/ 1/13:11- 37	87/ 1/16:11-118	87/ 1/19:11- 23	87/ 1/21:11- 73
87/ 1/22:11- 26	87/ 1/23:11- 19	87/ 1/23:11- 37	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11
87/ 2/20:11- 19	87/ 2/27:11- 55	87/ 3/ 5:11- 3	87/ 3/19:11- 15	87/ 3/24:11- 50		

PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	11	11	11	11	11	11	11	12	12	12	12	12
DAY	1	11	16	27	28	29	29	12	13	13	17	18
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	29	39	1	149	39	30	58	10	30	49	16	29
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	6	7	10	11	12	13	14	18	19	20	23	24
SEED?	Y	N	Y	N	Y	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	290	723	618	66	123	224	105	408	80	344	114	329
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	59.8	142.0	100.6	1.2	29.2	81.2	34.4	82.4	23.8	81.5	36.7	43.7
67 RFLUX 3 DEG - MASS........(KTON)	157	300	486	1	44	108	67	182	27	185	62	81
68 RFLUX 3 DEG - MEAN........(M3/S)	261	500	810	2	73	179	111	304	45	309	103	136

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	84	85	85	85	85	85	85	85	85	85
MONTH	12	12	12	1	1	1	1	1	2	2	2	2
DAY	19	19	20	7	15	15	18	18	7	16	23	28
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	59	60	67	14	13	38	41	25	81	30	49	82
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	25	26	28	30	31	32	34	35	38	37	40	41
SEED?	N	Y	Y	N	N	Y	N	Y	N	N	Y	Y
SAMPLE?	N	Y	Y	Y	N	Y	N	Y	N	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	97	72	363	353	137	69	51	84	190	52	98	153
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	24.3	20.3	65.0	83.0	33.7	21.2	19.7	29.8	34.4	8.4	32.4	54.8
67 RFLUX 3 DEG - MASS.........(KTON)	32	22	202	160	93	50	37	60	66	7	7	142
68 RFLUX 3 DEG - MEAN.........(M3/S)	53	37	336	267	155	83	62	99	110	11	63	236

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	2	3	3	3	3	3	3	3	10	10	10	11
DAY	28	1	1	1	12	12	13	13	16	29	29	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	143	5	76	124	1	75	10	1	1	4	35	10
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	42	43	44	45	46	47	48	49	53	54	55	56
SEED?	Y	N	Y	N	Y	Y	N	N	Y	N	Y	Y
SAMPLE?	Y	N	Y	N	Y	Y	N	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	176	162	248	78	60	58	11	400	345	265	682	483
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	64.6	35.2	55.0	37.9	29.7	2.3	5.9	70.4	63.3	66.4	26.0	129.6
67 RFLUX 3 DEG - MASS.........(KTON)	112	87	120	53	41	2	4	183	66	95	23	266
68 RFLUX 3 DEG - MEAN.........(M3/S)	187	144	200	88	68	3	7	304	110	159	38	444

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	85	85	85	86	86	86	86	86	86	86
MONTH	11	11	12	12	12	1	1	1	1	1	1	1
DAY	9	26	3	14	30	3	7	14	14	15	18	29
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	6	12	38	68	15	8	13	240	184	37	20
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	60	61	62	65	67	68	71	73	74	76	77	78
SEED?	Y	Y	Y	N	N	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	N	Y	N	Y	N	N	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	530	83	120	381	98	33	86	283	329	100	34	76
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	75.7	8.9	27.8	78.3	.0	13.4	37.1	50.5	39.8	28.7	8.7	8.7
67 RFLUX 3 DEG - MASS........(KTON)	97	7	50	142	0	9	57	97	36	36	10	8
68 RFLUX 3 DEG - MEAN.........(M3/S)	161	12	84	237	0	15	94	161	65	61	17	13

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	2	2	3	3	3	3	3	3
DAY	5	5	7	7	13	22	3	3	10	10	12	13
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	13	131	6	37	125	13	10	31	7	33	25	4
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	80	81	82	84	91	93	95	96	99	100	101	102
SEED?	N	Y	N	Y	Y	N	Y	Y	Y	Y	N	N
SAMPLE?	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	71	374	231	527	135	138	57	81	307	98	227	217
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	26.3	100.4	37.8	145.8	50.4	45.2	1.7	24.9	74.1	19.4	53.6	95.3
67 RFLUX 3 DEG - MASS........(KTON)	67	139	82	288	76	63	1	29	111	53	127	120
68 RFLUX 3 DEG - MEAN.........(M3/S)	111	232	137	479	127	105	2	49	185	88	212	200

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	3	3	3	3	11	11	11	11	11	12	12	12
DAY	14	14	14	24	22	24	26	26	27	1	1	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	54	36	56	43	46	6	27	54	18	21	94	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	103	104	105	106	113	114	117	118	119	120	121	122
SEED?	N	N	Y	Y	N	Y	N	N	N	N	Y	N
SAMPLE?	N	N	Y	Y	N	Y	N	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	246	217	130	92	148	379	560	194	775	399	683	259
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	47.8	49.5	65.0	19.7	51.2	94.8	129.1	42.7	154.6	90.5	94.1	75.9
67 RFLUX 3 DEG - MASS........(KTON)	62	61	84	25	77	200	215	48	385	306	305	153
68 RFLUX 3 DEG - MEAN........(M3/S)	103	101	139	42	128	334	359	81	641	511	508	255

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	86	87	87	87	87	87	87	87	87	87	87	87
MONTH	12	1	1	1	1	1	1	1	2	2	2	2
DAY	19	13	16	19	21	22	23	23	3	3	6	20
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	5	37	118	23	73	26	19	37	8	15	47	11
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	125	128	130	131	133	134	135	136	144	145	151	152
SEED?	Y	Y	Y	N	N	Y	Y	N	N	Y	Y	N
SAMPLE?	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	449	177	118	119	121	295	464	627	383	259	335	322
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	48.5	13.6	19.2	15.2	.2	84.7	56.0	116.4	27.6	46.3	31.9	28.8
67 RFLUX 3 DEG - MASS........(KTON)	78	9	17	20	0	159	86	219	37	116	71	56
68 RFLUX 3 DEG - MEAN........(M3/S)	130	15	29	34	0	265	144	365	62	194	119	94

	85	86	87	88	89
YEAR	87	87	87	87	87
MONTH	2	2	3	3	3
DAY	20	27	5	19	24
SEQUENCE #	11	11	11	11	11
TRACK #	19	55	3	15	50
DBZ THRESHOLD	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30
CASE # IF APPLICABLE	153	154	156	166	169
SEED?	Y	N	N	N	N
SAMPLE?	Y	N	N	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS					
28 VOLUME - MEAN...............(KM3)	595	61	186	68	75
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS					
52 AREA 3 DEG - MEAN..........(KM2)	77.5	9.8	56.4	19.2	29.7
67 RFLUX 3 DEG - MASS.........(KTON)	245	10	83	12	54
68 RFLUX 3 DEG - MEAN.........(M3/S)	408	17	138	40	90

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 10:57:27

TIME-DEPENDENT PROPERTIES - 10.0 to 20.0 mins after Decision Time.

CASES:- 86

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84/11/ 1:11- 29   84/11/11:11- 39   84/11/16:11-  1   84/11/27:11-149   84/11/28:11- 39   84/11/29:11- 30   84/11/29:11- 58
84/12/12:11- 10   84/12/13:11- 30   84/12/13:11- 49   84/12/17:11- 16   84/12/18:11- 29   84/12/19:11- 59   84/12/19:11- 60
84/12/20:11- 67   85/ 1/ 7:11- 14   85/ 1/15:11- 13   85/ 1/15:11- 38   85/ 1/18:11- 41   85/ 1/18:11- 25   85/ 2/ 7:11- 81
85/ 2/16:11- 30   85/ 2/23:11- 49   85/ 2/28:11- 82   85/ 2/28:11-143   85/ 3/ 1:11-  5   85/ 3/ 1:11- 76   85/ 3/ 1:11-124
85/ 3/12:11-  1   85/ 3/12:11- 75   85/ 3/13:11- 10   85/ 3/13:11-  1   85/10/16:11-  1   85/10/29:11-  4   85/10/29:11- 35
85/11/ 2:11- 10   85/11/ 9:11- 41   85/11/26:11-  6   85/12/ 3:11- 12   85/12/14:11- 38   86/ 1/ 3:11- 15   86/ 1/ 7:11-  8
86/ 1/14:11- 13   86/ 1/14:11-240   86/ 1/15:11-184   86/ 1/18:11- 37   86/ 1/29:11- 20   86/ 2/ 5:11- 13   86/ 2/ 5:11-131
86/ 2/ 7:11-  6   86/ 2/ 7:11- 37   86/ 2/13:11-125   86/ 2/22:11- 13   86/ 3/ 3:11- 31   86/ 3/10:11-  7   86/ 3/10:11- 33
86/ 3/12:11- 25   86/ 3/13:11-  4   86/ 3/14:11- 54   86/ 3/14:11- 36   86/ 3/14:11- 56   86/ 3/24:11- 43   86/11/22:11- 46
86/11/24:11-  6   86/11/26:11- 27   86/11/26:11- 54   86/11/27:11- 18   86/12/ 1:11- 21   86/12/ 1:11- 94   86/12/ 2:11-  3
86/12/19:11-  5   87/ 1/13:11- 37   87/ 1/16:11-118   87/ 1/19:11- 23   87/ 1/21:11- 73   87/ 1/22:11- 26   87/ 1/23:11- 19
87/ 1/23:11- 37   87/ 2/ 3:11-  8   87/ 2/ 3:11- 15   87/ 2/ 6:11- 47   87/ 2/20:11- 11   87/ 2/20:11- 19   87/ 2/27:11- 55
87/ 3/ 5:11-  3   87/ 3/24:11- 50
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PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	11	11	11	11	11	11	11	12	12	12	12	12
DAY	1	11	16	27	28	29	29	12	13	13	17	18
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	29	39	1	149	39	30	58	10	30	49	16	29
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	6	7	10	11	12	13	14	18	19	20	23	24
SEED?	Y	N	Y	N	Y	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	321	690	677	105	93	280	149	380	85	402	58	176
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	73.5	126.9	115.4	12.3	30.2	105.3	60.2	75.2	18.5	120.3	21.3	34.9
67 RFLUX 3 DEG - MASS........(KTON)	189	231	610	9	42	117	90	177	27	191	30	41
68 RFLUX 3 DEG - MEAN........(M3/S)	316	385	1016	15	70	195	150	295	45	319	51	68

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	84	85	85	85	85	85	85	85	85	85
MONTH	12	12	12	1	1	1	1	1	2	2	2	2
DAY	19	19	20	7	15	15	18	18	7	16	23	28
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	59	60	67	14	13	38	41	25	81	30	49	82
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	25	26	28	30	31	32	34	35	38	37	40	41
SEED?	N	Y	Y	N	N	Y	N	Y	N	N	Y	Y
SAMPLE?	N	Y	Y	Y	N	Y	N	Y	N	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	64	38	200	368	185	158	66	110	223	13	181	105
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	26.2	14.3	57.3	68.6	55.4	61.5	32.2	47.7	47.0	.9	63.7	36.5
67 RFLUX 3 DEG - MASS.........(KTON)	26	9	101	172	104	113	41	73	74	0	96	60
68 RFLUX 3 DEG - MEAN.........(M3/S)	44	17	169	287	174	188	68	122	124	0	160	100

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	2	3	3	3	3	3	3	3	10	10	10	11
DAY	28	1	1	1	12	12	13	13	16	29	29	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	143	5	76	124	1	75	10	1	1	4	35	10
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	42	43	44	45	46	47	48	49	53	54	55	56
SEED?	Y	N	Y	N	Y	Y	N	N	Y	N	Y	Y
SAMPLE?	Y	N	Y	N	Y	Y	N	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	189	207	360	22	24	79	5	534	376	276	784	544
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	59.4	56.2	81.0	14.1	12.8	11.6	3.0	108.0	80.8	79.2	39.3	160.2
67 RFLUX 3 DEG - MASS.........(KTON)	119	143	171	16	14	16	0	335	164	85	51	307
68 RFLUX 3 DEG - MEAN.........(M3/S)	198	238	284	27	24	27	4	558	274	142	86	512

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	85	85	86	86	86	86	86	86	86	86
MONTH	11	11	12	12	1	1	1	1	1	1	1	2
DAY	9	26	3	14	3	7	14	14	15	18	29	5
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	6	12	38	15	8	13	240	184	37	20	13
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	60	61	62	65	68	71	73	74	76	77	78	80
SEED?	Y	Y	Y	N	Y	N	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	N	Y	N	N	Y	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	679	47	167	270	20	67	491	887	34	25	50	93
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN...........(KM2)	97.4	5.2	36.3	74.2	15.0	31.6	106.3	134.9	15.1	7.9	3.4	34.7
67 RFLUX 3 DEG - MASS.........(KTON)	163	1	65	103	1	42	163	199	15	3	3	76
68 RFLUX 3 DEG - MEAN.........(M3/S)	272	6	108	171	16	70	272	332	25	14	5	127

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	2	3	3	3	3	3	3	3
DAY	5	7	7	13	22	3	10	10	12	13	14	14
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	131	6	37	125	13	31	7	33	25	4	54	36
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	81	82	84	91	93	96	99	100	101	102	103	104
SEED?	Y	N	Y	Y	N	Y	Y	Y	N	N	N	N
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	249	42	706	80	150	39	354	100	181	127	413	49
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN...........(KM2)	71.2	13.6	194.4	35.6	47.4	12.9	87.4	27.0	67.3	71.9	96.1	21.0
67 RFLUX 3 DEG - MASS.........(KTON)	109	24	404	36	54	15	152	50	149	89	232	15
68 RFLUX 3 DEG - MEAN.........(M3/S)	181	40	673	60	90	25	254	84	249	149	387	24

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	86	86	87
MONTH	3	3	11	11	11	11	11	12	12	12	12	1
DAY	14	24	22	24	26	26	27	1	1	2	19	13
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	56	43	46	6	27	54	18	21	94	3	5	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	105	106	113	114	117	118	119	120	121	122	125	128
SEED?	Y	Y	N	Y	N	N	N	N	Y	N	Y	Y
SAMPLE?	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	41	131	99	377	577	109	936	446	789	265	518	148
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	30.3	47.7	35.0	102.0	144.3	29.9	167.5	130.5	131.9	84.4	38.4	25.2
67 RFLUX 3 DEG - MASS........(KTON)	25	53	41	203	283	29	374	328	290	134	46	20
68 RFLUX 3 DEG - MEAN........(M3/S)	42	88	69	338	471	49	623	547	483	224	77	34

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	87	87	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	1	1	2	2	2	2	2	2
DAY	16	19	21	22	23	23	3	3	6	20	20	27
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	118	23	73	26	19	37	8	15	47	11	19	55
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	130	131	133	134	135	136	144	145	151	152	153	154
SEED?	Y	N	N	Y	Y	N	N	Y	Y	N	Y	N
SAMPLE?	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	88	187	227	148	275	588	357	288	580	359	650	15
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	26.5	28.2	9.5	31.3	39.7	96.8	27.6	56.0	48.7	43.5	86.3	.7
67 RFLUX 3 DEG - MASS........(KTON)	25	45	14	74	49	202	27	103	87	60	190	0
68 RFLUX 3 DEG - MEAN........(M3/S)	41	76	23	124	81	336	44	172	145	101	317	1

	85	86
YEAR	87	87
MONTH	3	3
DAY	5	24
SEQUENCE #	11	11
TRACK #	3	50
DBZ THRESHOLD	30	30
TRACK PARAMETERS - MAX SPEED	90	90
MAX TIME INTERVAL	30	30
CASE # IF APPLICABLE	156	169
SEED?	N	N
SAMPLE?	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS		
28 VOLUME - MEAN...............(KM3)	41	26
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS		
52 AREA 3 DEG - MEAN..........(KM2)	24.1	15.7
67 RFLUX 3 DEG - MASS.........(KTON)	21	29
68 RFLUX 3 DEG - MEAN.........(M3/S)	36	49

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 11:41:48

TIME-DEPENDENT PROPERTIES - 20.0 to 30.0 mins after Decision Time.

CASES:- 85

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84/10/30:11-139   84/11/ 1:11- 29   84/11/11:11- 39   84/11/16:11-  1   84/11/27:11-149   84/11/28:11- 39   84/11/29:11- 30
84/11/29:11- 58   84/12/12:11- 10   84/12/13:11- 30   84/12/13:11- 49   84/12/14:11- 38   84/12/17:11- 16   84/12/18:11- 29
84/12/19:11- 59   84/12/20:11- 67   85/ 1/ 7:11- 14   85/ 1/15:11- 13   85/ 1/15:11- 38   85/ 1/15:11-150   85/ 1/18:11- 41
85/ 1/18:11- 25   85/ 2/ 7:11- 81   85/ 2/23:11- 49   85/ 2/28:11- 82   85/ 2/28:11-143   85/ 3/ 1:11-  5   85/ 3/ 1:11- 76
85/ 3/ 1:11-124   85/ 3/12:11-  1   85/ 3/12:11- 75   85/ 3/13:11-  1   85/10/16:11-  1   85/10/29:11-  4   85/10/29:11- 35
85/11/ 2:11- 10   85/11/ 9:11- 41   85/12/ 3:11- 12   85/12/14:11- 38   86/ 1/ 3:11-149   86/ 1/ 7:11-  8   86/ 1/14:11- 13
86/ 1/14:11-240   86/ 1/15:11-184   86/ 1/29:11- 20   86/ 2/ 5:11- 13   86/ 2/ 5:11-131   86/ 2/ 7:11-  6   86/ 2/ 7:11-159
86/ 2/ 7:11- 37   86/ 2/10:11-125   86/ 2/13:11-125   86/ 2/22:11- 13   86/ 3/ 3:11- 31   86/ 3/10:11-  7   86/ 3/10:11- 33
86/ 3/12:11- 25   86/ 3/13:11-  4   86/ 3/14:11- 54   86/ 3/14:11- 36   86/ 3/14:11- 56   86/ 3/24:11- 43   86/11/22:11- 46
86/11/24:11-  6   86/11/26:11- 27   86/11/26:11- 54   86/11/27:11- 18   86/12/ 1:11- 21   86/12/ 1:11- 94   86/12/ 2:11-  3
86/12/19:11-  5   87/ 1/13:11- 37   87/ 1/16:11-118   87/ 1/19:11- 23   87/ 1/21:11- 73   87/ 1/22:11- 26   87/ 1/23:11- 19
87/ 1/23:11- 37   87/ 2/ 3:11-  8   87/ 2/ 3:11- 15   87/ 2/ 6:11- 47   87/ 2/20:11- 11   87/ 2/20:11- 19   87/ 3/ 5:11-  3
87/ 3/24:11- 50
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PROPERTY VALUE LIMITS

	MIN	MAX	
7 MEAN RANGE	10.0	80.0	KM
9 VOL AT DECISION TIME	0	750	KM3
244 TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	10	11	11	11	11	11	11	11	12	12	12	12
DAY	30	1	11	16	27	28	29	29	12	13	13	14
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	29	39	1	149	39	30	58	10	30	49	38
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	6	7	10	11	12	13	14	18	19	20	21
SEED?	N	Y	N	Y	N	Y	Y	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	8	163	594	635	84	79	213	97	336	87	191	44
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	.0	48.2	135.2	116.4	10.1	28.6	74.7	45.5	68.8	21.1	83.8	10.0
67 RFLUX 3 DEG - MASS.........(KTON)	0	59	213	655	8	3	87	54	165	30	83	8
66 RFLUX 3 DEG - MEAN.........(M3/S)	0	99	356	1091	14	60	145	91	275	49	138	16

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	84	84	85	85	85	85	85	85	85	85
MONTH	12	12	12	12	1	1	1	1	1	1	2	2
DAY	17	18	19	20	7	15	15	15	18	18	7	23
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	16	29	59	67	14	13	38	150	41	25	81	49
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	23	24	25	28	30	31	32	33	34	35	38	40
SEED?	N	N	N	Y	N	N	Y	Y	N	Y	N	Y
SAMPLE?	N	N	N	Y	Y	N	Y	Y	N	Y	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	13	36	20	51	364	143	162	71	112	77	153	283
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	10.4	10.5	10.7	27.5	73.0	57.6	66.7	2.4	53.1	35.2	46.7	107.7
67 RFLUX 3 DEG - MASS........(KTON)	4	11	7	28	170	96	93	3	79	65	66	174
68 RFLUX 3 DEG - MEAN........(M3/S)	11	18	13	47	284	160	154	5	131	108	110	290

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	2	2	3	3	3	3	3	3	10	10	10	11
DAY	28	28	1	1	1	12	12	13	16	29	29	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	82	143	5	76	124	1	75	1	1	4	35	10
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	41	42	43	44	45	46	47	49	53	54	55	56
SEED?	Y	Y	N	Y	N	Y	Y	N	Y	N	Y	Y
SAMPLE?	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	111	139	322	379	13	11	80	536	300	439	890	168
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	34.6	39.6	80.7	88.2	9.6	6.4	15.5	149.0	65.5	90.6	58.8	53.7
67 RFLUX 3 DEG - MASS........(KTON)	81	98	191	165	1	4	20	265	159	102	101	132
68 RFLUX 3 DEG - MEAN........(M3/S)	135	163	319	275	18	7	33	441	265	170	168	220

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	85	86	86	86	86	86	86	86	86	86
MONTH	11	12	12	1	1	1	1	1	1	2	2	2
DAY	9	3	14	3	7	14	14	15	29	5	5	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	12	38	149	8	13	240	184	20	13	131	6
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	60	62	65	70	71	73	74	76	78	80	81	82
SEED?	Y	Y	N	Y	N	N	N	N	N	N	Y	N
SAMPLE?	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	757	76	217	55	25	592	1093	10	48	90	442	20
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	130.8	27.5	68.0	12.0	16.0	133.1	196.0	7.3	2.2	39.8	89.1	9.4
67 RFLUX 3 DEG - MASS........(KTON)	230	44	77	8	14	237	68	1	2	52	224	17
68 RFLUX 3 DEG - MEAN........(M3/S)	383	73	128	18	23	394	535	8	3	87	374	29

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	2	3	3	3	3	3	3	3
DAY	7	7	10	13	22	3	10	10	12	13	14	14
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	159	37	125	125	13	31	7	33	25	4	54	36
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	83	84	85	91	93	96	99	100	101	102	103	104
SEED?	N	Y	N	Y	N	Y	Y	Y	N	N	N	N
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	143	728	15	11	33	29	447	143	85	34	369	19
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	55.6	190.3	1.7	6.9	17.5	12.1	106.5	41.6	38.7	25.8	108.2	10.0
67 RFLUX 3 DEG - MASS........(KTON)	57	468	0	4	15	0	194	68	101	7	166	10
68 RFLUX 3 DEG - MEAN........(M3/S)	138	780	1	8	26	21	323	114	169	38	276	17

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	86	86	87
MONTH	3	3	11	11	11	11	11	12	12	12	12	1
DAY	14	24	22	24	26	26	27	1	1	2	19	13
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	56	43	46	6	27	54	18	21	94	3	5	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	105	106	113	114	117	118	119	120	121	122	125	128
SEED?	Y	Y	N	Y	N	N	N	N	Y	N	Y	Y
SAMPLE?	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	8	273	53	362	602	44	1227	248	484	332	692	24
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	6.1	112.3	22.4	110.0	153.6	16.7	141.4	106.6	158.2	94.7	95.7	5.8
67 RFLUX 3 DEG - MASS........(KTON)	4	52	23	211	325	16	468	129	223	136	214	4
68 RFLUX 3 DEG - MEAN........(M3/S)	7	188	38	352	542	27	780	215	372	226	356	8

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	87	87	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	1	1	2	2	2	2	2	3
DAY	16	19	21	22	23	23	3	3	6	20	20	5
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	118	23	73	26	19	37	8	15	47	11	19	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	130	131	133	134	135	136	144	145	151	152	153	156
SEED?	Y	N	N	Y	Y	N	N	Y	Y	N	Y	N
SAMPLE?	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	51	302	98	69	192	338	353	770	552	270	540	14
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	20.6	37.8	13.3	26.9	17.0	100.8	26.6	125.3	46.8	38.7	108.5	12.3
67 RFLUX 3 DEG - MASS........(KTON)	13	54	18	38	16	133	30	304	69	49	160	2
68 RFLUX 3 DEG - MEAN........(M3/S)	30	89	30	64	27	222	51	507	115	82	267	15

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..............................................................................................................
                                           85

  YEAR                                     87
  MONTH                                     3
  DAY                                      24
  SEQUENCE #                               11
  TRACK #                                  50

  DBZ THRESHOLD                            30
  TRACK PARAMETERS - MAX SPEED             90
             MAX TIME INTERVAL             30

  CASE # IF APPLICABLE                    169
  SEED?                                     N
  SAMPLE?                                   Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS


===============================
 28 VOLUME - MEAN...............(KM3)      22

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS
============================================
 52 AREA 3 DEG - MEAN..........(KM2)     15.2
 67 RFLUX 3 DEG - MASS........(KTON)        0
 68 RFLUX 3 DEG - MEAN........(M3/S)       37

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TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 12: 2:49

TIME-DEPENDENT PROPERTIES - 30.0 to 40.0 mins after Decision Time.

CASES:- 70

84/10/30:11-139	84/11/ 1:11- 29	84/11/11:11- 39	84/11/16:11- 1	84/11/27:11-149	84/11/29:11- 30	84/11/29:11- 58
84/12/12:11- 10	84/12/13:11- 30	84/12/13:11- 49	84/12/14:11- 38	84/12/18:11- 29	84/12/20:11- 67	85/ 1/ 7:11- 14
85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/15:11-150	85/ 1/18:11- 41	85/ 1/18:11- 25	85/ 2/ 7:11- 81	85/ 2/23:11- 49
85/ 2/28:11- 82	85/ 2/28:11-143	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/12:11- 75	85/ 3/13:11- 1	85/10/16:11- 1
85/10/29:11- 4	85/10/29:11- 35	85/11/ 2:11- 10	85/11/ 9:11- 41	85/12/ 3:11- 12	85/12/14:11- 38	86/ 1/ 3:11-149
86/ 1/ 7:11- 8	86/ 1/14:11- 13	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11-159
86/ 2/ 7:11- 37	86/ 2/10:11-125	86/ 2/22:11- 13	86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/14:11- 54
86/ 3/14:11- 36	86/ 3/14:11- 56	86/11/22:11- 46	86/11/24:11- 6	86/11/26:11- 27	86/11/26:11- 54	86/11/27:11- 18
86/12/ 1:11- 21	86/12/ 1:11- 94	86/12/ 2:11- 3	86/12/19:11- 5	87/ 1/19:11- 23	87/ 1/21:11- 73	87/ 1/22:11- 26
87/ 1/23:11- 19	87/ 1/23:11- 37	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11	87/ 2/20:11- 19

PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	10	11	11	11	11	11	11	12	12	12	12	12
DAY	30	1	11	16	27	29	29	12	13	13	14	18
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	29	39	1	149	30	58	10	30	49	38	29
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	6	7	10	11	13	14	18	19	20	21	24
SEED?	N	Y	N	Y	N	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	24	95	321	560	66	231	67	337	32	28	255	17
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	6.7	34.7	103.7	132.2	9.2	81.0	32.3	64.5	7.5	15.5	49.1	4.5
67 RFLUX 3 DEG - MASS.........(KTON)	6	8	109	718	1	106	35	163	5	12	67	1
68 RFLUX 3 DEG - MEAN.........(M3/S)	10	48	181	1197	14	177	59	271	10	20	112	10

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	85	85	85	85	85	85	85	85	85	85	85
MONTH	12	1	1	1	1	1	1	2	2	2	2	3
DAY	20	7	15	15	15	18	18	7	23	28	28	1
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	67	14	13	38	150	41	25	81	49	82	143	5
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	28	30	31	32	33	34	35	38	40	41	42	43
SEED?	Y	N	N	Y	Y	N	Y	N	Y	Y	Y	N
SAMPLE?	Y	Y	N	Y	Y	N	Y	N	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	7	411	48	114	121	102	94	84	222	113	102	367
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	5.7	72.7	30.5	47.2	22.1	44.1	38.5	24.4	79.1	33.5	35.6	80.6
67 RFLUX 3 DEG - MASS.........(KTON)	2	210	34	57	67	69	55	40	118	85	8	185
68 RFLUX 3 DEG - MEAN.........(M3/S)	7	350	57	94	112	115	92	67	197	142	134	308

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	86	86
MONTH	3	3	3	10	10	10	11	11	12	12	1	1
DAY	1	12	13	16	29	29	2	9	3	14	3	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	76	75	1	1	4	35	10	41	12	38	149	8
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	44	47	49	53	54	55	56	60	62	65	70	71
SEED?	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	325	26	441	306	616	751	94	876	30	281	127	23
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	91.1	7.2	123.8	62.0	135.7	84.8	40.9	132.3	15.9	88.7	28.0	13.2
67 RFLUX 3 DEG - MASS.........(KTON)	145	6	201	196	217	162	75	218	8	127	26	13
68 RFLUX 3 DEG - MEAN.........(M3/S)	242	9	336	326	361	270	125	363	28	211	43	22

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	1	1	2	2	2	2	2	2	2	3	3	3
DAY	14	29	5	5	7	7	7	10	22	10	10	12
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	13	20	13	131	6	159	37	125	13	7	33	25
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	73	78	80	81	82	83	84	85	93	99	100	101
SEED?	N	N	N	Y	N	N	Y	N	N	Y	Y	N
SAMPLE?	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	596	60	102	625	34	68	600	13	6	782	232	68
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	136.8	3.2	33.6	109.6	15.8	35.4	173.9	3.0	4.3	190.9	67.3	27.8
67 RFLUX 3 DEG - MASS........(KTON)	208	3	65	279	33	36	366	2	1	336	98	66
68 RFLUX 3 DEG - MEAN........(M3/S)	347	4	108	465	55	61	611	3	5	561	163	110

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	3	3	3	11	11	11	11	11	12	12	12	12
DAY	14	14	14	22	24	26	26	27	1	1	2	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	54	36	56	46	6	27	54	18	21	94	3	5
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	103	104	105	113	114	117	118	119	120	121	122	125
SEED?	N	N	Y	N	Y	N	N	N	N	Y	N	Y
SAMPLE?	N	N	Y	N	Y	N	N	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	166	87	14	25	292	747	18	1533	63	107	287	699
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	73.4	26.8	6.9	13.4	105.5	114.5	9.8	154.2	28.0	52.2	96.9	132.5
67 RFLUX 3 DEG - MASS........(KTON)	64	30	7	8	150	260	7	485	25	52	153	392
68 RFLUX 3 DEG - MEAN........(M3/S)	107	50	13	18	250	433	13	809	41	86	256	653

	61	62	63	64	65	66	67	68	69	70
YEAR	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	1	2	2	2	2	2
DAY	19	21	22	23	23	3	3	6	20	20
SEQUENCE #	11	11	11	11	11	11	11	11	11	11
TRACK #	23	73	26	19	37	8	15	47	11	19
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	131	133	134	135	136	144	145	151	152	153
SEED?	N	N	Y	Y	N	N	Y	Y	N	Y
SAMPLE?	N	N	Y	Y	Y	Y	Y	Y	Y	Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS

	61	62	63	64	65	66	67	68	69	70
28 VOLUME - MEAN...............(KM3)	534	28	56	150	120	470	1363	320	126	379

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

	61	62	63	64	65	66	67	68	69	70
52 AREA 3 DEG - MEAN..........(KM2)	59.4	3.6	31.4	4.5	66.7	58.6	198.5	32.1	22.6	71.7
67 RFLUX 3 DEG - MASS.........(KTON)	109	2	3	3	18	99	530	30	23	124
68 RFLUX 3 DEG - MEAN.........(M3/S)	181	9	46	4	99	166	884	50	38	207

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 12:13:42

TIME-DEPENDENT PROPERTIES - 40.0 to 50.0 mins after Decision Time.

CASES:- 56

84/10/30:11-139	84/11/11:11- 39	84/11/16:11- 1	84/11/29:11- 30	84/11/29:11- 58	84/12/12:11- 10	84/12/13:11- 49
84/12/14:11- 38	85/ 1/ 7:11- 14	85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/15:11-150	85/ 1/18:11- 41	85/ 1/18:11- 25
85/ 2/ 7:11- 81	85/ 2/23:11- 49	85/ 2/28:11- 82	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/12:11- 75	85/ 3/13:11- 1
85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35	85/11/ 2:11- 10	85/11/ 9:11- 41	85/12/14:11- 38	86/ 1/ 3:11-149
86/ 1/ 7:11- 8	86/ 1/14:11- 13	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11-159
86/ 2/ 7:11- 37	86/ 2/10:11-125	86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/14:11- 54	86/ 3/14:11- 36
86/11/24:11- 6	86/11/26:11- 27	86/11/27:11- 18	86/12/ 1:11- 21	86/12/ 1:11- 94	86/12/ 2:11- 3	86/12/19:11- 5
87/ 1/19:11- 23	87/ 1/23:11- 19	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11	87/ 2/20:11- 19

PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	85	85	85	85
MONTH	10	11	11	11	11	12	12	12	1	1	1	1
DAY	30	11	16	29	29	12	13	14	7	15	15	15
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	39	1	30	58	10	49	38	14	13	38	150
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	7	10	13	14	18	20	21	30	31	32	33
SEED?	N	N	Y	Y	N	N	N	N	N	N	Y	Y
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	25	114	403	210	58	282	9	763	412	28	21	52
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	12.4	45.9	114.7	74.9	23.4	59.6	5.4	122.9	83.0	21.3	9.5	17.6
67 RFLUX 3 DEG - MASS........(KTON)	10	26	543	83	30	140	4	170	212	0	9	26
68 RFLUX 3 DEG - MEAN........(M3/S)	16	59	905	139	49	233	7	284	353	29	14	43

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	1	1	2	2	2	3	3	3	3	10	10	10
DAY	18	18	7	23	28	1	1	12	13	16	29	29
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	25	81	49	82	5	76	75	1	1	4	35
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	34	35	38	40	41	43	44	47	49	53	54	55
SEED?	N	Y	N	Y	Y	N	Y	Y	N	Y	N	Y
SAMPLE?	N	Y	N	Y	Y	N	Y	Y	Y	Y	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	90	208	37	233	71	212	106	11	418	287	721	440
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	34.5	98.4	10.5	77.7	24.2	58.5	40.1	2.7	78.1	66.0	162.8	84.0
67 RFLUX 3 DEG - MASS........(KTON)	32	144	14	136	51	107	42	2	142	185	316	153
68 RFLUX 3 DEG - MEAN........(M3/S)	79	240	23	227	86	179	89	4	236	309	527	254

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	86	86	86	86	86	86	86	86	86
MONTH	11	11	12	1	1	1	1	2	2	2	2	2
DAY	2	9	14	3	7	14	29	5	5	7	7	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	10	41	38	149	8	13	20	13	131	6	159	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	56	60	65	70	71	73	78	80	81	82	83	84
SEED?	Y	Y	N	Y	N	N	N	N	Y	N	N	Y
SAMPLE?	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	92	958	99	180	7	402	28	140	662	19	8	491
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	42.7	127.4	45.3	32.5	5.3	119.9	.8	35.6	148.3	14.1	6.3	188.4
67 RFLUX 3 DEG - MASS........(KTON)	21	238	44	34	3	151	1	73	347	5	1	301
68 RFLUX 3 DEG - MEAN........(M3/S)	105	396	74	56	7	252	1	122	578	23	6	501

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	3	3	3	3	3	11	11	11	12	12	12
DAY	10	10	10	12	14	14	24	26	27	1	1	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	125	7	33	25	54	36	6	27	18	21	94	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	85	99	100	101	103	104	114	117	119	120	121	122
SEED?	N	Y	Y	N	N	N	Y	N	N	N	Y	N
SAMPLE?	Y	Y	Y	Y	N	N	Y	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	62	814	145	67	90	216	207	713	1434	13	41	111
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	11.4	211.1	41.5	37.8	51.3	53.4	74.2	118.2	166.5	7.2	13.9	45.8
67 RFLUX 3 DEG - MASS........(KTON)	10	339	63	43	1	72	126	303	460	2	4	51
68 RFLUX 3 DEG - MEAN........(M3/S)	16	565	105	72	63	120	211	505	767	8	22	85

	49	50	51	52	53	54	55	56
YEAR	86	87	87	87	87	87	87	87
MONTH	12	1	1	2	2	2	2	2
DAY	19	19	23	3	3	6	20	20
SEQUENCE #	11	11	11	11	11	11	11	11
TRACK #	5	23	19	8	15	47	11	19
DBZ THRESHOLD	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	125	131	135	144	145	151	152	153
SEED?	Y	N	Y	N	Y	Y	N	Y
SAMPLE?	Y	N	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS								
28 VOLUME - MEAN..............(KM3)	676	571	91	388	1199	117	35	339
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS								
52 AREA 3 DEG - MEAN..........(KM2)	203.0	61.9	.8	56.3	181.7	18.5	8.3	54.9
67 RFLUX 3 DEG - MASS........(KTON)	467	134	0	136	481	5	5	75
68 RFLUX 3 DEG - MEAN........(M3/S)	778	224	1	226	802	22	8	124

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 12:19:24

TIME-DEPENDENT PROPERTIES - 50.0 to 60.0 mins after Decision Time.

CASES:- 42

84/10/30:11-139	84/11/16:11- 1	84/11/29:11- 30	84/11/29:11- 58	84/12/12:11- 10	84/12/13:11- 49	84/12/14:11- 38
85/ 1/ 7:11- 14	85/ 1/15:11- 38	85/ 1/15:11-150	85/ 1/18:11- 25	85/ 2/ 7:11- 81	85/ 2/23:11- 49	85/ 2/28:11- 82
85/ 3/ 1:11- 5	85/ 3/13:11- 1	85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35	85/11/ 9:11- 41	85/12/14:11- 38
86/ 1/ 3:11-149	86/ 1/14:11- 13	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 37	86/ 2/10:11-125
86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/14:11- 36	86/11/24:11- 6	86/11/26:11- 27	86/11/27:11- 18
86/12/ 2:11- 3	86/12/19:11- 5	87/ 1/19:11- 23	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/20:11- 11	87/ 2/20:11- 19

PROPERTY VALUE LIMITS

	MIN	MAX	
7 MEAN RANGE	10.0	80.0	KM
9 VOL AT DECISION TIME	0	750	KM3
244 TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	85	85	85	85	85
MONTH	10	11	11	11	12	12	12	1	1	1	1	2
DAY	30	16	29	29	12	13	14	7	15	15	18	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	1	30	58	10	49	38	14	38	150	25	81
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	10	13	14	18	20	21	30	32	33	35	38
SEED?	N	Y	Y	N	N	N	N	N	Y	Y	Y	N
SAMPLE?	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	12	333	178	61	192	11	1046	370	12	27	184	18
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	7.6	103.4	62.8	23.3	52.2	6.4	135.1	62.7	5.9	9.3	83.2	7.2
67 RFLUX 3 DEG - MASS........(KTON)	4	447	68	27	103	1	200	204	0	1	119	8
68 RFLUX 3 DEG - MEAN........(M3/S)	9	745	113	45	172	7	333	341	7	17	198	13

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	85	85	85	85	85	85	85	85	85	86	86	86
MONTH	2	2	3	3	10	10	10	11	12	1	1	1
DAY	23	28	1	13	16	29	29	9	14	3	14	29
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	49	82	5	1	1	4	35	41	38	149	13	20
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	40	41	43	49	53	54	55	60	65	70	73	78
SEED?	Y	Y	N	N	Y	N	Y	Y	N	Y	N	N
SAMPLE?	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	303	21	79	450	244	949	214	812	78	190	97	14
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN...........(KM2)	101.8	11.5	21.5	80.7	69.6	212.0	37.1	148.6	29.2	46.9	45.4	.6
67 RFLUX 3 DEG - MASS.........(KTON)	210	14	19	116	197	360	55	290	32	59	39	1
68 RFLUX 3 DEG - MEAN.........(M3/S)	350	23	31	193	328	600	105	483	54	99	65	1

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	3	3	3	3	11	11	11	12
DAY	5	5	7	10	10	10	12	14	24	26	27	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	13	131	37	125	7	33	25	36	6	27	18	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	80	81	84	85	99	100	101	104	114	117	119	122
SEED?	N	Y	Y	N	Y	Y	N	N	Y	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	118	479	605	367	440	116	103	360	202	526	1206	45
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN...........(KM2)	35.3	156.9	246.6	53.8	154.7	26.4	41.6	63.8	46.7	120.3	167.6	8.5
67 RFLUX 3 DEG - MASS.........(KTON)	42	259	392	50	191	40	59	122	170	204	487	9
68 RFLUX 3 DEG - MEAN.........(M3/S)	71	431	653	84	318	75	99	204	283	340	811	16

	37	38	39	40	41	42
YEAR	86	87	87	87	87	87
MONTH	12	1	2	2	2	2
DAY	19	19	3	3	20	20
SEQUENCE #	11	11	11	11	11	11
TRACK #	5	23	8	15	11	19
DBZ THRESHOLD	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30
CASE # IF APPLICABLE	125	131	144	145	152	153
SEED?	Y	N	N	Y	N	Y
SAMPLE?	Y	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS						
28 VOLUME - MEAN...............(KM3)	470	736	75	1179	16	414
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS						
52 AREA 3 DEG - MEAN...........(KM2)	152.7	78.5	24.3	174.6	4.2	73.2
67 RFLUX 3 DEG - MASS.........(KTON)	326	178	36	8	0	87
68 RFLUX 3 DEG - MEAN.........(M3/S)	543	297	60	798	4	145

APPENDIX B

PAWS : Summary of all storms tracked by radar on all operational days.

DAY PROPERTIES ON FILE

Year	Month	Day	Ses	# Tracks	ATI	Max V	Max ROI V	Max Top	Max Dbz
82	11	12	11	2	49	250	.484	11940	52.4
82	11	19	11	19	505	2218	.859	14239	63.6
82	11	20	11	16	945	3633	1.710	16365	54.3
82	11	21	11	14	163	261	.148	12139	65.3
82	11	24	11	29	1166	1462	.771	15044	66.3
82	11	29	11	84	1905	1805	1.803	16005	63.7
82	12	7	11	15	267	409	.510	10119	59.5
82	12	8	11	53	1593	1837	1.254	15750	61.2
82	12	10	11	6	407	1087	.290	13499	65.0
82	12	15	11	8	460	613	.863	13142	61.5
82	12	16	11	43	795	766	.902	15295	61.1
82	12	17	11	17	216	609	.700	13975	56.2
82	12	23	11	48	2286	5041	2.941	17080	63.0
82	12	29	11	31	1472	2452	5.440	16238	61.0
82	12	30	11	47	1260	1674	3.285	16694	61.6
82	12	31	11	56	791	405	.285	12041	55.3
83	1	3	11	52	1925	2728	1.744	16761	59.6
83	1	4	11	37	749	736	.695	14987	60.6
83	1	5	11	63	1355	1189	1.205	15385	69.8
83	1	19	11	4	67	252	.282	10637	55.5
83	1	21	11	40	1186	1072	1.385	15791	58.7
83	2	2	11	34	705	798	.902	14790	60.3
83	2	3	11	3	115	345	.555	14258	58.4
83	2	4	11	27	833	1643	1.676	16548	63.7
83	2	7	11	33	1024	1365	1.712	18355	59.6
83	2	8	11	11	199	236	.261	12308	57.9
83	2	11	11	23	597	865	.603	14081	63.2
83	2	12	11	49	1196	1287	1.177	14078	62.4
83	3	3	11	34	1482	1838	2.022	15725	65.4
83	3	7	11	3	119	259	.503	11760	56.7
83	3	8	11	7	197	841	.765	12499	64.1
83	3	15	11	20	362	853	.677	13889	57.3
83	3	18	11	5	36	176	.340	9601	59.8
83	3	22	11	19	646	1091	2.098	15832	65.2
83	3	31	11	10	45	83	.132	9229	57.8
83	4	4	11	10	328	1166	.873	13871	58.6
83	4	5	11	9	257	1064	.985	15271	55.7
83	4	11	11	67	1855	1350	1.286	11918	64.0
83	4	12	11	23	670	415	.519	12133	60.9
83	4	13	11	68	2705	2121	1.174	15927	62.2
83	4	15	11	31	664	1233	1.178	13883	65.3
83	10	13	11	16	329	597	.527	11579	59.0
83	10	20	11	10	132	558	.616	7986	60.4
83	10	21	11	6	272	369	.525	10690	58.7
83	10	24	11	26	805	905	1.096	10870	62.6
83	11	4	11	6	205	633	.991	14213	57.8
83	11	5	11	99	2628	1702	2.772	14765	64.7
83	11	6	11	38	2533	1689	1.117	14762	63.3
83	11	9	11	15	610	1388	.324	15035	63.1
83	11	12	11	7	486	631	.539	12142	64.0
83	11	14	11	36	1320	1323	2.139	14711	64.3
83	11	15	11	2	197	1030	1.478	11433	59.4
83	11	16	11	9	635	1227	.774	13604	63.1
83	11	17	11	25	1136	1174	.849	14022	66.3
83	11	18	11	14	284	787	.115	12761	58.8
83	11	23	11	2	129	643	.480	14886	62.2
83	11	24	11	28	580	1098	2.221	15316	54.7
83	12	7	11	15	424	602	.718	14450	61.6

83	12	9	11	41	1344	2625	2.156	18015	62.7
83	12	12	11	18	521	761	.808	15416	58.7
83	12	30	11	35	1290	1047	1.206	12934	65.6
84	1	2	11	88	2029	1398	1.264	16294	63.1
84	2	2	11	17	303	208	.241	13200	59.6
84	2	6	11	10	285	805	.895	16574	58.7
84	2	8	11	15	1264	3689	1.815	19257	62.5
84	2	15	11	16	345	680	.698	12703	54.6
84	2	20	11	32	644	408	.628	13575	59.5
84	2	24	11	92	2859	3684	.966	13325	67.0
84	3	2	11	13	115	301	.282	13335	51.4
84	3	7	11	65	1849	1364	1.186	15828	63.5
84	3	20	11	22	498	997	1.622	14505	60.9
84	3	21	11	24	446	427	.479	10271	57.6
84	3	30	11	8	107	154	.293	6931	53.7
84	4	8	11	77	2251	2424	1.031	16439	62.4
84	4	17	11	15	379	739	.712	12084	60.8
84	4	25	11	15	113	57	.079	7663	52.1
84	10	8	11	6	47	204	.327	9335	53.8
84	10	15	11	18	827	967	1.359	10382	64.1
84	10	19	11	12	230	442	.445	12686	55.7
84	10	22	11	114	3014	2282	1.245	13642	67.8
84	10	29	11	15	536	915	1.150	13879	61.8
84	10	30	11	66	1390	900	.959	11595	63.6
84	11	1	11	168	4188	3560	2.263	14803	70.9
84	11	10	11	4	206	1237	.445	14064	54.7
84	11	11	11	9	247	748	1.089	12875	54.8
84	11	12	11	275	9225	9458	5.912	15698	69.3
84	11	16	11	39	1432	1733	1.055	13113	71.7
84	11	27	11	29	1252	800	1.092	13439	61.2
84	11	28	11	46	1791	1743	1.609	14850	66.1
84	11	29	11	104	1426	837	1.147	11191	68.0
84	12	4	11	6	97	261	.325	11845	52.4
84	12	10	11	123	4109	3720	2.560	16852	65.9
84	12	12	11	27	1191	2408	1.195	15505	63.7
84	12	13	11	83	1375	1815	1.327	14931	64.8
84	12	14	11	54	1323	2400	1.398	15407	58.7
84	12	17	11	23	469	902	1.198	14998	59.4
84	12	18	11	23	956	1161	1.710	15942	58.3
84	12	19	11	40	999	988	.918	15881	58.2
84	12	20	11	44	537	538	.569	14916	62.8
85	1	4	11	47	2929	3790	2.477	18446	62.7
85	1	7	11	24	475	484	.697	13932	62.8
85	1	15	11	109	1609	1211	.795	14498	65.2
85	1	17	11	64	1381	1180	.580	10996	63.7
85	1	18	11	84	1722	2038	1.069	16807	67.6
85	2	7	11	33	486	305	.399	13075	56.8
85	2	16	11	22	358	433	.547	15476	50.9
85	2	23	11	57	1550	1500	1.648	14360	59.4
85	2	28	11	48	1245	629	.980	15474	59.5
85	3	1	11	42	1259	1407	1.465	16766	68.3
85	3	8	11	3	45	153	.217	9915	52.2
85	3	12	11	24	595	292	.627	12279	59.2
85	3	13	11	39	756	572	.521	13629	60.6
85	10	8	11	15	620	1313	1.079	12665	54.1
85	10	8	22	15	600	1313	1.079	12665	54.1
85	10	14	11	6	496	750	.457	12731	60.8
85	10	14	22	6	496	750	.457	12731	60.8
85	10	16	11	9	1159	1537	.825	13543	60.4
85	10	16	22	10	1160	1537	.572	13543	60.4
85	10	29	11	51	2786	5875	2.034	17321	61.4
85	10	29	22	49	2786	5875	2.034	17321	61.4
85	11	2	11	17	696	738	1.080	14021	58.2

85	11	2	22	17	695	738	1.080	14021	58.2
85	11	7	11	49	859	964	1.087	16217	58.1
85	11	7	22	47	852	964	1.087	16217	58.1
85	11	8	11	68	3491	2661	2.657	14306	62.0
85	11	8	22	68	3510	2661	2.657	14306	62.0
85	11	9	11	123	4005	3216	2.564	16249	60.8
85	11	9	22	110	4027	3216	2.564	16249	60.8
85	11	22	11	22	452	1379	1.550	14214	54.2
85	11	22	22	22	452	1379	1.550	14214	54.2
85	11	26	11	5	58	288	.279	10134	56.3
85	11	26	22	5	58	288	.279	10134	56.3
85	12	3	11	12	259	548	.514	11934	55.0
85	12	3	22	12	259	548	.514	11934	55.0
85	12	4	22	7	35	65	.092	8436	54.2
85	12	7	11	57	2204	1447	2.089	14624	61.0
85	12	7	22	57	2203	1447	2.089	14624	61.0
85	12	14	11	76	1413	1356	1.179	15470	56.9
85	12	14	22	74	1407	1356	1.179	15470	63.1
85	12	30	11	55	2144	2555	1.675	16554	65.7
85	12	30	22	54	2130	2555	1.675	16554	65.7
86	1	3	11	44	1419	1119	1.113	13384	60.3
86	1	3	22	39	1398	1119	1.113	13384	60.3
86	1	7	11	9	261	287	.294	11467	58.1
86	1	7	22	9	261	287	.294	11467	58.1
86	1	13	11	39	2102	5375	2.378	17588	61.0
86	1	13	22	39	2102	5375	2.378	17588	61.0
86	1	14	11	55	2835	2241	2.304	18051	61.1
86	1	14	22	54	2806	2241	1.782	18051	61.1
86	1	15	11	103	3645	7168	5.209	18170	63.5
86	1	15	22	96	3590	7168	5.209	18170	63.5
86	1	18	11	63	961	402	.305	12090	61.1
86	1	18	22	66	968	402	.305	12090	61.1
86	1	29	11	70	1338	1056	.975	15976	64.5
86	1	29	22	71	1367	1056	.975	15976	64.5
86	2	5	11	95	1887	1057	.964	14100	60.8
86	2	5	22	97	1905	1057	.964	14100	60.8
86	2	7	11	66	2854	2592	1.839	15869	60.9
86	2	7	22	63	2792	2592	1.839	15869	60.9
86	2	10	11	47	1013	799	.968	12092	60.4
86	2	10	22	49	1004	799	.968	12092	60.4
86	2	11	11	75	2853	1536	1.603	13575	66.0
86	2	11	22	72	2836	1536	1.603	13575	66.0
86	2	12	11	62	2823	1848	1.501	14701	67.5
86	2	12	22	61	2802	1848	1.983	14701	67.5
86	2	13	11	47	710	593	.344	13219	58.4
86	2	13	22	51	714	593	.344	13219	58.4
86	2	21	11	41	841	889	.888	14915	57.0
86	2	21	22	41	841	889	.888	14915	57.0
86	2	22	11	74	2553	3177	2.440	17183	59.1
86	2	22	22	73	2533	3177	2.440	17183	59.1
86	3	3	11	18	404	724	.447	13882	56.6
86	3	3	22	16	393	724	.447	13882	56.6
86	3	6	11	32	469	401	.424	13351	58.1
86	3	6	22	30	460	401	.424	13351	58.1
86	3	10	11	116	3531	2271	2.160	15897	61.1
86	3	12	11	30	741	583	.650	15336	60.3
86	3	12	22	30	740	583	.650	15336	60.3
86	3	13	11	10	368	461	.537	14149	60.2
86	3	13	22	10	368	461	.537	14149	60.2
86	3	14	11	40	1099	2170	1.086	16224	58.3
86	3	14	22	39	1087	2170	1.086	16224	58.3
86	3	24	11	91	1532	787	.885	12625	55.9
86	3	24	22	81	1480	787	.674	12625	55.9

86	10	27	11	97	2837	2091	2.000	14511	64.3
86	11	18	11	31	1266	2947	2.627	15472	56.1
86	11	22	11	11	131	222	.161	11009	57.9
86	11	24	11	7	316	463	.473	11079	58.3
86	11	25	11	25	478	297	.526	10196	58.8
86	11	26	11	46	1331	901	.779	13959	61.0
86	11	27	11	18	1302	1630	.786	15681	65.0
86	12	1	11	28	1039	815	.835	14746	63.1
86	12	2	11	44	1359	1072	.998	14224	60.9
86	12	3	11	41	709	930	1.430	13982	70.2
86	12	19	11	44	3373	3005	2.772	13992	70.5
87	1	7	11	8	504	2783	1.699	15324	62.1
87	1	13	11	25	1049	1928	1.481	16704	59.8
87	1	16	11	75	980	427	.456	13456	56.2
87	1	19	11	68	3773	5870	5.365	20128	67.8
87	1	21	11	29	1647	3676	2.194	17222	62.6
87	1	22	11	13	639	1347	.798	16753	60.0
87	1	23	11	20	371	672	.687	14506	57.1
87	1	28	11	23	1269	4687	5.338	18202	57.1
87	1	29	11	8	145	505	.831	14998	56.4
87	1	30	11	41	2852	8931	5.079	18271	69.5
87	2	2	11	27	1630	2366	1.740	16641	64.4
87	2	3	11	100	5311	4817	6.579	16688	67.0
87	2	4	11	50	987	848	1.255	16406	63.2
87	2	6	11	14	290	624	.684	17322	60.2
87	2	20	11	45	900	766	.801	14896	57.4
87	2	27	11	76	2857	5841	4.713	16840	69.5
87	3	5	11	4	217	1221	.708	15695	59.7
87	3	6	11	24	2232	3544	3.799	16236	63.0
87	3	9	11	46	2329	5648	3.290	15622	68.7
87	3	13	11	38	1583	2045	1.536	16323	70.7
87	3	19	11	27	980	590	.787	15262	66.0
87	3	24	11	31	663	552	.727	12042	65.9
88	3	16	11	6	73	815	1.035	14826	48.6
88	3	17	11	17	318	467	.764	13787	50.5
88	4	7	11	26	382	278	.362	10857	56.7
88	4	8	11	23	317	274	.234	9941	49.8
88	10	17	11	77	2416	2942	2.866	15486	59.7
88	11	3	11	68	3550	3189	2.816	15987	65.9
88	11	9	11	56	4365	4728	4.729	14416	62.0
88	11	26	11	43	1050	764	.530	14102	66.0
88	11	28	11	108	3909	4081	4.194	16004	64.8
88	12	2	11	89	2035	1500	2.394	13955	57.0
88	12	5	11	49	3942	3514	2.080	13769	60.5
88	12	12	11	92	3244	1446	1.474	12855	62.8
88	12	15	11	91	2752	1762	1.801	19635	63.4
88	12	20	11	35	778	1591	1.420	14662	58.6
88	12	21	11	138	5196	4882	6.637	16349	63.8
89	1	9	11	153	5201	2722	1.918	14871	61.3
89	1	10	11	45	1467	1267	.679	14477	63.0
89	1	11	11	61	1600	1042	1.082	13686	60.4
89	2	14	11	263	3836	3020	1.709	22080	60.6
89	3	1	11	37	998	925	.766	13614	60.3
89	3	2	11	135	2916	1457	1.596	15172	58.7
89	3	13	11	62	1659	2366	1.368	15551	54.2

END OF DATA

APPENDIX C : LEGAL CONSIDERATIONS

1 INTRODUCTION

This appendix presents a slightly abbreviated report, specially commissioned by NSI for this planning study, by Prof M A Rabie and Prof M M Loubser of the Faculty of Law, University of Stellenbosch. Their report is entitled "**Legal aspects of weather modification**" and addresses the general field of weather modification, of which rainfall stimulation is, of course, a part. Our abbreviation concerns certain introductory passages which repeat to some degree material presented elsewhere or which relate to material not directly of concern to our study.

2. WEATHER MODIFICATION LEGISLATION

2.1 Introduction

Weather modification statutes were first promulgated in the US, where the first state legislation appeared during 1951. By the mid 1970s some two thirds of the states had enacted weather modification laws.[1] In spite of pleas for pre-emption of the entire field of weather modification,[2] federal involvement has been restricted to a 1971 weather modification statute aimed merely at gathering information through a report requirement and the obligation on federal agencies to file environmental impact statements in terms of the National Environmental Policy Act of 1970.[3] The federal government has consistently declined to become involved in the direct regulation of weather modification. As far as state legislation is concerned, the past decade has witnessed a trend towards regulatory de-emphasis in respect of weather modification control.[4]

In South Africa weather modification legislation has been enacted only at national level. The eventual promulgation of legislation was indirectly induced by a serious drought which prevailed during 1967 and which stimulated the Department of Water Affairs to request the Treasury's assistance in funding precipitation augmentation. This request was refused on account of the view of the scientific advisory council of the prime minister that the modification of precipitation was not a proven technology but that research should first be conducted. As a result, the national co-ordinating committee for hydrological research was established, comprising the Departments of Water Affairs and of Agriculture, the Weather Bureau (then part of the Department of Transport), the Rand Water Board and the CSIR.

This led to the Department of Water Affairs' taking the initiative by having the Water Amendment Act 45 of 1972 promulgated, through which a new chapter[5] was inserted in the Water Act 54 of 1956, dealing with the control of activities which may alter the natural occurrence of certain types of atmospheric precipitation. The passing of the Act was preceded by extensive evidence on weather modification which had been submitted to the select committee dealing with the Water Amendment Bill.[6] Certain amendments were later effected by the Water Amendment Act 42 of 1975.

Meanwhile the Department of Transport, which through the Weather Bureau, also displayed a particular interest in weather modification, less than a month later, during June 1972, had its own legislation on weather modification promulgated by Parliament; it took the form of a separate Act ie the Weather Modification Control Act 78 of 1972. In most respects the Act was similar and to some extent even identical to the above-mentioned chapter of the Water Act. In one important respect, however, the Act deviated from the Water Act: it defined weather modification as excluding any modification of precipitation, as defined in the Water Act.[7] In other words, the two statutes were not intended to cover the same field. However, in view of the comprehensive field encompassed by the definition of "modification of precipitation",[8] there was not much scope for the application of the Act, especially since all weather modification projects in South Africa thus far comprise activities which fall within that definition. Nevertheless, it was foreseen - already during the debate on the Weather Modification

Control Bill[9] - that the existence of two sets of legislation of the same tenor may cause uncertainty and confusion both among control bodies and those subject to the legislation. The Act, accordingly, was short-lived and endured for only 3 years, after which it was repealed by the above-mentioned Water Amendment Act of 1975. The Water Act, nevertheless, required that the Minister of Transport - in whose department the Weather Bureau resided until 1985 - be consulted when licences were issued or cancelled.[10]

2.2 Weather modification control body

In theory there are various administrative bodies that may qualify for the responsibility of controlling weather modification. Bodies that come to mind are the central government Departments of Water Affairs, Agricultural Economics and Marketing (or the white own affairs' Department of Agriculture and Water Supply) and Environment Affairs (Weather Bureau), the Water Research Commission and the CSIR. It is even conceivable that a body may be established with the sole aim of controlling weather modification.

It is submitted that the current position is satisfactory. Control should be effected at national level in order to be uniform. This would rule out weather modifications being regarded as an own affair. Moreover, it should be exercised by a body with the necessary infrastructure and experience in administering control legislation. In other words, bodies that have been established primarily for research purposes, such as the Water Research Commission and the CSIR, would not qualify. Furthermore, since weather modification in South Africa has been related only to modification of precipitation which have have an effect on the run-off of water, or the quantity of ground water, it seems advisable that control should be related to a body concerned with the control of water. Although agriculture thus far seems to have been the principal potential beneficiary of weather modification, the department concerned is not geared to exercising the necessary control. Finally, the trend seems to be against creating new ad hoc administrative bodies with limited assignments, especially where the issue subject to control can comfortably be accommodated within the ambit of an existing administrative body. This leaves the Departments of Water Affairs and of Environment Affairs as the principal contenders for controlling weather modification. This issue was already raised during the early 1970s when the Department of Water Affairs contended with the Department of Transport - to whose jurisdiction the Weather Bureau belonged at the time - for control, to such a degree that for some years, as has been pointed out, two similar sets of legislation prevailed, both aimed at controlling weather modification, but by different control bodies. The issue was eventually resolved in favour of vesting sole administrative control in the Department of Water Affairs, with the Weather Bureau acting as technical consultant and research body. Since 1985 the Weather Bureau belongs to the Department of Environment Affairs. In view of the fact that both the Departments of Water Affairs and of Environment Affairs now form part of the same ministry, the position seems to be satisfactory.

2.3 Administrative control

Weather modification control in terms of the above legislation is exercised principally by virtue of empowering provisions which set up a licence and permit system, from which certain activities are excluded.

2.3.1 Actions exempted from control

2.3.1.1 Modification of precipitation by the state

The state is expressly empowered to carry out or to cause to be carried out operations to effect any modification of precipitation.[11]

2.3.1.2 Exemptions granted by minister

The Minister of Water Affairs is authorised, after consultation with the advisory committee, to grant a written exemption to any person from compliance with any provision of the chapter in the Water Act dealing with weather modification, to the extent determined by him, and subject to the conditions which he may wish to impose. Such exemption may be granted in the following circumstances:

(a) if he is satisfied that compliance with any provision is impracticable in the particular circumstances, or
(b) that an exemption from such compliance in those circumstances is not likely to cause any loss or damage, or
(c) for any other reason deemed sufficient by him.[12]

The minister may at any time withdraw any exemption or amend or withdraw any condition subject to which an exemption was granted.[13]

Failure to comply with a condition of an exemption would seem to amount to a criminal offence.[14]

2.3.2 Actions subject to control

2.3.2.1 Modification of precipitation

The basic action which the Act subjects to control is that of "modification of precipitation". This is defined as a modification of the natural occurrence of atmospheric precipitation which may have an effect on the run-off of water or on the quantity of underground water.[15] It is to be noted that what is subjected to control is not weather modification in the broad sense, but only modification of **precipitation** which **may** have a particular consequence i e in affecting the **run-off** of **water** or the **quantity** of **underground water**. However, almost any type of weather modification may have some influence on the amount of precipitation which reaches the earth and may accordingly positively or negatively affect the run-off of water or the quantity of groundwater. The definition, accordingly, is more comprehensive than it might seem at the first glance.

The Weather Modification Control Act 78 of 1972 contained a comprehensive definition of weather modification as meaning the artificial promoting, accelerating, increasing, aggravating, impeding, suppressing, retarding or altering of the natural occurrence of rain, snow, fog, hail or similar atmospheric precipitation, or lightning or a tornado or cyclone or a similar atmospheric phenomenon.[16] However, as has been pointed out,[17] it excluded any modification of precipitation as defined above, and thereby excised from its ambit of control the major field of weather modification activities, and, in fact, all intentional weather modification operations currently carried out in South Africa.

2.3.2.2 Intentional modification of precipitation

Control over intentional modification of precipitation is exercised in principle through administrative law provisions, while the criminal penalty is prescribed as an indirect or subsidiary sanction which is to be invoked only if and when basic administrative controls should fail.

A person who wishes in a lawful manner wilfully to effect any modification of precipitation or wilfully to perform any act to effect such modification, is required to enter into an agreement with a permit holder and to obtain a licence.[18] A licence is required of an individual who will be in charge of an operation, while a permit is required for the operation. This dual requirement may serve to ensure that both the operator and the project are sound. Before its amendment in 1975, the chapter on modification of precipitation provided that a permit could be issued only to a licence holder.[19] In other words, the licensee and the permit holder had to be the same person.[20] The position was changed to the presently prevailing one by the Water Amendment Act 42 of 1975.

(a) Professional licences

It is of great importance that persons undertaking modification of precipitation should be sufficiently competent to perform this potentially hazardous task. Among the factors that obviously should be taken into account would be educational qualifications and operational experience.

Issue of licence:

A licence to effect such modification of precipitation as may be authorized, may be obtained from the Minister of Water Affairs by any person who, in the opinion of the Minister, possesses adequate technical knowledge and skill.[21] Before 1985, when the Weather Bureau was still part of the Department of Transport, the Minister, prior to issuing the licence, was obliged to consult with the Minister of Transport[22] and he had to be satisfied that the technical knowledge and skill possessed by the applicant, were at least as adequate as the Minister of Transport may have recommended.[23] Since the Weather Bureau now resides within the Department of Environment Affairs, the Minister of Environment Affairs should now be substituted for the Minister of Transport. However, since both the Departments of Water Affairs and of Environment Affairs form part of the same ministry, there obviously is no room for consultation.

Cancellation of licence:

A licence remains valid indefinitely. However, the Minister may at any time cancel any licence if in his opinion the licence holder no longer meets the qualifications for a licence.[24] Neither the state nor the Minister is liable for any loss sustained by any person on account of such cancellation.[25]

(b) Operational permits

The permit system is the key to effective regulation of weather modification, because it is through this mechanism that control may be exercised over individual projects in order to ensure that public health, safety and the environment will be subjected to the least possible risk of harm.

Application preceded by publication:
Since the weather directly affects everyone in the area concerned, the legislature has wisely required that every application for a permit must be preceded by the publication of the applicant's intention to submit the application in question.[26] This must be done by notice in the gazette and in both official languages in a newspaper circulating in the area where it is intended to cause any modification of precipitation to be effected.[27] Such notices must contain certain particulars and must state that written representations supporting or opposing the application may be submitted to the Director General: Water Affairs.[28] An application for a permit must be submitted to the Director General, together with proof of the publication of such notices.[29] Since proof of such publication and, as will be pointed out, consideration of received representations by the advisory committee are conditions precedent to the issuance of a permit, the opportunity for public participation in the eventual decision on the permit application is guaranteed. How effective this will be depends in large measure upon whether such formal notices in fact reach the public and whether members of the public are sufficiently informed and capable of rendering a meaningful input. Public participation may lead to improved decision-making and to a break-down in resistance against weather modification operations.

Issue of permit:
A permit may be issued by the Minister of Water Affairs only to a person who, in the opinion of the Minister, commands sufficient financial means.[30]

After all representations have been received, the difficult policy decision arises as to whether or not the permit application should be approved. This the Minister must do after consultation with the advisory committee,[31] which must advise the Minister in this regard, but only after it has considered all the representations that have been submitted by the public.[32] It may in a given area be difficult to weigh the potential benefits of cloud seeding, which may include increased run-off in a river cathment, thereby filling dams, against the potential harm, such as rainfall stimulation during a holiday season or when certain crops are being harvested. Such a decision, nevertheless, pales into insignificance when compared with the issues which face a decision-maker confronted with the question of hurricane diversion.[33]

If a permit application is approved, it would authorize the applicant to cause such modification of precipitation to be effected by any licence holder in such area and during such period as may be specified. The permit is usually valid for one year or one season at a certain place.

Conditions; furnishing of information:
A permit is subject to such conditions as the Minister may require.[34] The conditions may inter alia relate to the method, equipment and material which may be used in the operation.[35] A permit functions almost like a franchise to operate in a given area for a specified period, carrying out a particular project in a prescribed manner.

Moreover, the conditions may require the furnishing of information to the Director General during and after the operations concerned.[36] It should be a fundamental role of the Minister and the Department of Water Affairs to maintain a central data bank on weather modification, containing scientific information and reports from inter alia weather modification experimenters and commercial operators. In this way the success or failure of weather modification, as well as its effects, can be continuously monitored. Such information may also serve as a basis upon which future applications for permits may be evaluated. According to the Act the furnishing of information may be required of the permit holder. However, it may be assumed that it is really the licence holder who is the person qualified to render the required information. In other words, it may have been more satisfactory if the Act itself had imposed a specific obligation upon every licence holder to submit a report to the Minister on each operation which he performs. The permit holder can of course require such a report from the licence holder as part of their agreement and then submit it, together with his own information, to the Minister. However, it would seem advisable that the licence holder should also be required independently to keep records and to submit reports on his operations. The Act does not presently seem to authorise the subjection of a licence to conditions,[37] which means that the Minister cannot require reports from licence holders. Weather modification may also be effected by virtue of an exemption.[38] Since an exemption may be granted subject to conditions,[39] reports may - and should - be required of such operators.

Failure to comply with any such condition amounts to a criminal offence.[40]

Security for compensation:
Furthermore, an obligation is imposed upon a permit holder, before causing any modification of precipitation to be effected by a licence holder, for the purpose of paying compensation for any damage, to furnish such security[41] by way of insurance as may be determined by the Minister on the recommendation of the advisory committee.[42] Failure to comply with this provision also amounts to a criminal offence.[43]

Withdrawal or variation of permit:
Finally, the Minister may at any time withdraw a permit, or vary any condition specified therein, if in his opinion the method, equipment or material specified in such permit to be used to effect modification of precipitation has caused or may cause undesirable changes in the weather conditions or damage or if the permit holder has not observed any condition in the permit.[44] Neither the state nor the Minister is liable for any loss sustained on account of any variation of a condition or

withdrawal of a permit.[45]

2.3.2.3 Unintentional modification of precipitation

An administrative abatement notice procedure is authorised in respect of instances where modification of precipitation is caused unintentionally. Although it would seem, unlike instances of intentional modification, as if causation is a requisite for the operation of this provision, it is actually the Minister of Water Affairs' opinion which is decisive. If the Minister is of the opinion that any person is unintentionally causing any modification of precipitation, he may in writing direct that person to take such remedial steps at his own cost as the Minister may deem necessary and specify in such direction.[46] Failure to comply with such direction constitutes a criminal offence.[47] Moreover, upon failure of that person to carry out such steps to the satisfaction of the Minister within the specified time, the Minister is authorised to cause such steps to be carried out and to recover the costs thereby incurred from that person.[48]

In other words, just as in the case of intentional modification, primary control is effected administratively, while the criminal sanction is used as a back-up or subsidiary sanction. However, the abatement notice procedure can potentially function effectively by itself, since it relates to positive steps that can be taken to combat and control unintentional modification directly, even in the event of the responsible person's failing to comply with the direction, while the costs involved may also be recovered from him. Actually, this provision confers extensive powers upon the Minister, since a great many activities in effect contribute to a modification of precipitation and therefore are subject to control in terms of the provision. For instance, drivers of motor vehicles are unintentionally causing such modification, because the lead contained in petrol is a more effective seeding material than those materials normally used for cloud seeding. Again, the sulphur dioxide and iron oxide gases emanating from certain factories are exceptionally effective seeding agents. In fact, the smoke emanating from every grass or other fire affects the weather in serving as condensation nuclei.[49] Although there is extensive legislative provision for air pollution control,mainly the Atmospheric Pollution Prevention Act 45 of 1965,[50] most forms of such air pollution could conceivably also be controlled by virtue of the above provision of the Water Act.

2.4 The criminal sanction

2.4.1 Intentional modification of precipitation

Indirect or subsidiary control over intentional weather modification is accomplished through the criminal sanction in that in terms of the Water Act it is a criminal offence wilfully to effect any modification of precipitation or wilfully to perform any act to effect any such modification except in circumstances which the Act authorises.[51]

2.4.1.1 Elements of the offence

(a) Actus reus

Reference has already been made to the definition of the phrase "modification of precipitation."[52] It would seem that what is threatened with punishment is firstly the causation of such modification, since the provision speaks of **effecting** modification. To "effect" means to bring about or to accomplish, while the Afrikaans text speaks of "teweegbring", which is a synonym for "veroorsaak". However, it seems that causation need not necessarily be proved; the provision relates also to the performance of any act to effect modification, which seem sto mean any act calculated to effect such modification, even though it did not in fact have that result.

(b) Unlawfulness

The primae facie unlawfulness of a contravention of the provision in question may be precluded by the presence of certain circumstances which the Act regards as excluding liability. Such circumstances comprise the following:

(1) performance in pursuance of an agreement with a permit holder <u>and</u> under the authority of a licence
or
(2) performance under the authority of an exemption and in accordance with any conditions which may have been specified in the exemption.[53]

It would seem that these circumstances do not amount to negative elements of the offence concerned - which otherwise need to be set forth in the charge and proved by the state - but that they, in fact, constitute exceptions, in terms of the Criminal Procedure Act 51 of 1977,[54] which need not be specified in the charge and which do not from part of the offence, but which may be relied upon by the accused and proved by him as a defence to the charge.[55]

This conclusion is strengthened by the use of the word "except" in the above provision.[56] Contrary to the position in respect of common law grounds of justification, the onus of proof would therefore be on the accussed to prove the presence of the above-mentioned circumstances if he should wish to preclude the inference that his conduct was unlawful.[57]

(c) <u>Mens rea</u>

The form of <u>mens rea</u> required for conviction of the offence would, on account of the word "wilfully",[58] seem to be intention. The Afrikaans equivalent of "wilfully" in the above provision is "opsetlik". This is underscored by the existence of another provision which regulates instances in which modification of precipitation was caused unintentionally.[59]

(d) Penalties

According to the penalty clause of the chapter on weather modification,[60] any person convicted of an offence in terms of this chapter is liable to the penalties prescribed in the Water Act's general penalty clause.[61] This provision, however, although referring specifically to other sections, does not refer to the above clause or to any other provision of the chapter on weather modification. The prescribed penalty, nevertheless, is a maximum fine of R10 000 or imprisonment not exceeding 12 months of both such fine and imprisonment. In the case of a second or subsequent conviction the maximum fine is R20 000 or imprisonment not exceeding 12 months or both such fines and imprisonment.[62] Provision is also made for continuing offences[63] and for vicarious liability.[64] Moreover, the court may assess the monetary value of any advantage gained or likely to be gained by the person in consequence of the offence in question and, in addition to any other punishment, may impose a fine equal to the amount so assessed, or in default of payment, to imprisonment for a period not exceeding 12 months.[65] A magistrate's court is authorised to impose any of the abovementioned penalties.[66]

Finally, the court convicting a person of any offence in terms of the Act, may in the same criminal proceedings award damages in favour of someone who has suffered loss or damage on account of the offence in question.[67]

2.4.2 Other offences

The general penalty clause of the Water Act's chapter on weather modification[68] refers to two specific offences ie the failure to comply with a direction relating to the unintentional modification of precipitation[69] and the failure to comply with any condition of a permit.[70] It furthermore contains a so-called blanket penalty clause in that it provides that a contravention of any provision of the chapter concerned constitutes an offence. Although explicit reference is made only to conditions of a permit, the failure to comply with any condition of an exemption[71] should also be punishable by virtue of the blanket provision. Moreover, it is this provision which renders the wilfull effecting of any modification of precipitation without authorisation an offence.[72] The blanket provision also covers the causing of modification of precipitation by a permit holder, without furnishing the required security.[73]

However, it is uncertain which other provisions of the chapter in question were intended by the legislature to constitute offences. This problem is part and parcel of the undersirability of the prescription by legislatures of blanket penalty clauses.[74] Certain provisions are not susceptible of contravention[75] and therefore cannot come within the purview of the blanket clause. Moreover, the only remaining provisions that are amenable to contravention do not seem to have been intended to constitute offences.[76]

2.5 Application of the Water Act

In view of the fact that there have been very few weather modification projects in South Africa,[77] and that the only two on-going projects are presently conducted by or under the auspices of the state - which is exempted from control - the Water Act, in its application to weather modification, has to a large extent been dormant. Nevertheless its provisions seem to be potentially effective, given satisfactory administrative control.

2.6 Environmental impact assessment

Weather modification is an activity which has a potentially detrimental effect upon the environment. Such activities should ideally be identified in advance and their potential impact be studied, revealed and evaluated before they are permitted to be undertaken. As has just been shown, the Water Act, indeed, administratively regulates activities related to the modification of precipitation.

Such activities may now also be controlled in terms of the Environment Conservation Act 73 of 1989. The Minister of Environment Affairs is authorised, after consultation with certain bodies, and with the concurrence of various bodies,[78] by notice in the gazette to identify those activities - including water use and chemical treatment, which activities seem comprehensive enough to include modification of precipitation - which in his opinion may have a substantial detrimental effect on the environment,[79] whether in general or in respect of certain areas.[80] Once an activity has been so identified, no person may undertake it or cause it to be undertaken except by virtue of a written authorization issued by the Minister or other relevant body.[81] Contravention of this provision amounts to an offence.[82] Such authorisation, moreover, must be preceded by a consideration of an environmental impact report.[83] The authorisation in question may be refused or granted subject to conditions.[84] Failure to comply with a condition, besides amounting to an offence,[85] may lead to withdrawal of the authorisation.[86]

The Environment Conservation Act has not yet been implemented as far as identified activities are concerned.

2.7 Weather modification policy

The state has not yet formulated a comprehensive weather modification policy. This may be attributed to the fact that modification of precipitation is still very much in the experimental stage, with the state itself leading the pioneering effort. If and when weather modification reaches a widespread operational stage, the formulation of a national policy would be advisable, in order to guide commercial operators, and, in fact, all other relevant activities.

Since 1989 legislation now makes provision for the formulation of binding state policy in respect of a variety of environmental aspects. The Environment Conservation Act 73 of 1989 authorises the Minister of Environmental Affairs, after consultation with certain bodies, and with the concurrence of various bodies,[87] by notice in the gazette to determine the general policy to be applied with a view, inter alia, to the protection of natural systems, the effective application of natural resources and the protection of the environment against disturbance as a result of human activities.[88] This authorisation seems extensive enough to include the determination of a national weather modification policy. Once determined, such policy is binding in that each minister, administrator and government institution upon which any power has been conferred or to which any duty has been assigned in connection with the environment[89] by or under any law, is obliged to exercise such power and perform such duty in accordance with that policy.[90] Moreover, the duty to act in accordance with the policy may also be extended to the private sector.[91]

2.8 Other environmental legislation

Environmental legislation is to a substantial degree related to the control of land use. Insofar as weather modification activities concern land use, e.g. the operation of land-based generators, they may conceivably be controlled, for instance, by virtue of legislation in respect of noise[92] or air[93] pollution. Generally, however, modification of precipitation is effected by activities related to the use of aircraft. In such instances, the relevant applicable legislation - besides legislation concerning aircraft and their operation - would be that relating to water [94] and air pollution control.

3 RIGHTS IN RESPECT OF PRECIPITATION

In order to discuss rights with regard to precipitation, it is necessary first to consider certain issues relating to property law.

3.1 Status of the air

The air, like flowing water, is regarded as res omnium communes, things which are destined for common use and regarded as being extra commercium.[95]

3.2 **Ownership of air : generally**

Being a thing not subject to commercial enterprise, the air as such is not the subject of private ownership. This statement, however, should be qualified thereby that if air is reduced to possession by someone, it may become the subject of private ownership. In the first place, air, as atmosphere, may be subjected to possession, e.g. by being compressed into a cylinder.[96] Secondly air, as space, may be capable of being reduced to possession and thus be a thing in commercio, for instance according to American law, in terms of which units of airspace may be regarded separately from ownership of the land, and thus be the subject of commercial exploitation.[97]

3.3 **Ownership of clouds**

3.3.1 **By appropriation**

While it is readily foreseeable that space may be occupied and thus reduced to possession, it seems unlikely that a cloud in the sky, which is part of the atmosphere, could ever by practically appropriated. An air-tight container of huge proportions would be required for such and operation.

3.3.2 **Through Land ownership**

A further relevant question, irrespective of whether a cloud can be physically appropriated, is whether or not the owner of land beneath a cloud qualifies as owner of that cloud merely on account of his land beneath a cloud qualifies as owner of that cloud merely on account of his land ownership, according to the Roman law maxim cuius est solum eius est usque ad caelum et ad inferos.[98]

In a country such as the US, this adage was never taken literally, but was a figurative phrase to express the full and complete nature of land ownership, extending, as it does, to whatever super-adjacent airspace was necessary of convenient to the enjoyment of the land.[99] For instance, land ownership would include that portion of space which can be occupied with buildings, or may be used with trees and fences. Such uses are connected with the use which is made of the surface itself.

In South Africa, however, the ad ad caelum principle of Roman law seems still to apply,[100] although there is some uncertainty as to how far the dominium extends upwards.[101] Moreover, the landowner's rights have been restricted by legislation and by the contending rights of neighbouring land owners. Furthermore, the above principle has been abolished in the case of sectional property.[102]

In any case, it seems that the principle applies only to the air as spce and not to the air as atmosphere. Clouds as objects passing through a person's airspace may rather be likened to wild animals that may be present on his land. Ownership of such animals does not flow automatically from ownership of the land. Mention has already been made of the difficulty of appropriating a cloud. Furthermore, it would seem impossible to assert legal title to a cloud, since it is in a state of constant flux, changing its shape, location, content and size, In face, an individual cloud in respect of an individual piece of land can hardly be discerned. Whereas the airspace above a landowner's property can be determined as a more or less fixed position relative to the earth's surface, the corpus of the atmosphere resides in that relative position only transiently.[103]

The conclusion, in other words, is that clouds remain common property and cannot form the subject of private ownership.

3.4 The status of precipitation

3.4.1 In the air

The formation of rain, snow, dew etc as a result of condensation of moisture from the state of vapour renders water available to the earth. Before such water reaches the earth, it would seem to qualify as res omnium communes.

3.4.2 **On the ground**

3.4.2.1 Normal precipitation

Once it reaches the earth, it may qualify as private or public water (or may form part of the sea). Precipitation which reaches land or private impoundments, would qualify as private water, insofar as it is regarded as "water which rises of falls naturally on any land".[104] However, once it reaches a public stream, it would be regarded as public water, since public water means any water flowing or found in the bed of a public stream.[105]

An uncertainty, however, arises if such water should be regarded as a source of a public stream. It has been held- confirming a rule already laid down in Van Heerden V Weise[106] in 1880 - that if a river conforms to the requirements of a public stream, such public character adheres also to the river's sources, even though a particular source does not conform to the attributes of a public stream.[107] Nevertheless a contrary view was expressed obiter in Le Roux v Kruger.[108]

3.4.2.2 Modified precipitation

There seems to be little doubt that once water joins a public stream, it would qualify as public water, irrespective of its origin, since the definition of public water includes **any** water found in the bed of a public stream. In other words, if the water derived through stimulated rainfall reaches a public stream, it would be viewed as public water.

Some uncertainty, nevertheless, exists as to whether precipitation, derived from modifying activities, which falls on private land, should be regarded as private water. This is due to the definition of private water referring to water which falls **naturally** on land. It would seem that, even though the precipitation may have been artificially induced, or augmented, it nonetheless falls naturally on the land in question, with the implication that, like normal precipitation, it should qualify as private water.

3.5 Right to the use of clouds

Since clouds are regarded as res omnium communes, they can, in principle, be used by anyone, subject of course, to statutory restrictions imposed in the public interest and to the rights of other individuals in respect of such use. The most important point to make here is that modification of precipitation is subject to the Water Act, which, in principle, requires administrative authorisation for such activities.[109]

3.6 Rights relating to precipitation derived from clouds

3.6.1 Right of landowner to natural precipitation

Analogies to water law have been drawn in an attempt at establishing a landowner's right to atmospheric precipitation. The most obvious analogy is the riparian right of a landowner abutting a public stream. However, water in the atmosphere cannot readily be compared to water flowing in a river. For instance, there is no fixed stream or source of the water which, moreover does not flow in a known and defined channel.

Moreover, an analogy with riparian rights would imply that only landowners would in principle have water rights in respect of the atmosphere, while, clearly, the interest in respect of atmospheric precipitation is fundamental to the life of everybody.

Following from a riparian owner's right to the normal flow, it has been suggested in the US that a landowner has a general right freely to enjoy the use of his land in its natural condition: ownership of land insures more than only the occupation and use of the soil and vegetation, since it protects the reasonable use of all the elements nature places on the surface. Precipitation, like air, oxygen and sunshine, is essential to many reasonable uses of the land, In fact, plant and animal life are ultimately dependent upon rainfall.[110]

Among the implications of such a right would be that an interference therewith would be constituted by a cloud seeder who through his activities deprives the landowner of his natural precipitation or who causes a flood. A major problem here is the difficulty of furnishing proof that the precipitation was due not to the prevailing natural weather condition, but to the weather modifier's interference.

3.6.2 Rights to augmented precipitation

3.6.2.1 Landowner

Augmented precipitation can reach a landowner in different ways, either directly as rainfall on his land, or through increased streamflow of a public stream to which his land is riparian.

If the proposition is accepted that a landowner has a right to natural precipitation, this would entitle him only to that amount of water and not to the additional water derived through weather modification activities practised by another. Once again, the practical difficulty arises as to proof that the augmented precipitation was due to such activities and not to normal weather conditions.

Insofar as modified precipitation which reaches the land of a private landowner is regarded as private water, the Water Act determines that the sole and exclusive use and enjoyment of such water vests in the landowner.[111]

Where modified precipitation qualifies as public water on account of its being contained in a public stream riparian landowners' rights in respect of such water are determined irrespective thereof that streamflow may have been augmented on account of weather modification activities practised by another.

3.6.2.2 **Weather modifier**

A consideration of the potential rights of a cloud seeder to any augmented precipitation effected by his activities, should take account of two factors. Firstly, this remains a hypothetical issue since rainfall stimulation in South Africa has thus far been practised only by the state and only on an experimental basis. The related factor is that, in view of the rather scant evidence of the success of rainfall stimulation, it will be very difficult to quantify the right of a cloud seeder to the enhanced precipitation, even if such modification of precipitation by a private individual is authorised by the state.

A further problem facing a cloud seeder or his principal, is that it seems very difficult, if not impossible, to restrict the benefits of cloud seeding to a single unit or even a group of units of land. Others, who have not shared in the costs of the venture, are bound to join in the benefits, given the possibility of successful cloud seeding. It does not seem practically or legally feasible to retrieve the augmented precipitation from such persons. This means that the person who has commissioned the cloud seeding will have to be content with relying upon the doubtful base of enrichment, should he wish to recover anything from the beneficiary landowner. The First difficulty relates to the requirements of proof that the landowner has indeed been enriched and that such enrichment occurred as a result of the cloud seeder's activities.[112] Moreover, our law does not recognise a general enrichment action and the above instance does not seem to fit into any of the traditional enrichment actions. The most that can probably be hoped for, is a reliance upon an extension - as provided for in Nortje v Pool NO[113] - of either the traditional action for negotiorum gestio[114] or for accessio.[115]

The best satisfaction that a cloud seeder might achieve, is if he succeeds in steering the augmented rainfall onto his own land, or where he is not an interested landowner, but an agent of a landowner, and effects a modification of precipitation on the latter's land. Such precipitation, as has been noted, may be regarded as private water over which the landowner may dispose as he wishes. Moreover, the Water Act, in addition, provides that where a landowner obtains, by artificial means on his own land, a supply of water which is not derived from a public stream, such water shall be deemed to be private water.[116] It should be noted, however, that the above satisfaction is dependent upon two uncertain conditions i.e. the successful stimulation of rainfall and accuracy in striking the target area.

1. For general surveys, see Davis Weather modification law developments 1974 Ohlahoma Law Review 409, Davis Uniformity among weather modification laws 1976 Journal of Irrigation and Drainage Engineering 285, Davis Legal uncertainties of weather modification in Thomas (ed) Legal and scientific uncertainties of weather modification (1977) 32 and Davis Legal aspects of weather modification 1983 Journal of Irrigation and Drainage Engineering 128.

2. E g Hunt Weather modification and the law in Fleagle Weather modification Science and public policy (1969) 118, 135.

3. See generally Johnson Federal organization for control of weather modification 1970 Natural Resources Journal 222.

4. Davis Future legal regulation of weather modification 1988 Journal of Irrigation and Drainage Engineering 705, 706-7.

5. I e chapter IIIA.

6. Supra n 12.

7. Par 4.3.2.1.

8. Ibid.

9. Debatte van die Volksraad 29 May 1972, 8401-8413.

10. Sections 33C(1) and (2) and 33E(1).

11. Section 33B(1). Cf par 4.3.2.1 for the definition of this phrase.

12. Section 33B(3)(a).

13. Section 33B(3)(b).

14. Cf par 4.4.2.

15. Section 33A.

16. Section 1(iii).

17. Par 4.1

18. Section 33B(2).

19. Sections 33C and 33D(1) of Act 45 of 1972.

20. Cf Report of the Select Committee supra n 12, 27-8.

21. Section 33C(1).

22. *Ibid*.

23. Section 33C(2).

24. Section 33E(1). Consultation with the Minister of Transport (now Environment Affairs) is required. But see the previous paragraph.

25. Section 33E(2).

26. Section 33D(2)(a).

27. Section 33D(2)(b).

28. Section 33D(2)(c).

29. Section 33D(2)(a).

30. Section 33D(1).

31. Section 33D(1).

32. Section 33D(2)(d).

33. Cf Breuer supra n 9, 140-4.

34. Section 33D(1).

35. Section 33(D)(3).

36. Ibid.

37. Cf s 33B(2).

38. Par 4.3.1.2.

39. Section 33B(2).

40. Section 33I.

41. Cf s 33D(4)(b).

42. Section 33D(4)(a).

43. Section 33I. Cf par 4.4.2.

44. Section 33E(1).

45. Section 33E(2).

46. Section 33H.

47. Section 33I. Cf par 4.4.2.

48. Section 33H.

49. See the Report of the Select Committee supra n 12, 21-2.

50. See generally Fuggle & Rabie Environmental concerns in South Africa (1983) ch 13.

51. Sections 33B(2), 33I and 170(2).

52. Par 4.3.2.1.

53. Section 33B(2)

54. Section 90.

55. Cf generally Rabie Statutory defences in criminal law 1985 SACC 223, 224-9.

56. _R v Richter_ 1920 OPD 249, _R v Moosa_ 1955 (3) SA 442 (A); _R v Von Wielligh_ 1959 (4) SA 352 (A); _S v Tshwape_ 1964 (4) SA 327 (C) and _S v Macdonald_ 1968 (2) SA 236 (T)

57. In addition to s 90, cf also s 250(1) of the Criminal Procedure Act.

58. Cf Milton _South African criminal law and procedure_ Vol III 2nd ed by Milton & Cowling (1988) Liability 11-13.

59. Section 33H. See par 4.3.23.

60. Section 33I

61. Section 170(2).

62. _Ibid_

63. Section 170(4)

64. Section 170 (5A)(a), (b) and (c).

65. Section 170 (5B)

66. Section 170(6).

67. Section 171.

68. Section 33I.

69. Par 4.3.2.3.

70. Par 4.3.2.2.(b).

71. Par 4.3.2.1.

72. Par 4.3.2.2.

73. Section 33D(4)(a)

74. Rabie & Strauss Punishment. An introduction to principles (4th ed 1985) 72-5

75. I e ss 33A, 33B(1) and (3)(a) and (b), 33D(2) and (3), 33E(1) and (2), 33F(2) and 33G

76. Issue of a licence contrary to the provisions of 33C(1) or (2) is not presently possible, since the Minister of Water Affairs also holds the portfolio of Environment Affairs. Even if the latter portfolio should be separated from the former, it is unlikely that the legislature intended the Minister to be guilty of an offence if he should act contrary to the above provisions, since the appropriate remedy in such an instance would be for someone with locus standi to have the Minister's action set aside on review. The same would apply in case of failure by the Minister to appoint an advisory committee in terms of s 33F(1) and a corresponding failure to consult such committee, as he is obliged to do virtue of s 33(D)(1).

77. Par 3.2

78. Section 21(3).

79. "Environment" is defined comprehensively as the aggregate of surrounding objects, conditions and influences that influence the life and habits of man or any other organism or collection of organisms: s 1(x).

80. Section 21(1) and (2).

81. Section 22(1).

82. Section 29(4).

83. Section 22(2).

84. 84 Section 22(3).

85. Section 22 (4).

86. Section 22(4).

87. Section 2(2).

88. Section 2(1)

89. Cf n 93 supra for a definition of the concept of "environment".

90. Section 3.

91. "Government institution" includes any body, company or close corporation established by or under any law or any other institution or body recognized by the minister by notice in the gazette: s 1(xii).

92. Fuggle & Rabie supra n 64, ch 16.

93. Fuggle & Rabie supra n 64, ch 13.

94. Fuggle & Rabie supra n 64, ch 14.

95. Van der Merwe Sakereg (2nd ed 1989) 29-31.

96. Van der Merwe supra n 109, 30

97. Cf Pienaar Legal aspects of private airspace development 1987 CILSA 94, 97-100. On ownership of airspace, see also Cowen New patterns of landownership (1984) 45-50.

98. Van der Merwe supra n 109, 31 n 84.

99. Pienaar supra n 111, 97; Note: Who owns the clouds? 1949 Standford Law Review 43, 48-9.

100. Van der Merwe supra n 109, 190.

101. Rocher v Registrar of Deeds 1911 TPD 311, 315.

102. Pienaar supra n 111, 100.

103. McKenzie Weather modification: a review of the science and the law 1976 Environmental law 387, 407.

104. See the definition of "private water" in s 1 of the Water Act.

105. Section 1 of the Water Act.

106. 1880 Buch AC 5.

107 See Nunes Sources of public streams in modern South African law 1975 Acta Juridica 298, 310-31; Hall on Water rights in South Africa (1974) by Hall & Burger 21-2; Vos Principles of South African water law (1978) 8-9.

108. 1986(1) SA 327 (C) 332-46

109. Par 4.3.2.

110. Note: Who owns the clouds? supra n 113, 53-4

111. Section 5(1)

112. Cf Lotz Title Enrichment in Joubert (ed) The law of South Africa Vol 9 (1979) par 64.

113. 1966(3) SA 96(A). De Vos Verrykingsaanspreeklikheid in die Suid-Afrikaanse reg (3rd ed 1987) ch 5.

114. Cf Lotz supra n 126, pars 78-80.

115. Cf de Vos supra n 127, 224-43.

116. Section 6(2)

4. LEGAL LIABILITY FOR WEATHER MODIFICATION

4.1 Introduction

Weather modification necessarily involves hazards of legal liability, because of the conflicting interests of persons affected thereby. One man's welcome rain may become another's flood, and cloud seeding directed at bringing rain on one property may cause a hail storm on another. Claims for damages and prohibitory interdict proceedings are likely to be based upon allegations of unlawful and negligent interference with natural climatic conditions, and significant issues in the fields of delict and property law may arise in such proceedings.

While forms of weather modification have been carried out for many years in South Africa, and although weather modification has been regulated by the Water Act[1] since 1972, there has been virtually no discussion in South Africa of the legal issues involved, and as far as can be ascertained, no litigation dealing directly with weather modification has come before the South African courts. Much of the comparative legal material in this regard is of American origin, and reported cases dealing directly with weather modification likewise are to be found mostly in American law reports.

Although weather modification may directly or indirectly cause personal injury and many other kinds of harm; property damage and nuisance to land owners are clearly the most likely forms of grievance to arise from weather modification, and the following discussion will be devoted mainly to the legal remedies arising from property damage and nuisance. The obvious examples of damage that may be caused by weather modification are flood damage, damage caused by drought through efforts directed at hail suppression, and hail damage caused by efforts directed at precipitation.[2] It appears that the substances used to seed clouds, for example silver iodide or dry ice, have not been proven to cause any substantial damage to land, owing to the extreme dilution of these substances in the atmosphere.[3]

Actual property damage will give rise to an action for damages, and prospective damage and nuisance to an application for an interdict prohibiting the offending weather modification activities. In both cases the legal remedy is based upon an act causing or threatening harm by unlawful infringement of property rights. Causation and the unlawfulness of the act complained of are the central questions, while the other elements of a delict, namely fault (in the form of negligence or intent) and damage, will sometimes also be in issue.

Some fifteen cases involving weather modification have been heard in the United States and injunctions (interdicts) prohibiting weather modification activities have been granted in some cases, but to date it appears that damages have not been awarded.[4] The most common difficulty experienced by plaintiffs has been an inability to prove causation, for example that the flood or hail storm that destroyed crops was caused by the weather modification and would not have ccurred naturally.

This difficulty does not arise to the same extent where an interdict is applied for, because a prohibitory interdict will be granted where there is unlawful conduct or the threat of unlawful conduct involving nuisance or a real risk of damage, even though damage has not yet actually occurred.[5] In the following discussion of the South African law the issues of unlawfulness, causation, fault (negligence or intent) and damage will be dealt with in that order.

4.2 Unlawfulness

4.2.1 Property damage caused or threatened

Unlawfulness or wrongfulness is that quality of the harmful activity which makes it an actionable delict.[6] Unlawfulness is indicated by the infringement of a legal right of the injured person or the breach of a legal duty owed to him. It is trite law that not every kind of harm that one person causes another is actionable, even if such harm is caused carelessly or intentionally. Thus a trade loss caused by lawful competition is not actionable. However, all physical harm to person or property caused by a positive act is prima facie unlawful.[7] Although in exceptional circumstances such harm may turn out to have been justified and therefore lawfully caused, for example to ward off an unlawful attack on person or property (ie in a self defence situation), or to avert some greater harm (ie in a situation of necessity); generally physical harm to person or property caused by a positive act will be unlawful.

It follows therefore that property damage caused or threatened by weather modification will be prima facie unlawful, for example flood damage, drought damage through efforts directed at hail suppression and hail damage through efforts directed at precipitation. Once it is proved that weather modification caused such damage or that it involves a real risk of such damage occurring, it can be accepted generally that the weather modifier's activities are unlawful. (Proof of causation of damage, the main difficulty facing the plaintiff in a weather modification case, is discussed below).

Once unlawful causation of damage or prospective damage has been proved, the plaintiff will be entitled to a prohibitory interdict against the continuation of weather modification activities already in operation or against proposed modification activities. In addition an action for compensatory damages will lie where damage has already occurred; but for the purposes of such an action the plaintiff would need to prove that the weather modifier not only acted unlawfully, but also negligently, ie that in conducting such activities he reasonably should have foreseen the possibility of the damage and should have guarded against it. (The aspect of negligence in this context is discussed below.)

Although there is no reported South African case on liability for flood damage caused by weather modification, there are cases on liability for alteration of natural drainage and consequent flooding of neighbouring land by rain water. In such a case liability is imposed by application of the <u>actio aquae pluviae arcendae</u> or the <u>interdictum quod vi aut clam</u>, both ancient Roman law remedies. These remedies are partly interdicts and partly actions for damages;

damages being recoverable for loss suffered after litis contestatio[8]. These remedies are based upon the principle that a land owner acts unlawfully if, by means of artificial works, he discharges onto his neighbour's property rain water which would not have flowed there naturally, or concentrates or increases the natural flow of rain water to the detriment of his neighbour.[9] Liability is imposed regardless of whether the act was performed negligently.[10] The liability attaches to the person actually responsible for the flooding and not to the owner qua owner of the land upon which the natural drainage was altered. By an extension of the ambit of the actio aquae pluviae arcendae or the interdictum quod vi aut clam a weather modifier who actually causes flooding by interference with natural rainfall could likewise be held liable. However, the courts are more likely to base such liability on the ordinary principles of delictual liability for patrimonial loss (the extended Aquilian action for all kinds of patrimonial loss), rather than extending the ambit of the archaic actio aquae pluviae arcendae or interdictum quod vi aut clam in order to deal with the modern day phenomenon of weather modification.

4.2.2 Nuisance

Even if there is no question of property damage, the weather modifier may nevertheless act unlawfully merely by causing a nuisance to a property owner, for example by overflying aircraft or by the noise from discharging seeding substances into the clouds. Implicit in the ownership of land is not only the right to its use for residential, commercial or agricultural purposes, but also a right to derive from it a reasonable amount of comfort, convenience and enjoyment. Any substantial interference with the use and peacable enjoyment of the owner's land and airspace will constitute nuisance. In such a case the property owner could apply for a prohibitory interdict against the offending activities. Such an interdict will be available only where the weather modification activities unlawfully infringe the rights of the aggrieved property owner.

Unlawfulness will be determined by the general principle of reasonableness. Weather modification activities will be unlawful if there is a substantial discrepancy between the harm suffered by the affected property owner and the benefit gained both by the person on whose behalf the weather modification is undertaken and by the community as a whole.[11]

The law of nuisance as likely to be applied to weather modification in American jurisdictions has been stated as follows; and South African courts are likely to take into account much the same considerations

> "Private nuisance has been defined as a disturbance or interference of the use and enjoyment of one's land. The interference must be unreasonable; not every disturbance will support the action. Thus a plaintiff may be required to submit to minor annoyances such as an unsightly spectacle near his house or a slight amount of noise or smoke.. Conversely, the world must have, so the courts say, oil refineries, smelters, noisy machinery, blasting-and anyone near them is bound to suffer some disconmfort. The job of the court is to weigh the gravity of the harm to the landowner-plaintiff against the utility of the defendant's conduct.. Again, weather modification activity could fit into the nuisance pattern. Assuming there is no malicious intent, however, the court may have a difficult job in weighing the utility of weather modification, which presumably is considerable, with the injury to the plaintiff, which conceivably could be severe."[12]

Courts will be less inclined to find actionable nuisance where there is no physical harm, but only personal discomfort or annoyance. In such cases recurrence or continuance of the discomfort or annoyance will become a factor.[13] Other relevant factors will be the extent of the nuisance caused; the nature of the locality, for example whether it is a quiet, rural area; the relative facility with which the offending party can avoid the nuisance; the personality of the complainant; and the economic consequences of either burdening the affected property owner with the nuisance or prohibiting the offending party from carrying out the weather modification.[14] In the unlikely event of weather modification being undertaken with a specific motive of harming one property owner without significantly advancing the interests of another, the improper motive will be strongly indicative of unreasonable and therefore unlawful conduct.[15]

The problem is illustrated by the 1950 American case of Slutsky v City of New York[16] . There the plaintiff sought a court order to prevent the city from conducting experimental cloud seeding in the Catskill Mountains for fear that it would adversely affect his vacation resort business. At the time the city of New York was experiencing a serious water shortage, which it hoped the seeding would remedy. The court ruled against the plaintiff, finding that the "problem of maintaining and supplying the inhabitants of the City of New York...with an adequate supply of pure and wholesome water" far outweighed possible inconvenience to the plaintiff.

Liability will depend not only on the manner and location of the weather modification, but also upon who conducts it and with what purpose.[17] Imposition of liability will be progressively less stringent, even to the point of allowing virtual immunity, as the activity is found to be socially valuable and in the public interest. Where the government licenses weather modification activities, the potential utility and social value of the licensed activity, and the very fact that the activities complained of were performed in terms of a license or permit, will be relevant to the question of lawfulness. The effect of licensing and the liability of the State as licensing authority are referred to in section 6.2.3 below.

In terms of the Aviation Act[18] the circumstances in which nuisance caused by aviation will give rise to a legal remedy are also determined by the general principle of reasonableness. Section 11 of the Act provides that no action shall lie for nuisance caused by overflying aircraft where the height of the aircraft is reasonable, having regard to wind, weather and all other circumstances, and subject to compliance with the provisions of the Aviation Act and other applicable legislative measures.[19]

To summarise: The essential question is whether the person who undertakes weather modification over a particular landowner's property acts reasonably towards surrounding landowners. In seeking an answer to this question, various circumstances surrounding the alleged nuisance are considered: The time and duration of the nuisance, the nature of the activities complained of, and the nature of the locality. The basic competition is between the utility of the defendant's conduct and the gravity of the harm suffered by the plaintiff.[20]

4.2.3 Permits and Licenses

Where a government department licenses weather modification activities in terms of a prescribed and properly followed procedure the public interest in regulating such activities, and the potential utility and social value of the licensed activity, would probably render the government department's conduct lawful in terms of the common law, even if damage is caused by the licensed activity. Where the licensing authority and the licensee acted reasonably and in the public interest, their conduct will be lawful, albeit contrary to some private interest. Thus in 1968 a lower court in Pennsylvania held that landowners beneath clouds had a property interest in the precipitation from them, but that this interest could be outweighed by the general public interest in properly approved cloud seeding operations.[21] The fact that the defendant weather modifier was in possession of a valid permit or license under the appropriate legislation will thus be relevant to the question whether his conduct was lawful.[22] The question of state liability for weather modification in South Africa has been governed by legislation since 1972. Section 33G of the Water Act[23] provides as follows:

> "The State or an officer of the State shall not be liable for any damage suffered as a result of the performance of any act authorized by a permit or license."

It must be noted that this exemption from liability applies only where a permit or a license has been issued. If some government department or parastatal body undertakes weather modification without a permit or license, as apparently authorized by s 33B of the Act, the exemption will not apply. A private holder of a permit or license is not protected by this exemption, although the fact that he acted under proper permit and license will be a relevant factor in deciding, by taking account of all the surrounding circumstances, whether he acted lawfully.

4.3 Causation

4.3.1 Theories of factual and legal causation

Causation as an element of delictual liability entails that the defendant is not liable unless his act in fact caused the complainant's harm. However, because the factual consequences of an act theoretically stretch into infinity a defendant is not liable for all the harm factually caused by his conduct. Factual causation is therefore a necessary but not by itself sufficient condition of liability.[24] Once factual causation of harm has been established, it must also be determined whether there is a sufficiently close or direct connection between the defendant's conduct and the harm it caused for the law to impose liability. This second question is one of legal causation or remoteness of damage, and concerns the formulation of principles whereby to limit liability. These two aspects of causation are explained as follows in the case of Minister of Police v Skosana[25]

> "Causation in the law of delict gives rise to two rather distinct problems. The first is a factual one and relates to the question as to whether the negligent act or omission in question caused or materially contributed to...the harm giving rise to the claim. If

> it did not, then no legal liability can arise and cadit quaestio. If it did, then the second problem becomes relevant, viz whether the negligent act or omission is linked to the harm sufficiently closely or directly for legal liability to ensue or whether, as it is said, the harm is too remote. This is basically a juridical problem in which considerations of legal policy may play a part."

The requirement of factual causation is satisfied if the harm in question would not have occurred but for the defendant's act, in other words, if the defendant's act is a necessary condition for the occurrence of the harm. In the Skosana case this is stated as follows:

> "The test is whether but for the negligent act or omission of the defendant the event giving rise to the harm in question would have occurred. This test is otherwise known as that of the causa (conditio) sine qua non and... no act, condition or omission can be regarded as a cause in fact unless it passes this test..."[26]

However, this "test" is open to criticism in that it provides no yardstick to determine whether an act was a necessary condition for harm that has occurred. If the test is applied by eliminating the negligent act complained about and substituting for it a careful act, and then asking whether the harm would still have occurred[27], it is still not clear by what yardstick the latter question is to be answered. It appears that factual causation will inevitably be determined by scientific knowledge and human experience and that the legal "test" of factual causation merely formulates a conclusion thus derived from knowledge and experience.[28]

Where factual causation has been established liability will be imposed only if the harm caused is also sufficiently closely linked to the defendant's act so as to satisfy the requirement of legal causation. The predominant view adopted in this regard in decided cases is that the harm must be a reasonably foreseeable result of the defendant's act. Because reasonable foreseeability is an element of negligence and may also be relevant for determining unlawfulness, the question arises whether legal causation is not coextensive with unlawfulness and negligence, rather than being an independent additional requirement for liability. [29] For present purposes it is unnecessary to enter into this debate, and it will suffice to accept that liability will be imposed only if it appears that the defendant's act was a substantial factor in producing the harm complained of, and that the harm thus factually caused was a kind of harm that the defendant reasonably should have foreseen and should have guarded against. The exact causal chain of events need not be foreseeable.[30] In American jurisdictions it is generally accepted that harm was not reasonably foreseeable if by hindsight it seems extraordinary that the harm should have occurred.[31]

The foreseeability of damage will depend on the circumstances of each case. There is evidence, for example, that the type of cloud that is suitable for seeding usually has a life span of 20 to 30 minutes and would normally dissipate if precipitation does not occur from in within that time. If the cloud would not have moved over a neighbouring property within that time, it could not have caused precipitation over that property in any event. It would therefore not be foreseeable that the seeding of such a cloud would deprive the neighbouring property of rainfall.[32] However, the seeding of a group of two or three of such clouds would involve the foreseeable danger of causing a hail storm.[33]

4.3.2 Proving factual causation

In American cases on weather modification proof of factual causation has been the most important obstacle to recovery of damages;[34] and the same problem of proof is likely to arise in a South African case of this nature. The plaintiff needs to prove factual causation in order to recover damages and also in order to prove nuisance. After almost two decades of research and operation in South Africa it appears as if no confident conclusions can be drawn as to the success or failure of rainfall stimulation or hail suppression; and in view of such uncertainty proof of factual causation of damage by weather modification is likely to present a major problem.[35]

The nature of this causation problem has been stated as follows:

> "The question of cause and effect is complicated by the fact that a small, artificially stimulated change in the weather is set against a confusing background of natural fluctuations of wide amplitude. Detection of anything other than a huge modulation of atmospheric processes is destined to be covered up by natural fluctuations. Thus, for example, the kind of effects now mentioned as conceivable by artificial rainmakers (say 10-20 percent increases or decreases) are very hard to detect against natural variability that may be twice as large."[36]

American cases illustrate the extent of the problem. In the 1964 case of Adams v California[37] , for example, the plaintiffs failed to convince the court that the flooding of Yuba City, California, would not have occurred "but for" the cloud seeding conducted on behalf of Pacific Gas and Electric Company. The court determined instead that the flood was caused by a freakish combination of storms and improper flood management by the state of California. Expert testimony at the trial indicated (1) that the cloud seeding in issue did not cause any additional rainfall to occur in the critical area, and (2) that there were too many broken links in the plaintiff's cause-effect chain. One expert pointed out the impossibility of proving cause and effect without establishing sufficiently controlled conditions and without a randomized selection of storms for testing. The experts agreed that there were several unknown factors in the chain of causation, any of which was sufficient to break the chain. Because the onus of proof rested upon the plaintifs, their case failed.

In three Texas cases in 1958, however, the plaintiffs successfully applied for court orders against weather modification activities.[38] The plaintiff cattle farmers obtained temporary court orders against a commercial weather modifier, who conducted cloud seeding operations aimed at hail suppression on behalf of grain, fruit and vegetable growers in the region. The cattle farmers claimed that the rainfall on their land had been reduced by the cloud seeding, and the court relied on statements by people of the region who said that they had observed how clouds which they recognised from experience as being rain bearing dissipated after cloud seeding. The court ordered that aircraft of the weather modification company shall no longer operate in the region. The court orders as initially issued applied to the entire surrounding area, but on appeal the orders were confirmed to apply only to weather modification activities over the plaintiffs' lands. The appellate court based its decision on the natural rights incident to ownership of land, stating that "the landowner is entitled to such precipitation as Nature deigns to bestow". Eventually the temporary orders were also confirmed by the Texas Supreme Court, which emphasised, however, that the case had not been tried upon the merits, and that the sole purpose of the temporary orders was to preserve the status quo until the complicated scientific and legal issues could be fully considered.

Proof of causation in the form of lay testimony as relied upon in these Soutwest Weather Research Inc cases is unlikely to be sustained in Texas since the 1974 case of Farmers and Ranchers for Natural Weather v Atmospherics Inc.[39] In the latter case the plaintiff's lay opinion and visual observation evidence, similar to that accepted in the 1958 Texas cases, was not sufficient to counter expert evidence by witnesses called by the defendant.[40]

In a Michigan case, Reinbold v Sumner Farmers Inc and Irving P Krick Inc, a farmer claimed that the seeding of an intended target area upwind from his farm caused a storm which ruined his crops. He had to prove that the seeding occurred in time to have had an impact on upon the storm and an adverse effect on his crops. He failed to prove such causation.[41]

Few such cases reach the courts, first perhaps because the distances at which weather modification effects may occur are so great that the putative plaintiff is unlikely ever to discover even the fact of weather modification activity.[42] If he does become aware of it, he faces a formidable problem in proving that the weather modification caused his loss.

Proof of what happened during a weather modification project will involve an attempt to reconstruct the flow of events in an air column of which the volume may range up to thousands of cubic kilometres, inclined at varying angles from the earth's surface and often moving at high speeds. The influence of variables such as pressure, temperature, humidity and the actions of submicroscopic particles in the air will further complicate the issue.[43]

To meet the burden of proving causation, a plaintiff must indicate a preponderance of probability, in other words that causation was more likely than not, and he could rely on expert witnesses, scientific data, or statistical probability analyses. Each of these methods poses its own problems.[44]

Experts in weather modification may be reluctant to testify as to the possible harmful effects of their science for fear of retarding growth in the field, or generating animosity from fellow professionals and business interests operating in the field. Even if experts agree to testify on behalf of a plaintiff, their varying experience and opinions, and the considerable scientific controversy over the scope and consistency of the effects of weather modification activities, may lead to widely conflicting testimony.

In the absence of expert testimony, a plaintiff would have to gather scientific data showing natural patterns of precipitation or hail. Such information, if available, is often incomplete or inaccurate. Meteorological data is mostly kept at ground level and only at widely spaced stations. Furthermore, its use in proving causation is limited due to the variability of individual clouds and storm systems. Scientific data may indicate long term weather patterns for an area, but could hardly prove how much precipitation a particular storm would have produced had it not been modified.

Statistical probability analyses, involving experiments to show the probability of certain weather phenomena occurring under certain meteorological conditions would be useful to a plaintiff only if it could be shown that such experiments were conducted under circumstances similar to those in issue in a particular case.[45] In any event, statistical probability by itself does not prove causation and some direct evidence related to the events under consideration. An analysis may show that it is highly probable that the seeding of particular clouds on a particular day would have resulted in a hail storm. It cannot, of course, show that the seeding did in fact cause the hail storm.

What is needed is reliable data to demonstrate statistically the actual effects of cloud seeding on any given cloud or storm system at any given time; and, in addition, complete recorded information about the prevailing conditions at the time of the weather modification which allegedly produced the harm. In the absence of such scientific information a court will be reluctant to make inferences or estimates of probabilities.

A further practical problem in this regard is that commercial weather modification contractors would not normally go to the expense of keeping detailed records of prevailing conditions, but would rather simply seed every cloud that comes along in an attempt to cause precipitation. Where it is alleged, for example, that the seeding of a few small clouds caused them to merge into one big cloud and resulted in a hailstorm, the absence of records as to the nature of the prevailing cloud systems at the time of seeding would make it extremely difficult to prove afterwards that hail damage was in fact caused by the precipitation attempt.[46] The irony is that a commercial operator who seeds clouds at random without prior study and without detailed record keeping would be more prone to make a mistake; while it would be more difficult to hold him liable because of a lack of detailed records. A scientific weather modifier who keeps detailed records, on the other hand, may be his own worst enemy. While proving the effectiveness of his own weather modification techniques, he may also in the process accumulate all the information needed by a plaintiff to prove that the weather modification had some harmful effect. Such information could be obtained by the plaintiff through discovery proceedings (aimed at full exchange of documentary evidence between the parties to litigation), and could then be used to prove his case.

In view of (1) the potential plaintiff's extremely onerous burden of proving causation, (2) the relatively underdeveloped state of weather modification science, and (3) the potential of resultant harm, it is suggested that a legislative provision be enacted to make it obligatory for a weather modifier to keep detailed records of all his operations.[47] Presently the Water Act[48] merely refers to the furnishing of information as a condition that may be laid down for the issue of a permit for undertaking weather modification activities. Detailed records of the weather modification activities would at least give the plaintiff a reasonable chance of proving any case that he may have. A further provision to shift the burden of proof to the weather modifier could also be considered,[49] but such a provision would unduly benefit a plaintiff who brings a spurious claim, and is therefore not recommended.

4.4 Fault

Liability for property damage (Aquilian liability) as a result of weather modification will be imposed only where the defendant is legally blameworthy, in other words, where the defendant had fault, either in the form of intention (dolus) or negligence (culpa).[50]

In South African law none of the recognised instances of strict or absolute liability (that is liability without fault) would apply to liability for weather modification. In American jurisdictions the doctrine of strict liability is generally adhered to for those who engage in an ultra hazardous activity, that is an activity involving a high degree of risk to others; but even under that doctrine it remains doubtful that weather modification aimed at precipitation or hail suppression will be regarded as such an ultra hazardous activity.[51] Hurricane diversion, on the other hand, involves such a high degree of risk of harm to others that it will probably be regarded by Amercan courts as an ultra hazardous activity, involving strict liability for damage caused.[52] For the purposes of delictual liability in South African law, however, it can be accepted that the plaintiff would need to prove fault on the part of the defendant, in the form of either intention or negligence.

Intention is a state of mind in which the will is directed at producing a particular result which is known to be unlawful. It is unlikely that weather modification will be undertaken with the intention of unlawfully causing damage to another.

Negligence is not a state of mind but an attribute of conduct: It is the failure to conform to the standard of conduct which the law demands in a particular situation. This standard is commonly expressed as that of the reasonable man or diligens paterfamilias. The following definition of negligence or culpa has often been accepted as authoritative by the courts:

"For the purposes of liability culpa arises if -

(a) a diligens paterfamilias in the position of the defendant -

(i) would foresee the reasonable possibility of his conduct injuring another in his person or property and causing him patrimonial loss; and

(ii) would take reasonable steps to guard against such occurence; and

(b) the defendant failed to take such steps."

Application of this standard in the context of weather modification means that there will be negligence if the defendant reasonably ought to have foreseen that the weather modification activities would harm another in his person or property, and failed to take steps that would have been reasonable in the circumstances to guard against such harm, for example by the precaution of giving warning.

This standard is simple in its formulation, but difficult to apply. The foreseeability aspect of negligence entails that one ought to foresee the reasonably foreseeable consequences of his acts. It is arguable that in the context of weather modification these consequences will be all unwanted types of weather.[54] It follows that the more scientifically unpredictable the results of cloud seeding are, the wider will be the range of unwanted and harmful weather developments which the cloud seeder reasonably ought to foresee as a result of his activities; and the wider the net of liability will be spread. The exact causal chain of events need not be foreseeable.[55]

The foreseeability of damage will depend on the circumstances of each case. There is evidence, for example, that the type of cloud that is suitable for seeding usually has a life span of 20 to 30 minutes and would normally dissipate if precipitation does not occur from in within that time. If the cloud would not have moved over a neighbouring property within that time, it could not have caused precipitation over that property in any event. It would therefore not be foreseeable that the seeding of such a cloud would deprive the neighbouring property of rainfall.[56] However, the seeding of a group of two or three of such clouds would involve the forseeable danger of causing a hail storm.[57]

The safeguarding aspect of negligence entails that one ought to take steps that would be reasonable in the circumstances to guard against the foreseeable harm. The question is what steps could be practicable to guard against the potentially harmful effects of weather modification, apart from refraining from weather modification altogether. The giving of advance warning seems to be an obvious precaution, and the failure to warn would indicate negligence. However, it is further arguable that warning by itself should not absolve the weather modifier from liability, because that would be tantamount to accepting the following as a complete defence: "I warned you--and you failed to complain or take precautions for your own protection."[58]

The standard of conduct expected of someone engaged in weather modification will be the standard care, skill and diligence that a professionally qualified person would ordinarily exercise when undertaking weather modification activities.[59] In the case of Adams v California cited above (the Yuba City flood case) the plaintiffs asserted, inter alia, that the defendants were negligent and committed professional malpractice by failing to meet the standard of conduct expected of a professional cloud seeder.[60] However, cases involving weather modification have not begun to establish specific guidelines as to the standards that must be adhered to in weather modification in order to avoid legal liability. It is clear, however, that the plaintiff would need to call expert witnesses to provide the court with scientific information; thus to enable the court to determine whether a weather modifier adhered to the standards normally met by members of that profession.

In this regard the plaintiff will experience practical problems similar to those involved in proving causation. Experts in weather modification, of whom there are probably only a limited number in South Africa, may be reluctant to testify against fellow professionals for fear of retarding growth in the field or generating animosity. Even if experts agree to testify on behalf of a plaintiff, their varying experience and opinions may lead to widely conflicting testimony; leaving the court unable to come to a decision other than granting absolution from the instance, meaning that the plaintiff failed to prove his case.

Because weather modification has the potential of causing extensive damage, it is arguable that South African law should adopt the American "ultra hazardous activity" doctrine to impose strict liability where damage is in fact caused by weather modification. A second argument in favour of adopting a strict liability doctrine is that the weather modifier is in a better position, by virtue of his effective control of operations and financial status, to bear and distribute any losses.[61] A third argument in favour of a strict liability doctrine is that, under such a doctrine, the plaintiff would still need to prove the difficult question of a causal relationship between the defendant's weather modification activities and the damage suffered; and therefore should not be saddled with having to prove negligence as well.[62] However, the counter argument is that weather modifcation is not only potentially harmful, but also potentially beneficial to the majority of people in a particular target area;[63] and this potentional benefit may be stifled by imposition of strict liability. It is suggested, with reliance upon the principle that a proven general public interest should take precedence over a private interest of demand, that the argument for imposition of strict liability for damages should be imposed without proof of fault; however difficult it might be to provide such proof of fault.

With regard to proof of negligence it is suggested that the Water Act[64] should prescribe that the proper advance warning should be given to persons who may be affected by the proposed weather modification activities, amplified by a further provision that, in the event of failure to give such warning, the onus will be on the weather modifier to prove that his weather modification activities generally and his failure to give warning in particular, did not constitute negligence in the circumstances of the case.[65]

4.5 Patrimonial loss

To succeed with an action for damages resulting from weather modification the complainant would need to prove a calculable pecuniary loss or diminution in his estate resulting from the defendant's unlawful and culpable conduct. Examples of loss that could result from weahter modification are damage to crops as a result of unseasonal rain and flood damage to crops, roads or buildings. Mere mental distress, inconvenience, annoyance, or fear is not enough to found an action for damages.[66]

4.6 Insurance

Provision is made in s 33D(4)(a) of the Water Act that any permit holder in terms of the Act shall, before causing modification of precipitation to be effected by any licence holder, and for the purpose of paying compensation for any resultant damage, furnish such security by way of insurance as may be determined by the responsible Minister on recommendation of the advisory committee appointed in terms of the Act. This provision raises the question whether liability for weather modification activities cannot simply be passed on to insurers.

This is no easy way out, because the insurance that will be involved here is liability insurance taken out by the weather modifier. The insurer will undertake to indemnify the weather modifier against any legal liability incurred as a result of the weather modification. Obviously the insurer will not pay out compensation to any person who complains of having suffered loss, but will require the complainant to prove legal liability on the part of the weather modifier. From the point of view of the potential plaintiff the existence of such liability insurance therefore does not make recovery of compensation any earlier. Insurance merely provides security for payment of compensation, should the plaintiff be able to prove legal liability for damages according to the normal principles of delictual liability, as discussed above.

Even if legislative provision is made for a new system of no fault insurance for recovery of compensation for loss caused by weather modification, the factual causation of such loss would still have to be proved, with all the difficulties which that entails for the plaintiff. It appears therefore that insurance has a peripheral role only with regard to the problems of legal liablitiy arising from weather modification.

1. Act 54 of 1956.

2. See the Report of the Select Committee on the Water Amendment Bill SC 7-'72 4.

3. Cf Julie Ferdon Federal weather modification projects: Compensating the landowner 26 (1984) Arizona Law Review 681 689.

4. See G N Heilbronn Some legal consequences of weather modification: An uncertain forecast Monash Univ L Rev Vol 6 (1979) 122 125; Julie Ferdon Federal weather modification projects: Compensating the landowner Arizona L Rev Vol 26 (1984) 681 686; Robert S Hunt Weather modification and the law, in Weather modification science and public policy (ed R G Fleagle) 1969 Univ of Washington Press 118 125-128; Ralph W Johnson Legal implications of weather modification, in Weather modification and the law (ed H J Taubenfeld) 1968 Oceana Publ 81-83.

5. See N J Van der Merwe and P J Olivier Die Onregmatige Daad in die Suid-Afrikaanse Reg (6 ed 1989) 250-251.

6. See in general P Q R Boberg The law of delict Vol 1 (1984) Juta & Co 30 et seq.

7. Cf the statement by Innes CJ in Cape Town Municipality v Paine 1923 AD 207 216-217: "Every man has a right not to be injured in his person or property by the negligence of another, and that involves a duty on each to exercise due and reasonable care."

8. See Van der Merwe & Olivier op cit 233-234; C G Van der Merwe Sakereg (2 ed 1989) 207; Cape Town Municipality v Benning 1917 AD 315 317; Breede River Irrigation Board v Brink 1936 AD 365; Van Schalkwyk v Van der Wath 1963 3 SA 636 (A).

9. See C G Van der Merwe op cit 206-207.

10. See Cape Town Municipality v Benning 1917 AD 315 317; and Breede River Irrigation Board v Brink 1936 AD 365.

11. See in general Regal v African Superslate (Pty) Ltd 1963 1 SA 102 (A) 107-108.

12. Robert S Hunt Weather modification and the law, in R G Fleagle: Weather modification science and public policy (1969) 118 123.

13. Cf Julie Ferdon Federal weather modification projects: Compensating the landowner 26 (1984) Arizona Law Review 681 690.

14. Cf Boberg op cit 34.

15. Cf J C Van der Walt Delict: Principles and Cases Butterworths (1979) par 27.

16. Cited by Julie Ferdon 26 (1984) Arizona Law Review 681 690-691.

17. See Vaughn C Ball Shaping the law of weather control 58 (1949) Yale Law Journal 213 232.

18. Act 74 of 1962.

19. Cf G N Heilbronn Some Legal Consequences of Weather Modification 6 (1979) Monash Univ Law Review 122 136-138, who gives a comparative survey of actionable trespass or nuisance arising from overflight of aircraft in the United Kingdom, Australia, the United States, and New Zealand.

20. Cf G N Heilbronn op cit 147.

21. Pennsylvania Natural Weather Association v Blue Ridge Weather Modification Association, referred to by Ray J Davis: Legal Uncertainties of Weather Modification, in W A Thomas (ed): Legal and Scientific Uncertainties of Weather Modification (1977) Duke Univ Press 38-39; and G N Heilbronn Some Legal Consequences of Weather Modification: An Uncertain Forecast 6 (1979) Monash Univ Law Review 122 128,130.

22. See G N Heilbronn op cit 130.

23. Act 54 of 1956.

24. Cf in general Boberg op cit 380-382.

25. 1977 1 SA 31 (A) 34.:

26. At 35.

27. Cf Boberg op cit 384.

28. Cf Boberg op cit 380 384.

29. Cf Boberg op cit 381.

30. Cf Ralph W Johnson op cit 109-112.

31. See Ralph W Johnson op cit 110.

32. See evidence presented to the select committee on the Water Amendment Bill, Report of the Select Committee on the Water Amendment Bill SC 7-'72 4.

33. Loc cit.

34. Cf Robert S Hunt Weather modification and the law, in R G Fleagle: Weather modification science and policy (1969) 128-129; Vaughn C Ball Shaping the law of weather control 58 (1949) The Yale Law Journal 213 230-232; Ray J Davis Legal uncertainties of weather modification, in W A Thomas (ed): Legal and Scientific Uncertainties of Weather Modification (1977) 32 40-41; H J Taubenfeld Weather Modification and the law (1968) 84-88,198; G N Heilbronn Some Legal Consequences of Weather Modification: An Uncertain Forecast 6 (1979) Monash Univ Law Review 122 126-127; A Gregory McKenzie Weather Modification: A Review of the Science and the Law 6 (1976) Environmental Law 387 426-428.

35. Cf Julie Ferdon Federal weather modification projects: Compensating the landowner 26 (1984) Arizona Law Review 681 686-688; Ray J Davis Legal uncertainties of weather modification, in W A Thomas (ed) Legal and scientific uncertainties of weather modification (1977) Duke Univ Press 40.

36. Ralph W Johnson Legal Implications of Weather Modification, in H J Taubenfeld (ed): Weather Modification and the Law (1968) 86

37. See Julie Ferdon, in the article cited above, at 687; and Ralrh W Johnson, in the article cited above, at 87-88.

38. The cases of Southwest Weather Research Inc v Duncan and Southwest Weather Research Inc v Rounsaville, and Southwest Weather Research Inc v Jones, referred to by Robert S Hunt Weather modification and the law supra 125-126; Georg Breuer Weather Modification: Prospects and Problems (1980) Cambridge Univ Press 134; and G N Heilbronn Some Legal Consequences of Weather Modification 6 (1979) Monash Univ Law Review 122 127.

39. Cited by G N Heilbronn op cit 127.

40. See G N Heilbronn loc cit.

41. See Ray J Davis Legal aspects of weather modification 109 (1983) Journal of Irrigation and Drainage Engineering 128 134.

42. Cf Vaugn C Ball Shaping the law of weather control 58 (1949) Yale Law Journal 213 230.

43. Cf Ball loc cit.

44. Cf Julie Ferdon in the article cited in note 24 above, at 687.

45. Cf generally Ralph W Johnson, in the article cited above at 107-108.

46. See Report of the Select Committee supra 14.

47. Cf Report of the Select Committee supra 15 para 26, 20-21 para 39 and 40.

48. Act 54 of 1956, s 33D(3).

49. Cf Julie Ferdon Federal weather modification projects: Compensating the landowner 26 (1984) Arizona Law Review 681 698.

50. Cf in general Boberg op cit 268-270

51. Cf Ralph W Johnson Legal Implications of Weather Modification, in H J Taubenfeld (ed): Weather Modification and the Law (1968) 123-124.

52. Cf Robert S Hunt Weather modification and the law, in R G Fleagle Weather modification science and public policy (1969) Univ of Washington Press 118 122-123.

53. Kruger v Coetzee 1966 2 SA 428 (A) 430.

54. See Ralph W Johnson op cit 122.

55. Cf Ralph W Johnson op cit 109-112.

56. See evidence presented to the select committee on the Water Amendment Bill, Report of the Select Committee on the Water Amendment Bill SC 7-'72 4.

57. Loc cit.

58. Cf Ralph W Johnson op cit 123.

59. Cf Ray J Davis Legal Uncertainties of Weather Modification, in W A Thomas (ed) Legal and Scientific Uncertainties of Weather Modification (1977) Duke Univ Press 39; and Robert S Hunt Weather Modification and the Law supra 124.

60. See Ray J Davis Legal aspects of weather modification 109 (1983) Journal of irrigation and drainage engineering 128 133.

61. Cf G N Heilbronn op cit 156-157

62. See Robert S Hunt Weather Modification and the Law supra 136.

63. Cf G N Heilbronn op cit 129-131, who refers to a 1968 Pennsylvania case Pennsylvania Natural Weather Association v Blue Ridge Weather Modification Association, where it was accepted that there may be a public right or interest in weather modification, which, if properly approved, will override the right or interest of a private landowner to the natural benefits of atmospheric resources such as the precipitation of rain.

64. Act 54 of 1956.

65. Cf Ralph W Johnson op cit 122-123.

66. Cf generally Boberg op cit 475-479; and see Ray J Davis Legal Uncertainties of Weather Modification, in W A Thomas (ed) Legal and Scientific Uncertainties of Weather Modification (1977) Duke Univ Press 38.

5. INTERNATIONAL LAW

5.1 International problems related to weather and climate modification

International problems caused by the application of weather modification technology may arise on account thereof that weather systems do not respect international political frontiers. For instance, cloud seeding over one country may lead to floods or droughts in a neighbouring country or deliberate or accidental hurricane diversion may lead to devastation in a country which otherwise might have been spared. The potential consequences of inadvertent weather and climate modification for the entire earth seem to be ominous indeed. This is dramatically illustrated by possible global warming due to the so-called green-house effect and the depletion of the ozone layer over certain areas. At the same time, it should be borne in mind that weather modification is designed to have beneficial effects and that it is not only harmful consequences which transcend international frontiers, but benefits as well.

5.2 Customary international law and case law

Customary international law traditionally emphasized the sovereignty of states, which implied considerable freedom of unilateral action. Activities which entailed detrimental consequences to the environment beyond national boundaries did not become the concern of the international community. In any case, intentional weather modification is a relatively recent development of the second part of the 20th Century.

Although no international-law decision is directly applicable to intentional weather modification, certain such decisions dealing with the application of customary international law nevertheless may have a bearing upon weather modification operations. Thus the Trail Smelter arbitration (United States v Canada 1941) confirmed that under the principles of international law, no state has the right to use or permit the use of its territory in such a manner as to cause injury by fumes in or to the territory of another or the properties of persons therein, when the instance has serious consequences and the injury established. The latter condition, would, in view of the relatively uncertain state of the art, prove to pose an almost insurmountable obstacle for victims of weather modification, if this decision should be applied by analogy to instances of intentional weather modification. Another relevant decision is the Lake Lanoux arbitration (France v Spain 1957) which recognized the principle that a state has a duty to take into account the rights and interests of a neighbouring state when using natural resources shared by more than one state. Finally, the Nuclear test cases (Australia v France, New Zealand v France 1974) seem to have recognized as a rule of customary international law, the obligation on states not to conduct atmospheric nuclear tests.

It is important to note that the rules of customary international law in principle form part of South African law.[1]

5.3 International agreements

There is no international agreement providing specifically for control over intentional weather modification. In fact, the United Nations' Convention on the Prohibition of Military Use of Environmental Modification Techniques (1976) explicitly states that its provisions do not hinder the use of environmental modification techniques for peaceful purposes. Provision is, nevertheless, made for the exchange of relevant information in the bilateral agreement between Canada and the US on The Exchange of Information on Weather Modification Activities (Washington 1975).

Moreover, there is no international agreement on liability for damage resulting from intentional weather modification activities. Nevertheless, the Convention on International Liability for Damage Caused by Space Objects (1972) seems to offer a model upon which a similar multilateral agreement for damage caused by weather modification operations may be based.[2]

Several bi-lateral and multi-lateral agreements provide for control over unintentional weather and climate modification, for instance the Convention on Long-range Transboundary Air Pollution (Geneva 1979), the Canada-US Memorandum concerning Transboundary Air Pollution (Washington 1980), the New York-Quebec Agreement on Acid Precipitation (Montreal 1982), the Convention on the Protection of the Ozone Layer (Vienna 1985) and the Protocol on Substances which deplete the Ozone Layer (Montreal 1987).

The Declaration on the Human Environment which was adopted at the UN Conference on the Human Environment, held in Stockholm in 1972, although not per se recognized as a source of international law, contains certain relevant principles which nevertheless have received some international recognition. These principles state that every nation has the responsibility to ensure that activities within its jurisdiction do not cause damage to the environment of other states or areas outside its national jurisdiction[3] and that states are obliged to develop the international law in respect of liability and compensation for the victims of environmental damage resulting from activities within their jurisdiction to areas beyond their jurisdiction.[4]

5.4 Military application

Although weather modification techniques do not presently seem to harbour such potential on a large scale, it is foreseeable that future technological progress may enable the use of weather and climate modification as a tool of warfare in causing prolonged droughts or major floods, in melting parts of the polar icecaps, in creating earthquakes, in diverting important ocean currents or in changing the ozone content of the stratosphere. In fact, in 1972 the US government admitted that it had used weather modification for military purposes for at least 5 years during the war in South-East Asia. Some 2600 secret missions were flown over Vietnam, Laos and Cambodia to seed clouds for purposes of bogging down enemy supply lines.[5]

An obvious first principle of the international control of intentional weather modification activities therefore should be that they should be restricted to peaceful purposes. Indeed, a USSR Draft Convention on Weather Modification (1974) sought to ensure that the technology be applied only for peaceful purposes. The United Nations' Convention on the Prohibition of Military Use of Environmental Modification Techniques (1976) now affirms this aim.

5.5 Future prospects

Possible methods of international control that may be contemplated, are the following:[6]

(a) a total prohibition on intentional weather modification;

(b) the establishment of international standards to be followed by states in their weather modification programmes;

(c) international supervision of such standards by a body such as the World Meteorological Organization (WMO);

(d) the introduction of an international licensing system or

(e) the establishment of an international monopoly on weather modification operations.

It has been suggested[7] that realistic goals at present would include the establishment of a reporting system whereunder states should be obliged to submit regular reports to the WMO on the weather modification activities for which they are responsible; such report could then be examined and published. Agreement could also be reached on the need for international consultation where there is a significant possibility of international implications resulting from weather modification operations. It seems obvious that there is a need for a world weather authority, probably within the WMO, to co-ordinate and administer all weather modification with international implications.[8]

1. Nduli v Minister of Justice 1978 (1) SA 893 (A). Cf Dugard International law is part of our law 1971 SALJ 13-15 and Booysen Volkereg. 'n Inleiding (1980) 73-7.

2. McKenzie supra n 117, 420-1..

3. Principle 21.

4. Principle 22.

5. Wood The status of weather modification activities under United States and international law 1977 Natural Resources Lawyer 367, 379-80.

6. Samuels International control of weather modification activities: peril or policy? 1973 Natural Resources Journal 327, 336-41.

7. Samuels supra n 6, 342.

8. Breuer supra n 9, 151-7.

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 9:52:55

TIME-DEPENDENT PROPERTIES - -10.0 to .0 mins after Decision Time.

CASES:- 85

84/11/ 1:11- 29	84/11/11:11- 39	84/11/16:11- 1	84/11/28:11- 39	84/11/29:11- 30	84/11/29:11- 58	84/12/12:11- 10
84/12/13:11- 30	84/12/13:11- 49	84/12/17:11- 16	84/12/18:11- 29	84/12/19:11- 59	84/12/19:11- 60	84/12/20:11- 67
85/ 1/ 7:11- 14	85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/18:11- 41	85/ 1/18:11- 25	85/ 2/ 7:11- 81	85/ 2/16:11- 30
85/ 2/28:11- 82	85/ 2/28:11-143	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/ 1:11-124	85/ 3/12:11- 1	85/ 3/13:11- 10
85/ 3/13:11- 1	85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35	85/11/ 2:11- 10	85/11/ 9:11- 41	85/11/26:11- 6
85/12/ 3:11- 12	85/12/14:11- 38	85/12/30:11- 68	86/ 1/ 3:11- 15	86/ 1/ 7:11- 8	86/ 1/14:11- 13	86/ 1/15:11-184
86/ 1/18:11- 37	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11- 37	86/ 2/13:11-125
86/ 2/22:11- 13	86/ 3/ 3:11- 10	86/ 3/ 3:11- 31	86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/13:11- 4
86/ 3/14:11- 54	86/ 3/14:11- 36	86/ 3/14:11- 56	86/ 3/24:11- 43	86/11/22:11- 46	86/11/24:11- 6	86/11/26:11- 27
86/11/26:11- 54	86/11/27:11- 18	86/12/ 1:11- 21	86/12/ 1:11- 94	86/12/ 2:11- 3	86/12/19:11- 5	87/ 1/13:11- 37
87/ 1/16:11-118	87/ 1/19:11- 23	87/ 1/21:11- 73	87/ 1/22:11- 26	87/ 1/23:11- 19	87/ 1/23:11- 37	87/ 2/ 3:11- 8
87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11	87/ 2/20:11- 19	87/ 2/27:11- 55	87/ 3/ 5:11- 3	87/ 3/19:11- 15
87/ 3/24:11- 50						

PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

A.2

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	11	11	11	11	11	11	12	12	12	12	12	12
DAY	1	11	16	28	29	29	12	13	13	17	18	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	29	39	1	39	30	58	10	30	49	16	29	59
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	6	7	10	12	13	14	18	19	20	23	24	25
SEED?	Y	N	Y	Y	Y	N	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	93	626	544	89	73	27	353	41	152	160	319	57
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	23.9	134.3	85.0	19.6	20.4	7.6	67.0	13.3	48.1	46.4	32.5	4.6
67 RFLUX 3 DEG - MASS........(KTON)	51	313	372	11	17	12	156	11	87	85	52	3
68 RFLUX 3 DEG - MEAN........(M3/S)	85	521	620	33	49	19	260	19	145	142	86	7

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	85	85	85	85	85	85	85	85	85	85
MONTH	12	12	1	1	1	1	1	2	2	2	2	3
DAY	19	20	7	15	15	18	18	7	16	28	28	1
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	60	67	14	13	38	41	25	81	30	82	143	5
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	26	28	30	31	32	34	35	38	37	41	42	43
SEED?	Y	Y	N	N	Y	N	Y	N	N	Y	Y	N
SAMPLE?	Y	Y	Y	N	Y	N	Y	N	N	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	91	300	163	104	43	39	59	118	83	176	310	106
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	20.1	41.7	44.6	18.4	10.7	14.7	23.9	14.1	9.3	42.8	106.2	32.8
67 RFLUX 3 DEG - MASS........(KTON)	39	104	79	39	3	5	36	25	9	133	178	65
68 RFLUX 3 DEG - MEAN........(M3/S)	64	174	132	65	49	38	60	41	14	222	297	108

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	3	3	3	3	3	10	10	10	11	11	11	12
DAY	1	1	12	13	13	16	29	29	2	9	26	3
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	76	124	1	10	1	1	4	35	10	41	6	12
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	44	45	46	48	49	53	54	55	56	60	61	62
SEED?	Y	N	Y	N	N	Y	N	Y	Y	Y	Y	Y
SAMPLE?	Y	N	Y	N	Y	Y	N	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	188	124	148	58	207	346	290	474	172	292	89	142
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	49.5	45.7	51.0	18.6	53.0	76.9	65.8	12.3	52.9	40.7	5.9	36.5
67 RFLUX 3 DEG - MASS........(KTON)	74	77	78	21	88	107	102	12	114	48	4	67
68 RFLUX 3 DEG - MEAN........(M3/S)	123	128	130	35	146	178	169	20	190	81	7	112

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	86	86	86	86	86	86	86	86	86	86
MONTH	12	12	1	1	1	1	1	1	2	2	2	2
DAY	14	30	3	7	14	15	18	29	5	5	7	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	38	68	15	8	13	184	37	20	13	131	6	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	65	67	68	71	73	76	77	78	80	81	82	84
SEED?	N	N	Y	N	N	N	N	N	N	Y	N	Y
SAMPLE?	Y	N	Y	N	Y	N	Y	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	316	62	15	94	207	81	21	81	13	238	184	588
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	55.9	.0	8.1	42.1	39.7	14.3	4.6	12.2	8.6	82.4	48.5	196.2
67 RFLUX 3 DEG - MASS........(KTON)	118	0	7	60	72	20	4	13	5	93	78	331
68 RFLUX 3 DEG - MEAN........(M3/S)	196	0	11	101	120	33	6	22	12	155	130	552

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	3	3	3	3	3	3	3	3	3	3
DAY	13	22	3	3	10	10	12	13	14	14	14	24
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	125	13	10	31	7	33	25	4	54	36	56	43
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	91	93	95	96	99	100	101	102	103	104	105	106
SEED?	Y	N	Y	Y	Y	Y	N	N	N	N	Y	Y
SAMPLE?	Y	N	Y	Y	Y	Y	Y	Y	N	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	39	92	65	171	156	87	212	209	167	243	222	20
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	12.2	31.3	5.7	35.6	31.1	18.3	42.0	81.0	20.3	49.4	81.8	5.2
67 RFLUX 3 DEG - MASS........(KTON)	12	43	5	72	70	48	142	98	0	103	146	4
68 RFLUX 3 DEG - MEAN........(M3/S)	19	72	8	121	117	80	237	163	23	171	243	7

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	87	87	87
MONTH	11	11	11	11	11	12	12	12	12	1	1	1
DAY	22	24	26	26	27	1	1	2	19	13	16	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	46	6	27	54	18	21	94	3	5	37	118	23
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	113	114	117	118	119	120	121	122	125	128	130	131
SEED?	N	Y	N	N	N	N	Y	N	Y	Y	Y	N
SAMPLE?	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	200	400	444	111	491	262	452	263	507	76	20	129
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	48.3	105.1	89.4	9.8	88.7	55.2	97.6	101.3	56.3	3.5	4.1	8.6
67 RFLUX 3 DEG - MASS........(KTON)	103	232	196	7	286	45	352	163	118	2	3	6
68 RFLUX 3 DEG - MEAN........(M3/S)	172	387	327	13	476	268	586	272	196	3	4	9

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	87	87	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	2	2	2	2	2	2	3	3
DAY	21	22	23	23	3	3	6	20	20	27	5	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	73	26	19	37	8	15	47	11	19	55	3	15
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	133	134	135	136	144	145	151	152	153	154	156	166
SEED?	N	Y	Y	N	N	Y	Y	N	Y	N	N	N
SAMPLE?	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	43	377	483	352	457	247	60	254	477	62	286	189
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	.0	54.4	41.7	72.9	14.9	46.3	.0	28.5	66.1	12.2	64.8	48.6
67 RFLUX 3 DEG - MASS........(KTON)	0	139	59	149	15	123	0	49	144	11	101	71
68 RFLUX 3 DEG - MEAN........(M3/S)	0	232	98	248	25	204	0	81	241	18	169	118

	85
YEAR	87
MONTH	3
DAY	24
SEQUENCE #	11
TRACK #	50
DBZ THRESHOLD	30
TRACK PARAMETERS - MAX SPEED	90
MAX TIME INTERVAL	30
CASE # IF APPLICABLE	169
SEED?	N
SAMPLE?	Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS

28 VOLUME - MEAN..............(KM3)	62

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

52 AREA 3 DEG - MEAN..........(KM2)	19.1
67 RFLUX 3 DEG - MASS........(KTON)	18
68 RFLUX 3 DEG - MEAN........(M3/S)	30

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 10:35:24

TIME-DEPENDENT PROPERTIES - .0 to 10.0 mins after Decision Time.

CASES:- 89

84/11/ 1:11- 29	84/11/11:11- 39	84/11/16:11- 1	84/11/27:11-149	84/11/28:11- 39	84/11/29:11- 30	84/11/29:11- 58
84/12/12:11- 10	84/12/13:11- 30	84/12/13:11- 49	84/12/17:11- 16	84/12/18:11- 29	84/12/19:11- 59	84/12/19:11- 60
84/12/20:11- 67	85/ 1/ 7:11- 14	85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/18:11- 41	85/ 1/18:11- 25	85/ 2/ 7:11- 81
85/ 2/16:11- 30	85/ 2/23:11- 49	85/ 2/28:11- 82	85/ 2/28:11-143	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/ 1:11-124
85/ 3/12:11- 1	85/ 3/12:11- 75	85/ 3/13:11- 10	85/ 3/13:11- 1	85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35
85/11/ 2:11- 10	85/11/ 9:11- 41	85/11/26:11- 6	85/12/ 3:11- 12	85/12/14:11- 38	85/12/30:11- 68	86/ 1/ 3:11- 15
86/ 1/ 7:11- 8	86/ 1/14:11- 13	86/ 1/14:11-240	86/ 1/15:11-184	86/ 1/18:11- 37	86/ 1/29:11- 20	86/ 2/ 5:11- 13
86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11- 37	86/ 2/13:11-125	86/ 2/22:11- 13	86/ 3/ 3:11- 10	86/ 3/ 3:11- 31
86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/13:11- 4	86/ 3/14:11- 54	86/ 3/14:11- 36	86/ 3/14:11- 56
86/ 3/24:11- 43	86/11/22:11- 46	86/11/24:11- 6	86/11/26:11- 27	86/11/26:11- 54	86/11/27:11- 18	86/12/ 1:11- 21
86/12/ 1:11- 94	86/12/ 2:11- 3	86/12/19:11- 5	87/ 1/13:11- 37	87/ 1/16:11-118	87/ 1/19:11- 23	87/ 1/21:11- 73
87/ 1/22:11- 26	87/ 1/23:11- 19	87/ 1/23:11- 37	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11
87/ 2/20:11- 19	87/ 2/27:11- 55	87/ 3/ 5:11- 3	87/ 3/19:11- 15	87/ 3/24:11- 50		

PROPERTY VALUE LIMITS

	MIN	MAX	
7 MEAN RANGE	10.0	80.0	KM
9 VOL AT DECISION TIME	0	750	KM3
244 TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	11	11	11	11	11	11	11	12	12	12	12	12
DAY	1	11	16	27	28	29	29	12	13	13	17	18
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	29	39	1	149	39	30	58	10	30	49	16	29
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	6	7	10	11	12	13	14	18	19	20	23	24
SEED?	Y	N	Y	N	Y	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	290	723	618	66	123	224	105	408	80	344	114	329
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	59.8	142.0	100.6	1.2	29.2	81.2	36.4	82.4	23.8	81.5	36.7	43.7
67 RFLUX 3 DEG - MASS........(KTON)	157	300	486	1	44	108	67	182	27	185	62	81
68 RFLUX 3 DEG - MEAN........(M3/S)	261	500	810	2	73	179	111	304	45	309	103	136

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	84	85	85	85	85	85	85	85	85	85
MONTH	12	12	12	1	1	1	1	1	2	2	2	2
DAY	19	19	20	7	15	15	18	18	7	16	23	28
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	59	60	67	14	13	38	41	25	81	30	49	82
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	25	26	28	30	31	32	34	35	38	37	40	41
SEED?	N	Y	Y	N	N	Y	N	Y	N	N	Y	Y
SAMPLE?	N	Y	Y	Y	N	Y	N	Y	N	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	97	72	363	353	137	69	51	84	190	52	98	153
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	24.3	20.3	65.0	83.0	33.7	21.2	19.7	29.8	34.4	8.4	32.4	54.8
67 RFLUX 3 DEG - MASS........(KTON)	32	22	202	160	93	50	37	60	66	7	7	142
68 RFLUX 3 DEG - MEAN........(M3/S)	53	37	336	267	155	83	62	99	110	11	63	236

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	2	3	3	3	3	3	3	3	10	10	10	11
DAY	28	1	1	1	12	12	13	13	16	29	29	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	143	5	76	124	1	75	10	1	1	4	35	10
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	42	43	44	45	46	47	48	49	53	54	55	56
SEED?	Y	N	Y	N	Y	Y	N	N	Y	N	Y	Y
SAMPLE?	Y	N	Y	N	Y	Y	N	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	176	162	248	78	60	58	11	400	345	265	682	483
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	64.6	35.2	55.0	37.9	29.7	2.3	5.9	70.4	63.3	66.4	26.0	129.6
67 RFLUX 3 DEG - MASS........(KTON)	112	87	120	53	41	2	4	183	66	95	23	266
68 RFLUX 3 DEG - MEAN........(M3/S)	187	144	200	88	68	3	7	304	110	159	38	444

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	85	85	85	86	86	86	86	86	86	86
MONTH	11	11	12	12	12	1	1	1	1	1	1	1
DAY	9	26	3	14	30	3	7	14	14	15	18	29
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	6	12	38	68	15	8	13	240	184	37	20
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	60	61	62	65	67	68	71	73	74	76	77	78
SEED?	Y	Y	Y	N	N	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	N	Y	N	Y	N	N	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	530	83	120	381	98	33	86	283	329	100	34	76
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	75.7	8.9	27.8	78.3	.0	13.4	37.1	50.5	39.8	28.7	8.7	8.7
67 RFLUX 3 DEG - MASS........(KTON)	97	7	50	142	0	9	57	97	36	36	10	8
68 RFLUX 3 DEG - MEAN........(M3/S)	161	12	84	237	0	15	94	161	65	61	17	13

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	2	2	3	3	3	3	3	3
DAY	5	5	7	7	13	22	3	3	10	10	12	13
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	13	131	6	37	125	13	10	31	7	33	25	4
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	80	81	82	84	91	93	95	96	99	100	101	102
SEED?	N	Y	N	Y	Y	N	Y	Y	Y	Y	N	N
SAMPLE?	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	71	374	231	527	135	138	57	81	307	98	227	217
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	26.3	100.4	37.8	145.8	50.4	45.2	1.7	24.9	74.1	19.4	53.6	95.3
67 RFLUX 3 DEG - MASS........(KTON)	67	139	82	288	76	63	1	29	111	53	127	120
68 RFLUX 3 DEG - MEAN........(M3/S)	111	232	137	479	127	105	2	49	185	88	212	200

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	3	3	3	3	11	11	11	11	11	12	12	12
DAY	14	14	14	24	22	24	26	26	27	1	1	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	54	36	56	43	46	6	27	54	18	21	94	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	103	104	105	106	113	114	117	118	119	120	121	122
SEED?	N	N	Y	Y	N	Y	N	N	N	N	Y	N
SAMPLE?	N	N	Y	Y	N	Y	N	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	246	217	130	92	148	379	560	194	775	399	683	259
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	47.8	49.5	65.0	19.7	51.2	94.8	129.1	42.7	154.6	90.5	94.1	75.9
67 RFLUX 3 DEG - MASS........(KTON)	62	61	84	25	77	200	215	48	385	306	305	153
68 RFLUX 3 DEG - MEAN........(M3/S)	103	101	139	42	128	334	359	81	641	511	508	255

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	86	87	87	87	87	87	87	87	87	87	87	87
MONTH	12	1	1	1	1	1	1	1	2	2	2	2
DAY	19	13	16	19	21	22	23	23	3	3	6	20
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	5	37	118	23	73	26	19	37	8	15	47	11
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	125	128	130	131	133	134	135	136	144	145	151	152
SEED?	Y	Y	Y	N	N	Y	Y	N	N	Y	Y	N
SAMPLE?	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	449	177	118	119	121	295	464	627	383	259	335	322
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	48.5	13.6	19.2	15.2	.2	84.7	56.0	116.4	27.6	46.3	31.9	28.8
67 RFLUX 3 DEG - MASS........(KTON)	78	9	17	20	0	159	86	219	37	116	71	56
68 RFLUX 3 DEG - MEAN........(M3/S)	130	15	29	34	0	265	144	365	62	194	119	94

	85	86	87	88	89
YEAR	87	87	87	87	87
MONTH	2	2	3	3	3
DAY	20	27	5	19	24
SEQUENCE #	11	11	11	11	11
TRACK #	19	55	3	15	50
DBZ THRESHOLD	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30
CASE # IF APPLICABLE	153	154	156	166	169
SEED?	Y	N	N	N	N
SAMPLE?	Y	N	N	N	Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS

28 VOLUME - MEAN..............(KM3)	595	61	186	68	75

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

52 AREA 3 DEG - MEAN..........(KM2)	77.5	9.8	56.4	19.2	29.7
67 RFLUX 3 DEG - MASS........(KTON)	245	10	83	12	54
68 RFLUX 3 DEG - MEAN........(M3/S)	408	17	138	40	90

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 10:57:27

TIME-DEPENDENT PROPERTIES - 10.0 to 20.0 mins after Decision Time.

CASES:- 86

84/11/ 1:11- 29	84/11/11:11- 39	84/11/16:11- 1	84/11/27:11-149	84/11/28:11- 39	84/11/29:11- 30	84/11/29:11- 58
84/12/12:11- 10	84/12/13:11- 30	84/12/13:11- 49	84/12/17:11- 16	84/12/18:11- 29	84/12/19:11- 59	84/12/19:11- 60
84/12/20:11- 67	85/ 1/ 7:11- 14	85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/18:11- 41	85/ 1/18:11- 25	85/ 2/ 7:11- 81
85/ 2/16:11- 30	85/ 2/23:11- 49	85/ 2/28:11- 82	85/ 2/28:11-143	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/ 1:11-124
85/ 3/12:11- 1	85/ 3/12:11- 75	85/ 3/13:11- 10	85/ 3/13:11- 1	85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35
85/11/ 2:11- 10	85/11/ 9:11- 41	85/11/26:11- 6	85/12/ 3:11- 12	85/12/14:11- 38	86/ 1/ 3:11- 15	86/ 1/ 7:11- 8
86/ 1/14:11- 13	86/ 1/14:11-240	86/ 1/15:11-184	86/ 1/18:11- 37	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131
86/ 2/ 7:11- 6	86/ 2/ 7:11- 37	86/ 2/13:11-125	86/ 2/22:11- 13	86/ 3/ 3:11- 31	86/ 3/10:11- 7	86/ 3/10:11- 33
86/ 3/12:11- 25	86/ 3/13:11- 4	86/ 3/14:11- 54	86/ 3/14:11- 36	86/ 3/14:11- 56	86/ 3/24:11- 43	86/11/22:11- 46
86/11/24:11- 6	86/11/26:11- 27	86/11/26:11- 54	86/11/27:11- 18	86/12/ 1:11- 21	86/12/ 1:11- 94	86/12/ 2:11- 3
86/12/19:11- 5	87/ 1/13:11- 37	87/ 1/16:11-118	87/ 1/19:11- 23	87/ 1/21:11- 73	87/ 1/22:11- 26	87/ 1/23:11- 19
87/ 1/23:11- 37	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11	87/ 2/20:11- 19	87/ 2/27:11- 55
87/ 3/ 5:11- 3	87/ 3/24:11- 50					

PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	11	11	11	11	11	11	11	12	12	12	12	12
DAY	1	11	16	27	28	29	29	12	13	13	17	18
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	29	39	1	149	39	30	58	10	30	49	16	29
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	6	7	10	11	12	13	14	18	19	20	23	24
SEED?	Y	N	Y	N	Y	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N

GROUP 2 - TOP,DEPTH,VOLUME,MASS

	1	2	3	4	5	6	7	8	9	10	11	12
28 VOLUME - MEAN..............(KM3)	321	690	677	105	93	280	149	380	85	402	58	176

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

	1	2	3	4	5	6	7	8	9	10	11	12
52 AREA 3 DEG - MEAN..........(KM2)	73.5	126.9	115.4	12.3	30.2	105.3	60.2	75.2	18.5	120.3	21.3	34.9
67 RFLUX 3 DEG - MASS........(KTON)	189	231	610	9	42	117	90	177	27	191	30	41
68 RFLUX 3 DEG - MEAN........(M3/S)	316	385	1016	15	70	195	150	295	45	319	51	68

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	84	85	85	85	85	85	85	85	85	85
MONTH	12	12	12	1	1	1	1	1	2	2	2	2
DAY	19	19	20	7	15	15	18	18	7	16	23	28
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	59	60	67	14	13	38	41	25	81	30	49	82
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	25	26	28	30	31	32	34	35	38	37	40	41
SEED?	N	Y	Y	N	N	Y	N	Y	N	N	Y	Y
SAMPLE?	N	Y	Y	Y	N	Y	N	Y	N	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	64	38	200	368	185	158	66	110	223	13	181	105
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	26.2	14.3	57.3	68.6	55.4	61.5	32.2	47.7	47.0	.9	63.7	36.5
67 RFLUX 3 DEG - MASS........(KTON)	26	9	101	172	104	113	41	73	74	0	96	60
68 RFLUX 3 DEG - MEAN........(M3/S)	44	17	169	287	174	188	68	122	124	0	160	100

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	2	3	3	3	3	3	3	3	10	10	10	11
DAY	28	1	1	1	12	12	13	13	16	29	29	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	143	5	76	124	1	75	10	1	1	4	35	10
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	42	43	44	45	46	47	48	49	53	54	55	56
SEED?	Y	N	Y	N	Y	Y	N	N	Y	N	Y	Y
SAMPLE?	Y	N	Y	N	Y	Y	N	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	189	207	360	22	24	79	5	534	376	276	784	544
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	59.4	56.2	81.0	14.1	12.8	11.6	3.0	108.0	80.8	79.2	39.3	160.2
67 RFLUX 3 DEG - MASS........(KTON)	119	143	171	16	14	16	0	335	164	85	51	307
68 RFLUX 3 DEG - MEAN........(M3/S)	198	238	284	27	24	27	4	558	274	142	86	512

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	85	85	86	86	86	86	86	86	86	86
MONTH	11	11	12	12	1	1	1	1	1	1	1	2
DAY	9	26	3	14	3	7	14	14	15	18	29	5
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	6	12	38	15	8	13	240	184	37	20	13
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	60	61	62	65	68	71	73	74	76	77	78	80
SEED?	Y	Y	Y	N	Y	N	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	N	Y	N	N	Y	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	679	47	167	270	20	67	491	887	34	25	50	93
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	97.4	5.2	36.3	74.2	15.0	31.6	106.3	134.9	15.1	7.9	3.4	34.7
67 RFLUX 3 DEG - MASS........(KTON)	163	1	65	103	1	42	163	199	15	3	3	76
68 RFLUX 3 DEG - MEAN........(M3/S)	272	6	108	171	16	70	272	332	25	14	5	127

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	2	3	3	3	3	3	3	3
DAY	5	7	7	13	22	3	10	10	12	13	14	14
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	131	6	37	125	13	31	7	33	25	4	54	36
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	81	82	84	91	93	96	99	100	101	102	103	104
SEED?	Y	N	Y	Y	N	Y	Y	Y	N	N	N	N
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	249	42	706	80	150	39	354	100	181	127	413	49
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	71.2	13.6	194.4	35.6	47.4	12.9	87.4	27.0	67.3	71.9	96.1	21.0
67 RFLUX 3 DEG - MASS........(KTON)	109	24	404	36	54	15	152	50	149	89	232	15
68 RFLUX 3 DEG - MEAN........(M3/S)	181	40	673	60	90	25	254	84	249	149	387	24

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	86	86	87
MONTH	3	3	11	11	11	11	11	12	12	12	12	1
DAY	14	24	22	24	26	26	27	1	1	2	19	1
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	13
TRACK #	56	43	46	6	27	54	18	21	94	3	5	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	105	106	113	114	117	118	119	120	121	122	125	128
SEED?	Y	Y	N	Y	N	N	N	N	Y	N	Y	Y
SAMPLE?	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	41	131	99	377	577	109	936	446	789	265	518	148
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	30.3	47.7	35.0	102.0	144.3	29.9	167.5	130.5	131.9	84.4	38.4	25.2
67 RFLUX 3 DEG - MASS........(KTON)	25	53	41	203	283	29	374	328	290	134	46	20
68 RFLUX 3 DEG - MEAN........(M3/S)	42	88	69	338	471	49	623	547	483	224	77	34

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	87	87	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	1	1	2	2	2	2	7	2
DAY	16	19	21	22	23	23	3	3	6	20	20	27
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	118	23	73	26	19	37	8	15	47	11	19	55
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	130	131	133	134	135	136	144	145	151	152	153	154
SEED?	Y	N	N	Y	Y	N	N	Y	Y	N	Y	N
SAMPLE?	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	88	187	227	148	275	588	357	288	580	359	650	15
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	26.5	28.2	9.5	31.3	39.7	96.8	27.6	56.0	48.7	43.5	86.3	.7
67 RFLUX 3 DEG - MASS........(KTON)	25	45	14	74	49	202	27	103	87	60	190	0
68 RFLUX 3 DEG - MEAN........(M3/S)	41	76	23	124	81	336	44	172	145	101	317	1

		85	86
YEAR		87	87
MONTH		3	3
DAY		5	24
SEQUENCE #		11	11
TRACK #		3	50
DBZ THRESHOLD		30	30
TRACK PARAMETERS - MAX SPEED		90	90
MAX TIME INTERVAL		30	30
CASE # IF APPLICABLE		156	169
SEED?		N	N
SAMPLE?		N	Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS

28	VOLUME - MEAN..............(KM3)	41	26

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

52	AREA 3 DEG - MEAN..........(KM2)	24.1	15.7
67	RFLUX 3 DEG - MASS........(KTON)	21	29
68	RFLUX 3 DEG - MEAN........(M3/S)	36	49

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 11:41:48

TIME-DEPENDENT PROPERTIES - 20.0 to 30.0 mins after Decision Time.

CASES:- 85

84/10/30:11-139	84/11/ 1:11- 29	84/11/11:11- 39	84/11/16:11- 1	84/11/27:11-149	84/11/28:11- 39	84/11/29:11- 30
84/11/29:11- 58	84/12/12:11- 10	84/12/13:11- 30	84/12/13:11- 49	84/12/14:11- 38	84/12/17:11- 16	84/12/18:11- 29
84/12/19:11- 59	84/12/20:11- 67	85/ 1/ 7:11- 14	85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/15:11-150	85/ 1/18:11- 41
85/ 1/18:11- 25	85/ 2/ 7:11- 81	85/ 2/23:11- 49	85/ 2/28:11- 82	85/ 2/28:11-143	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76
85/ 3/ 1:11-124	85/ 3/12:11- 1	85/ 3/12:11- 75	85/ 3/13:11- 1	85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35
85/11/ 2:11- 10	85/11/ 9:11- 41	85/12/ 3:11- 12	85/12/14:11- 38	86/ 1/ 3:11-149	86/ 1/ 7:11- 8	86/ 1/14:11- 13
86/ 1/14:11-240	86/ 1/15:11-184	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11-159
86/ 2/ 7:11- 37	86/ 2/10:11-125	86/ 2/13:11-125	86/ 2/22:11- 13	86/ 3/ 3:11- 31	86/ 3/10:11- 7	86/ 3/10:11- 33
86/ 3/12:11- 25	86/ 3/13:11- 4	86/ 3/14:11- 54	86/ 3/14:11- 36	86/ 3/14:11- 56	86/ 3/24:11- 43	86/11/22:11- 46
86/11/24:11- 6	86/11/26:11- 27	86/11/26:11- 54	86/11/27:11- 18	86/12/ 1:11- 21	86/12/ 1:11- 94	86/12/ 2:11- 3
86/12/19:11- 5	87/ 1/13:11- 37	87/ 1/16:11-118	87/ 1/19:11- 23	87/ 1/21:11- 73	87/ 1/22:11- 26	87/ 1/23:11- 19
87/ 1/23:11- 37	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11	87/ 2/20:11- 19	87/ 3/ 5:11- 3
87/ 3/24:11- 50						

PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	10	11	11	11	11	11	11	11	12	12	12	12
DAY	30	1	11	16	27	28	29	29	12	13	13	14
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	29	39	1	149	39	30	58	10	30	49	38
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	6	7	10	11	12	13	14	18	19	20	21
SEED?	N	Y	N	Y	N	Y	Y	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	8	163	594	635	84	79	213	97	336	87	191	44
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	.0	48.2	135.2	116.4	10.1	28.6	74.7	45.5	68.8	21.1	83.8	10.0
67 RFLUX 3 DEG - MASS........(KTON)	0	59	213	655	8	3	87	54	165	30	83	8
68 RFLUX 3 DEG - MEAN........(M3/S)	0	99	356	1091	14	60	145	91	275	49	138	16

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	84	84	84	85	85	85	85	85	85	85	85
MONTH	12	12	12	12	1	1	1	1	1	1	2	2
DAY	17	18	19	20	7	15	15	15	18	18	7	23
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	16	29	59	67	14	13	38	150	41	25	81	49
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	23	24	25	28	30	31	32	33	34	35	38	40
SEED?	N	N	N	Y	N	N	Y	Y	N	Y	N	Y
SAMPLE?	N	N	N	Y	Y	N	Y	Y	N	Y	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	13	36	20	51	364	143	162	71	112	77	153	283
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	10.4	10.5	10.7	27.5	73.0	57.6	66.7	2.4	53.1	35.2	46.7	107.7
67 RFLUX 3 DEG - MASS........(KTON)	4	11	7	28	170	96	93	3	79	65	66	174
68 RFLUX 3 DEG - MEAN........(M3/S)	11	18	13	47	284	160	154	5	131	108	110	290

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	2	2	3	3	3	3	3	3	10	10	10	11
DAY	28	28	1	1	1	12	12	13	16	29	29	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	82	143	5	76	124	1	75	1	1	4	35	10
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	41	42	43	44	45	46	47	49	53	54	55	56
SEED?	Y	Y	N	Y	N	Y	Y	N	Y	N	Y	Y
SAMPLE?	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	111	139	322	379	13	11	80	536	300	439	890	168
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	34.6	39.6	80.7	88.2	9.6	6.4	15.5	149.0	65.5	90.6	58.8	53.7
67 RFLUX 3 DEG - MASS........(KTON)	81	98	191	165	1	4	20	265	159	102	101	132
68 RFLUX 3 DEG - MEAN........(M3/S)	135	163	319	275	18	7	33	441	265	170	168	220

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	85	85	85	86	86	86	86	86	86	86	86	86
MONTH	11	12	12	1	1	1	1	1	1	2	2	2
DAY	9	3	14	3	7	14	14	15	29	5	5	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	12	38	149	8	13	240	184	20	13	131	6
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	60	62	65	70	71	73	74	76	78	80	81	82
SEED?	Y	Y	N	Y	N	N	N	N	N	N	Y	N
SAMPLE?	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	757	76	217	55	25	592	1093	10	48	90	442	20
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	130.8	27.5	68.0	12.0	16.0	133.1	196.0	7.3	2.2	39.8	89.1	9.4
67 RFLUX 3 DEG - MASS........(KTON)	230	44	77	8	14	237	68	1	2	52	224	17
68 RFLUX 3 DEG - MEAN........(M3/S)	383	73	128	18	23	394	535	8	3	87	374	29

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	2	3	3	3	3	3	3	3
DAY	7	7	10	13	22	3	10	10	12	13	14	14
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	159	37	125	125	13	31	7	33	25	4	54	36
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	83	84	85	91	93	96	99	100	101	102	103	104
SEED?	N	Y	N	Y	N	Y	Y	Y	N	N	N	N
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	143	728	15	11	33	29	447	143	85	34	369	19
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	55.6	190.3	1.7	6.9	17.5	12.1	106.5	41.6	38.7	25.8	108.2	10.0
67 RFLUX 3 DEG - MASS........(KTON)	57	468	0	4	15	0	194	68	101	7	166	10
68 RFLUX 3 DEG - MEAN........(M3/S)	138	780	1	8	26	21	323	114	169	38	276	17

	61	62	63	64	65	66	67	68	69	70	71	72
YEAR	86	86	86	86	86	86	86	86	86	86	86	87
MONTH	3	3	11	11	11	11	11	12	12	12	12	1
DAY	14	24	22	24	26	26	27	1	1	2	19	13
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	56	43	46	6	27	54	18	21	94	3	5	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	105	106	113	114	117	118	119	120	121	122	125	128
SEED?	Y	Y	N	Y	N	N	N	N	Y	N	Y	Y
SAMPLE?	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	8	273	53	362	602	44	1227	248	484	332	692	24
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	6.1	112.3	22.4	110.0	153.6	16.7	141.4	106.6	158.2	94.7	95.7	5.8
67 RFLUX 3 DEG - MASS........(KTON)	4	52	23	211	325	16	468	129	223	136	214	4
68 RFLUX 3 DEG - MEAN........(M3/S)	7	188	38	352	542	27	780	215	372	226	356	8

	73	74	75	76	77	78	79	80	81	82	83	84
YEAR	87	87	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	1	1	2	2	2	2	2	3
DAY	16	19	21	22	23	23	3	3	6	20	20	5
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	118	23	73	26	19	37	8	15	47	11	19	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	130	131	133	134	135	136	144	145	151	152	153	156
SEED?	Y	N	N	Y	Y	N	N	Y	Y	N	Y	N
SAMPLE?	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	51	302	98	69	192	338	353	770	552	270	540	14
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	20.6	37.8	13.3	26.9	17.0	100.8	26.6	125.3	46.8	38.7	108.5	12.3
67 RFLUX 3 DEG - MASS........(KTON)	13	54	18	38	16	133	30	304	69	49	160	2
68 RFLUX 3 DEG - MEAN........(M3/S)	30	89	30	64	27	222	51	507	115	82	267	15

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...........................................................................................................................................

                                              85

   YEAR                                       87
   MONTH                                       3
   DAY                                        24
   SEQUENCE #                                 11
   TRACK #                                    50

   DBZ THRESHOLD                              30
   TRACK PARAMETERS - MAX SPEED               90
              MAX TIME INTERVAL               30

   CASE # IF APPLICABLE                      169
   SEED?                                       N
   SAMPLE?                                     Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS



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 28 VOLUME - MEAN..............(KM3)        22

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS
============================================
 52 AREA 3 DEG - MEAN..........(KM2)      15.2
 67 RFLUX 3 DEG - MASS........(KTON)         0
 68 RFLUX 3 DEG - MEAN........(M3/S)        37

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TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 12: 2:49

TIME-DEPENDENT PROPERTIES - 30.0 to 40.0 mins after Decision Time.

CASES:- 70

84/10/30:11-139	84/11/ 1:11- 29	84/11/11:11- 39	84/11/16:11- 1	84/11/27:11-149	84/11/29:11- 30	84/11/29:11- 58
84/12/12:11- 10	84/12/13:11- 30	84/12/13:11- 49	84/12/14:11- 38	84/12/18:11- 29	84/12/20:11- 67	85/ 1/ 7:11- 14
85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/15:11-150	85/ 1/18:11- 41	85/ 1/18:11- 25	85/ 2/ 7:11- 81	85/ 2/23:11- 49
85/ 2/28:11- 82	85/ 2/28:11-143	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/12:11- 75	85/ 3/13:11- 1	85/10/16:11- 1
85/10/29:11- 4	85/10/29:11- 35	85/11/ 2:11- 10	85/11/ 9:11- 41	85/12/ 3:11- 12	85/12/14:11- 38	86/ 1/ 3:11-149
86/ 1/ 7:11- 8	86/ 1/14:11- 13	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11-159
86/ 2/ 7:11- 37	86/ 2/10:11-125	86/ 2/22:11- 13	86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/14:11- 54
86/ 3/14:11- 36	86/ 3/14:11- 56	86/11/22:11- 46	86/11/24:11- 6	86/11/26:11- 27	86/11/26:11- 54	86/11/27:11- 18
86/12/ 1:11- 21	86/12/ 1:11- 94	86/12/ 2:11- 3	86/12/19:11- 5	87/ 1/19:11- 23	87/ 1/21:11- 73	87/ 1/22:11- 26
87/ 1/23:11- 19	87/ 1/23:11- 37	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11	87/ 2/20:11- 19

PROPERTY VALUE LIMITS

		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	84	84	84	84
MONTH	10	11	11	11	11	11	11	12	12	12	12	12
DAY	30	1	11	16	27	29	29	12	13	13	14	18
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	29	39	1	149	30	58	10	30	49	38	29
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	6	7	10	11	13	14	18	19	20	21	24
SEED?	N	Y	N	Y	N	Y	N	N	N	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	24	95	321	560	66	231	67	337	32	28	255	17
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	6.7	34.7	103.7	132.2	9.2	81.0	32.3	64.5	7.5	15.5	49.1	4.5
67 RFLUX 3 DEG - MASS........(KTON)	6	8	109	718	1	106	35	163	5	12	67	1
68 RFLUX 3 DEG - MEAN........(M3/S)	10	48	181	1197	14	177	59	271	10	20	112	10

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	84	85	85	85	85	85	85	85	85	85	85	85
MONTH	12	1	1	1	1	1	1	2	2	2	2	3
DAY	20	7	15	15	15	18	18	7	23	28	28	1
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	67	14	13	38	150	41	25	81	49	82	143	5
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	28	30	31	32	33	34	35	38	40	41	42	43
SEED?	Y	N	N	Y	Y	N	Y	N	Y	Y	Y	N
SAMPLE?	Y	Y	N	Y	Y	N	Y	N	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	7	411	48	114	121	102	94	84	222	113	102	367
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	5.7	72.7	30.5	47.2	22.1	44.1	38.5	24.4	79.1	33.5	35.6	80.6
67 RFLUX 3 DEG - MASS........(KTON)	2	210	34	57	67	69	55	40	118	85	8	185
68 RFLUX 3 DEG - MEAN........(M3/S)	7	350	57	94	112	115	92	67	197	142	134	308

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	85	85	85	85	85	85	85	86	86
MONTH	3	3	3	10	10	10	11	11	12	12	1	1
DAY	1	12	13	16	29	29	2	9	3	14	3	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	76	75	1	1	4	35	10	41	12	38	149	8
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	44	47	49	53	54	55	56	60	62	65	70	71
SEED?	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN...............(KM3)	325	26	441	306	616	751	94	876	30	281	127	23
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	91.1	7.2	123.8	62.0	135.7	84.8	40.9	132.3	15.9	88.7	28.0	13.2
67 RFLUX 3 DEG - MASS........(KTON)	145	6	201	196	217	162	75	218	8	127	26	13
68 RFLUX 3 DEG - MEAN........(M3/S)	242	9	336	326	361	270	125	363	28	211	43	22

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	1	1	2	2	2	2	2	2	2	3	3	3
DAY	14	29	5	5	7	7	7	10	22	10	10	12
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	13	20	13	131	6	159	37	125	13	7	33	25
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	73	78	80	81	82	83	84	85	93	99	100	101
SEED?	N	N	N	Y	N	N	Y	N	N	Y	Y	N
SAMPLE?	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	596	60	102	625	34	68	600	13	6	782	232	68
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	136.8	3.2	33.6	109.6	15.8	35.4	173.9	3.0	4.3	190.9	67.3	27.8
67 RFLUX 3 DEG - MASS........(KTON)	208	3	65	279	33	36	366	2	1	336	98	66
68 RFLUX 3 DEG - MEAN........(M3/S)	347	4	108	465	55	61	611	3	5	561	163	110

	49	50	51	52	53	54	55	56	57	58	59	60
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	3	3	3	11	11	11	11	11	12	12	12	12
DAY	14	14	14	22	24	26	26	27	1	1	2	19
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	54	36	56	46	6	27	54	18	21	94	3	5
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	103	104	105	113	114	117	118	119	120	121	122	125
SEED?	N	N	Y	N	Y	N	N	N	N	Y	N	Y
SAMPLE?	N	N	Y	N	Y	N	N	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	166	87	14	25	292	747	18	1533	63	107	287	699
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	73.4	26.8	6.9	13.4	105.5	114.5	9.8	154.2	28.0	52.2	96.9	132.5
67 RFLUX 3 DEG - MASS........(KTON)	64	30	7	8	150	260	7	485	25	52	153	392
68 RFLUX 3 DEG - MEAN........(M3/S)	107	50	13	18	250	433	13	809	41	86	256	653

	61	62	63	64	65	66	67	68	69	70
YEAR	87	87	87	87	87	87	87	87	87	87
MONTH	1	1	1	1	1	2	2	2	2	2
DAY	19	21	22	23	23	3	3	6	20	20
SEQUENCE #	11	11	11	11	11	11	11	11	11	11
TRACK #	23	73	26	19	37	8	15	47	11	19
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	131	133	134	135	136	144	145	151	152	153
SEED?	N	N	Y	Y	N	N	Y	Y	N	Y
SAMPLE?	N	N	Y	Y	Y	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS										
28 VOLUME - MEAN..............(KM3)	534	28	56	150	120	470	1363	320	126	379
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS										
52 AREA 3 DEG - MEAN..........(KM2)	59.4	3.6	31.4	4.5	66.7	58.6	198.5	32.1	22.6	71.7
67 RFLUX 3 DEG - MASS........(KTON)	109	2	3	3	18	99	530	30	23	124
68 RFLUX 3 DEG - MEAN........(M3/S)	181	9	46	4	99	166	884	50	38	207

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 12:13:42

TIME-DEPENDENT PROPERTIES - 40.0 to 50.0 mins after Decision Time.

CASES:- 56

84/10/30:11-139	84/11/11:11- 39	84/11/16:11- 1	84/11/29:11- 30	84/11/29:11- 58	84/12/12:11- 10	84/12/13:11- 49
84/12/14:11- 38	85/ 1/ 7:11- 14	85/ 1/15:11- 13	85/ 1/15:11- 38	85/ 1/15:11-150	85/ 1/18:11- 41	85/ 1/18:11- 25
85/ 2/ 7:11- 81	85/ 2/23:11- 49	85/ 2/28:11- 82	85/ 3/ 1:11- 5	85/ 3/ 1:11- 76	85/ 3/12:11- 75	85/ 3/13:11- 1
85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35	85/11/ 2:11- 10	85/11/ 9:11- 41	85/12/14:11- 38	86/ 1/ 3:11-149
86/ 1/ 7:11- 8	86/ 1/14:11- 13	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 6	86/ 2/ 7:11-159
86/ 2/ 7:11- 37	86/ 2/10:11-125	86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/14:11- 54	86/ 3/14:11- 36
86/11/24:11- 6	86/11/26:11- 27	86/11/27:11- 18	86/12/ 1:11- 21	86/12/ 1:11- 94	86/12/ 2:11- 3	86/12/19:11- 5
87/ 1/19:11- 23	87/ 1/23:11- 19	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/ 6:11- 47	87/ 2/20:11- 11	87/ 2/20:11- 19

PROPERTY VALUE LIMITS

PROPERTY	MIN	MAX	
7 MEAN RANGE	10.0	80.0	KM
9 VOL AT DECISION TIME	0	750	KM3
244 TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	84	85	85	85	85
MONTH	10	11	11	11	11	12	12	12	1	1	1	1
DAY	30	11	16	29	29	12	13	14	7	15	15	15
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	39	1	30	58	10	49	38	14	13	38	150
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	7	10	13	14	18	20	21	30	31	32	33
SEED?	N	N	Y	Y	N	N	N	N	N	N	Y	Y
SAMPLE?	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	25	114	403	210	58	282	9	763	412	28	21	52
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	12.4	45.9	114.7	74.9	23.4	59.6	5.4	122.9	83.0	21.3	9.5	17.6
67 RFLUX 3 DEG - MASS........(KTON)	10	26	543	83	30	140	4	170	212	0	9	26
68 RFLUX 3 DEG - MEAN........(M3/S)	16	59	905	139	49	233	7	284	353	29	14	43

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	85	85	85	85	85	85	85	85	85	85	85	85
MONTH	1	1	2	2	2	3	3	3	3	10	10	10
DAY	18	18	7	23	28	1	1	12	13	16	29	29
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	41	25	81	49	82	5	76	75	1	1	4	35
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	34	35	38	40	41	43	44	47	49	53	54	55
SEED?	N	Y	N	Y	Y	N	Y	Y	N	Y	N	Y
SAMPLE?	N	Y	N	Y	Y	N	Y	Y	Y	Y	N	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	90	208	37	233	71	212	106	11	418	287	721	440
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	34.5	98.4	10.5	77.7	24.2	58.5	40.1	2.7	78.1	66.0	162.8	84.0
67 RFLUX 3 DEG - MASS........(KTON)	32	144	14	136	51	107	42	2	142	185	316	153
68 RFLUX 3 DEG - MEAN........(M3/S)	79	240	23	227	86	179	89	4	236	309	527	254

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	85	85	85	86	86	86	86	86	86	86	86	86
MONTH	11	11	12	1	1	1	1	2	2	2	2	2
DAY	2	9	14	3	7	14	29	5	5	7	7	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	10	41	38	149	8	13	20	13	131	6	159	37
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	56	60	65	70	71	73	78	80	81	82	83	84
SEED?	Y	Y	N	Y	N	N	N	N	Y	N	N	Y
SAMPLE?	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	92	958	99	180	7	402	28	140	662	19	8	491
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	42.7	127.4	45.3	32.5	5.3	119.9	.8	35.6	148.3	14.1	6.3	188.4
67 RFLUX 3 DEG - MASS........(KTON)	21	238	44	34	3	151	1	73	347	5	1	301
68 RFLUX 3 DEG - MEAN........(M3/S)	105	396	74	56	7	252	1	122	578	23	6	501

	37	38	39	40	41	42	43	44	45	46	47	48
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	3	3	3	3	3	11	11	11	12	12	12
DAY	10	10	10	12	14	14	24	26	27	1	1	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	125	7	33	25	54	36	6	27	18	21	94	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	85	99	100	101	103	104	114	117	119	120	121	122
SEED?	N	Y	Y	N	N	N	Y	N	N	N	Y	N
SAMPLE?	Y	Y	Y	Y	N	N	Y	N	Y	Y	Y	Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS

	37	38	39	40	41	42	43	44	45	46	47	48
28 VOLUME - MEAN..............(KM3)	62	814	145	67	90	216	207	713	1434	13	41	111

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

	37	38	39	40	41	42	43	44	45	46	47	48
52 AREA 3 DEG - MEAN..........(KM2)	11.4	211.1	41.5	37.8	51.3	53.4	74.2	118.2	166.5	7.2	13.9	45.8
67 RFLUX 3 DEG - MASS........(KTON)	10	339	63	43	1	72	126	303	460	2	4	51
68 RFLUX 3 DEG - MEAN........(M3/S)	16	565	105	72	63	120	211	505	767	8	22	85

	49	50	51	52	53	54	55	56
YEAR	86	87	87	87	87	87	87	87
MONTH	12	1	1	2	2	2	2	2
DAY	19	19	23	3	3	6	20	20
SEQUENCE #	11	11	11	11	11	11	11	11
TRACK #	5	23	19	8	15	47	11	19
DBZ THRESHOLD	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	125	131	135	144	145	151	152	153
SEED?	Y	N	Y	N	Y	Y	N	Y
SAMPLE?	Y	N	Y	Y	Y	Y	Y	Y

GROUP 2 - TOP,DEPTH,VOLUME,MASS

	49	50	51	52	53	54	55	56
28 VOLUME - MEAN..............(KM3)	676	571	91	388	1199	117	35	339

GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS

	49	50	51	52	53	54	55	56
52 AREA 3 DEG - MEAN..........(KM2)	203.0	61.9	.8	56.3	181.7	18.5	8.3	54.9
67 RFLUX 3 DEG - MASS........(KTON)	467	134	0	136	481	5	5	75
68 RFLUX 3 DEG - MEAN........(M3/S)	778	224	1	226	802	22	8	124

TRACK PROPERTIES AS COMPUTED BY 'TRACKPROPS'

15/ 1/1990 12:19:24

TIME-DEPENDENT PROPERTIES - 50.0 to 60.0 mins after Decision Time.

CASES:- 42

84/10/30:11-139	84/11/16:11- 1	84/11/29:11- 30	84/11/29:11- 58	84/12/12:11- 10	84/12/13:11- 49	84/12/14:11- 38
85/ 1/ 7:11- 14	85/ 1/15:11- 38	85/ 1/15:11-150	85/ 1/18:11- 25	85/ 2/ 7:11- 81	85/ 2/23:11- 49	85/ 2/28:11- 82
85/ 3/ 1:11- 5	85/ 3/13:11- 1	85/10/16:11- 1	85/10/29:11- 4	85/10/29:11- 35	85/11/ 9:11- 41	85/12/14:11- 38
86/ 1/ 3:11-149	86/ 1/14:11- 13	86/ 1/29:11- 20	86/ 2/ 5:11- 13	86/ 2/ 5:11-131	86/ 2/ 7:11- 37	86/ 2/10:11-125
86/ 3/10:11- 7	86/ 3/10:11- 33	86/ 3/12:11- 25	86/ 3/14:11- 36	86/11/24:11- 6	86/11/26:11- 27	86/11/27:11- 18
86/12/ 2:11- 3	86/12/19:11- 5	87/ 1/19:11- 23	87/ 2/ 3:11- 8	87/ 2/ 3:11- 15	87/ 2/20:11- 11	87/ 2/20:11- 19

PROPERTY VALUE LIMITS

PROPERTY		MIN	MAX	
7	MEAN RANGE	10.0	80.0	KM
9	VOL AT DECISION TIME	0	750	KM3
244	TCCL/DT500	2.0	100.0	

	1	2	3	4	5	6	7	8	9	10	11	12
YEAR	84	84	84	84	84	84	84	85	85	85	85	85
MONTH	10	11	11	11	12	12	12	1	1	1	1	2
DAY	30	16	29	29	12	13	14	7	15	15	18	7
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	139	1	30	58	10	49	38	14	38	150	25	81
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	5	10	13	14	18	20	21	30	32	33	35	38
SEED?	N	Y	Y	N	N	N	N	N	Y	Y	Y	N
SAMPLE?	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	12	333	178	61	192	11	1046	370	12	27	184	18
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	7.6	103.4	62.8	23.3	52.2	6.4	135.1	62.7	5.9	9.3	83.2	7.2
67 RFLUX 3 DEG - MASS........(KTON)	4	447	68	27	103	1	200	204	0	1	119	8
68 RFLUX 3 DEG - MEAN........(M3/S)	9	745	113	45	172	7	333	341	7	17	198	13

	13	14	15	16	17	18	19	20	21	22	23	24
YEAR	85	85	85	85	85	85	85	85	85	86	86	86
MONTH	2	2	3	3	10	10	10	11	12	1	1	1
DAY	23	28	1	13	16	29	29	9	14	3	14	29
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	49	82	5	1	1	4	35	41	38	149	13	20
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	40	41	43	49	53	54	55	60	65	70	73	78
SEED?	Y	Y	N	N	Y	N	Y	Y	N	Y	N	N
SAMPLE?	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	N
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	303	21	79	450	244	949	214	812	78	190	97	14
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	101.8	11.5	21.5	80.7	69.6	212.0	37.1	148.6	29.2	46.9	45.4	.6
67 RFLUX 3 DEG - MASS........(KTON)	210	14	19	116	197	360	55	290	32	59	39	1
68 RFLUX 3 DEG - MEAN........(M3/S)	350	23	31	193	328	600	105	483	54	99	65	1

	25	26	27	28	29	30	31	32	33	34	35	36
YEAR	86	86	86	86	86	86	86	86	86	86	86	86
MONTH	2	2	2	2	3	3	3	3	11	11	11	12
DAY	5	5	7	10	10	10	12	14	24	26	27	2
SEQUENCE #	11	11	11	11	11	11	11	11	11	11	11	11
TRACK #	13	131	37	125	7	33	25	36	6	27	18	3
DBZ THRESHOLD	30	30	30	30	30	30	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30	30	30	30	30	30	30
CASE # IF APPLICABLE	80	81	84	85	99	100	101	104	114	117	119	122
SEED?	N	Y	Y	N	Y	Y	N	N	Y	N	N	N
SAMPLE?	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS												
28 VOLUME - MEAN..............(KM3)	118	479	605	367	440	116	103	360	202	526	1206	45
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS												
52 AREA 3 DEG - MEAN..........(KM2)	35.3	156.9	246.6	53.8	154.7	26.4	41.6	63.8	46.7	120.3	167.6	8.5
67 RFLUX 3 DEG - MASS........(KTON)	42	259	392	50	191	40	59	122	170	204	487	9
68 RFLUX 3 DEG - MEAN........(M3/S)	71	431	653	84	318	75	99	204	283	340	811	16

	37	38	39	40	41	42
YEAR	86	87	87	87	87	87
MONTH	12	1	2	2	2	2
DAY	19	19	3	3	20	20
SEQUENCE #	11	11	11	11	11	11
TRACK #	5	23	8	15	11	19
DBZ THRESHOLD	30	30	30	30	30	30
TRACK PARAMETERS - MAX SPEED	90	90	90	90	90	90
MAX TIME INTERVAL	30	30	30	30	30	30
CASE # IF APPLICABLE	125	131	144	145	152	153
SEED?	Y	N	N	Y	N	Y
SAMPLE?	Y	N	Y	Y	Y	Y
GROUP 2 - TOP,DEPTH,VOLUME,MASS						
28 VOLUME - MEAN..............(KM3)	470	736	75	1179	16	414
GROUP 3 - AREA,RAIN FLUX,PRECIP WATER,RATIOS						
52 AREA 3 DEG - MEAN..........(KM2)	152.7	78.5	24.3	174.6	4.2	73.2
67 RFLUX 3 DEG - MASS........(KTON)	326	178	36	8	0	87
68 RFLUX 3 DEG - MEAN........(M3/S)	543	297	60	798	4	145

APPENDIX B

PAWS : Summary of all storms tracked by radar on all operational days.

DAY PROPERTIES ON FILE
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Year	Month	Day	Seq	# Tracks	ATI	Max V	Max ROT V	Max Top	Max Dbz
82	11	12	11	2	49	250	.484	11940	52.4
82	11	19	11	19	505	2218	.859	14239	63.6
82	11	20	11	16	945	3633	1.710	16365	54.3
82	11	21	11	14	163	261	.148	12139	65.3
82	11	24	11	29	1166	1462	.771	15044	66.3
82	11	29	11	84	1905	1805	1.803	16005	63.7
82	12	7	11	15	267	409	.510	10119	59.5
82	12	8	11	53	1593	1837	1.254	15750	61.2
82	12	10	11	6	407	1087	.290	13499	65.0
82	12	15	11	8	460	613	.863	13142	61.5
82	12	16	11	43	795	766	.902	15295	61.1
82	12	17	11	17	216	609	.700	13975	56.2
82	12	23	11	48	2286	5041	2.941	17080	63.0
82	12	29	11	31	1472	2452	5.440	16238	61.0
82	12	30	11	47	1260	1674	3.285	16694	61.6
82	12	31	11	56	791	405	.285	12041	55.3
83	1	3	11	52	1925	2728	1.744	16761	59.6
83	1	4	11	37	749	736	.695	14987	60.6
83	1	5	11	63	1355	1189	1.205	15385	69.8
83	1	19	11	4	67	252	.282	10637	55.5
83	1	21	11	40	1186	1072	1.385	15791	58.7
83	2	2	11	34	705	798	.902	14790	60.3
83	2	3	11	3	115	345	.555	14258	58.4
83	2	4	11	27	833	1643	1.676	16548	63.7
83	2	7	11	33	1024	1365	1.712	18355	59.6
83	2	8	11	11	199	236	.261	12308	57.9
83	2	11	11	23	597	865	.603	14081	63.2
83	2	12	11	49	1196	1287	1.177	14078	62.4
83	3	3	11	34	1482	1838	2.022	15725	65.4
83	3	7	11	3	119	259	.503	11760	56.7
83	3	8	11	7	197	841	.765	12499	64.1
83	3	15	11	20	362	853	.677	13889	57.3
83	3	18	11	5	36	176	.340	9601	59.8
83	3	22	11	19	646	1091	2.098	15832	65.2
83	3	31	11	10	45	83	.132	9229	57.8
83	4	4	11	10	328	1166	.873	13871	58.6
83	4	5	11	9	257	1064	.985	15271	55.7
83	4	11	11	67	1855	1350	1.286	11918	64.0
83	4	12	11	23	670	415	.519	12133	60.9
83	4	13	11	68	2705	2121	1.174	15927	62.2
83	4	15	11	31	664	1233	1.178	13883	65.3
83	10	13	11	16	329	597	.527	11579	59.0
83	10	20	11	10	132	558	.616	7986	60.4
83	10	21	11	6	272	369	.525	10690	58.7
83	10	24	11	26	805	905	1.096	10870	62.6
83	11	4	11	6	205	633	.991	14213	57.8
83	11	5	11	99	2628	1702	2.772	14765	64.7
83	11	6	11	38	2533	1689	1.117	14762	63.3
83	11	9	11	15	610	1388	.324	15035	63.1
83	11	12	11	7	486	631	.539	12142	64.0
83	11	14	11	36	1320	1323	2.139	14711	64.3
83	11	15	11	2	197	1030	1.478	11433	59.4
83	11	16	11	9	635	1227	.774	13604	63.1
83	11	17	11	25	1136	1174	.849	14022	66.3
83	11	18	11	14	284	787	.115	12761	58.8
83	11	23	11	2	129	643	.480	14886	62.2
83	11	24	11	28	580	1098	2.221	15316	54.7
83	12	7	11	15	424	602	.718	14450	61.6

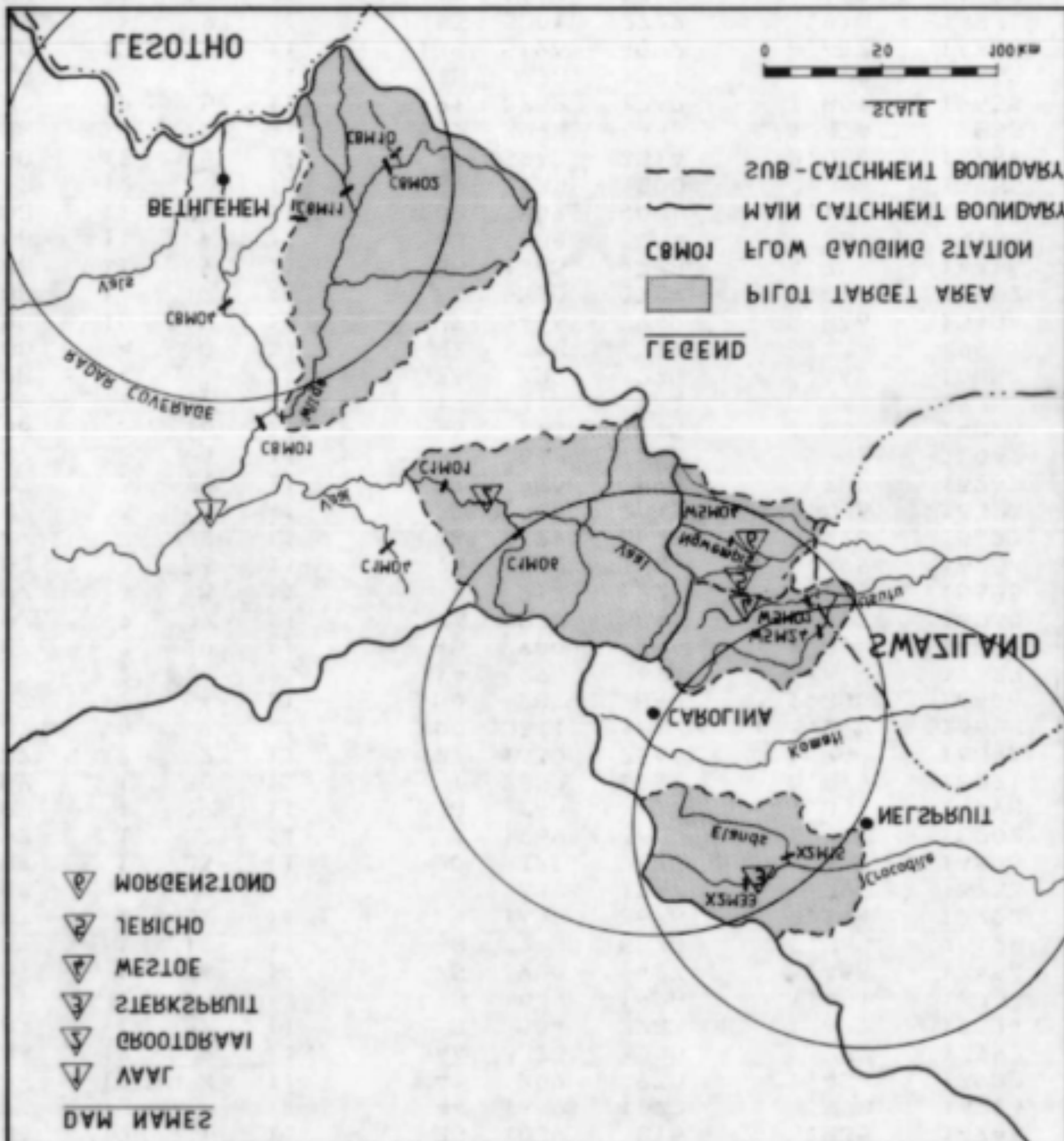
83	12	9	11	41	1344	2625	2.156	18015	62.7
83	12	12	11	18	521	761	.808	15416	58.7
83	12	30	11	35	1290	1047	1.206	12934	65.6
84	1	2	11	88	2029	1398	1.264	16294	63.1
84	2	2	11	17	303	208	.241	13200	59.6
84	2	6	11	10	285	805	.895	16574	58.7
84	2	8	11	15	1264	3689	1.815	19257	62.5
84	2	15	11	16	345	680	.698	12703	54.6
84	2	20	11	32	644	408	.628	13575	59.5
84	2	24	11	92	2859	3684	.966	13325	67.0
84	3	2	11	13	115	301	.282	13335	51.4
84	3	7	11	65	1849	1364	1.186	15828	63.5
84	3	20	11	22	498	997	1.622	14505	60.9
84	3	21	11	24	446	427	.479	10271	57.6
84	3	30	11	8	107	154	.293	6931	53.7
84	4	8	11	77	2251	2424	1.031	16439	62.4
84	4	17	11	15	379	739	.712	12084	60.8
84	4	25	11	15	113	57	.079	7663	52.1
84	10	8	11	6	47	204	.327	9335	53.8
84	10	15	11	18	827	967	1.359	10382	64.1
84	10	19	11	12	230	442	.445	12686	55.7
84	10	22	11	114	3014	2282	1.245	13642	67.8
84	10	29	11	15	536	915	1.150	13879	61.8
84	10	30	11	66	1390	900	.959	11595	63.6
84	11	1	11	168	4188	3560	2.263	14803	70.9
84	11	10	11	4	206	1237	.445	14064	54.7
84	11	11	11	9	247	748	1.089	12875	54.8
84	11	12	11	275	9225	9458	5.912	15698	69.3
84	11	16	11	39	1432	1733	1.055	13113	71.7
84	11	27	11	29	1252	800	1.092	13439	61.2
84	11	28	11	46	1791	1743	1.609	14850	66.1
84	11	29	11	104	1426	837	1.147	11191	68.0
84	12	4	11	6	97	261	.325	11845	52.4
84	12	10	11	123	4109	3720	2.560	16852	65.9
84	12	12	11	27	1191	2408	1.195	15505	63.7
84	12	13	11	83	1375	1815	1.327	14931	64.8
84	12	14	11	54	1323	2400	1.398	15407	58.7
84	12	17	11	23	469	902	1.198	14998	59.4
84	12	18	11	23	956	1161	1.710	15942	58.3
84	12	19	11	40	999	988	.918	15881	58.2
84	12	20	11	44	537	538	.569	14916	62.8
85	1	4	11	47	2929	3790	2.477	18446	62.7
85	1	7	11	24	475	484	.697	13932	62.8
85	1	15	11	109	1609	1211	.795	14498	65.2
85	1	17	11	64	1381	1180	.580	10996	63.7
85	1	18	11	84	1722	2038	1.069	16807	67.6
85	2	7	11	33	486	305	.399	13075	56.8
85	2	16	11	22	358	433	.547	15476	50.9
85	2	23	11	57	1550	1500	1.648	14360	59.4
85	2	28	11	48	1245	629	.980	15474	59.5
85	3	1	11	42	1259	1407	1.465	16766	68.3
85	3	8	11	3	45	153	.217	9915	52.2
85	3	12	11	24	595	292	.627	12279	59.2
85	3	13	11	39	756	572	.521	13629	60.6
85	10	8	11	15	620	1313	1.079	12665	54.1
85	10	8	22	15	600	1313	1.079	12665	54.1
85	10	14	11	6	496	750	.457	12731	60.8
85	10	14	22	6	496	750	.457	12731	60.8
85	10	16	11	9	1159	1537	.825	13543	60.4
85	10	16	22	10	1160	1537	.572	13543	60.4
85	10	29	11	51	2786	5875	2.034	17321	61.4
85	10	29	22	49	2786	5875	2.034	17321	61.4
85	11	2	11	17	696	738	1.080	14021	58.2

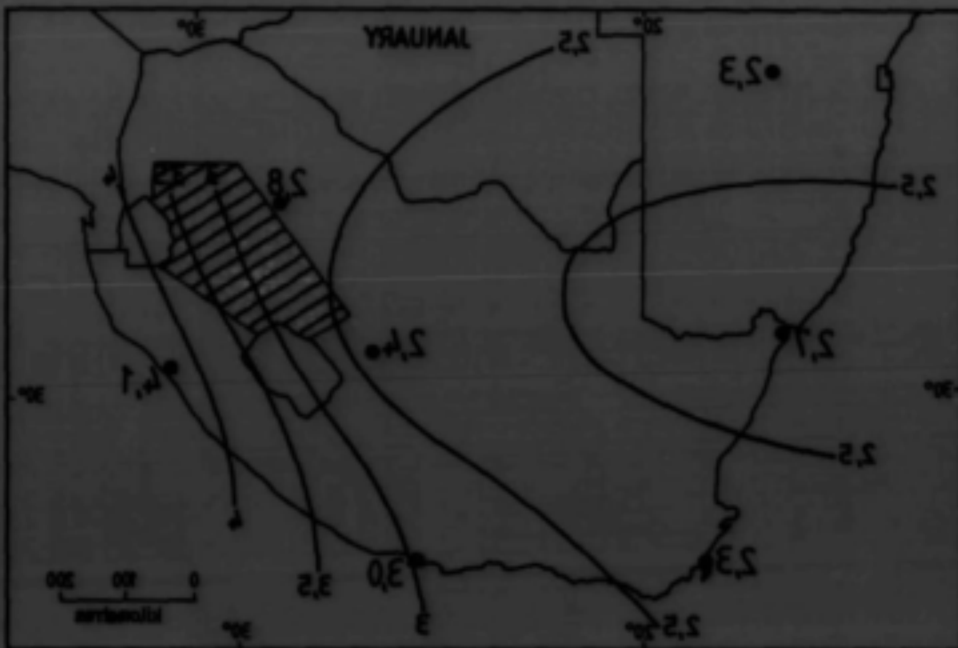
85	11	2	22	17	695	738	1.080	14021	58.2
85	11	7	11	49	859	964	1.087	16217	58.1
85	11	7	22	47	852	964	1.087	16217	58.1
85	11	8	11	68	3491	2661	2.657	14306	62.0
85	11	8	22	68	3510	2661	2.657	14306	62.0
85	11	9	11	123	4005	3216	2.564	16249	60.8
85	11	9	22	110	4027	3216	2.564	16249	60.8
85	11	22	11	22	452	1379	1.550	14214	54.2
85	11	22	22	22	452	1379	1.550	14214	54.2
85	11	26	11	5	58	288	.279	10134	56.3
85	11	26	22	5	58	288	.279	10134	56.3
85	12	3	11	12	259	548	.514	11934	55.0
85	12	3	22	12	259	548	.514	11934	55.0
85	12	4	22	7	35	65	.092	8436	54.2
85	12	7	11	57	2204	1447	2.089	14624	61.0
85	12	7	22	57	2203	1447	2.089	14624	61.0
85	12	14	11	76	1413	1356	1.179	15470	56.9
85	12	14	22	74	1407	1356	1.179	15470	63.1
85	12	30	11	55	2144	2555	1.675	16554	65.7
85	12	30	22	54	2130	2555	1.675	16554	65.7
86	1	3	11	44	1419	1119	1.113	13384	60.3
86	1	3	22	39	1398	1119	1.113	13384	60.3
86	1	7	11	9	261	287	.294	11467	58.1
86	1	7	22	9	261	287	.294	11467	58.1
86	1	13	11	39	2102	5375	2.378	17588	61.0
86	1	13	22	39	2102	5375	2.378	17588	61.0
86	1	14	11	55	2835	2241	2.304	18051	61.1
86	1	14	22	54	2806	2241	1.782	18051	61.1
86	1	15	11	103	3645	7168	5.209	18170	63.5
86	1	15	22	96	3590	7168	5.209	18170	63.5
86	1	18	11	63	961	402	.305	12090	61.1
86	1	18	22	66	968	402	.305	12090	61.1
86	1	29	11	70	1338	1056	.975	15976	64.5
86	1	29	22	71	1367	1056	.975	15976	64.5
86	2	5	11	95	1887	1057	.964	14100	60.8
86	2	5	22	97	1905	1057	.964	14100	60.8
86	2	7	11	66	2854	2592	1.839	15869	60.9
86	2	7	22	63	2792	2592	1.839	15869	60.9
86	2	10	11	47	1013	799	.968	12092	60.4
86	2	10	22	49	1004	799	.968	12092	60.4
86	2	11	11	75	2853	1536	1.603	13575	66.0
86	2	11	22	72	2836	1536	1.603	13575	66.0
86	2	12	11	62	2823	1848	1.501	14701	67.5
86	2	12	22	61	2802	1848	1.983	14701	67.5
86	2	13	11	47	710	593	.344	13219	58.4
86	2	13	22	51	714	593	.344	13219	58.4
86	2	21	11	41	841	889	.888	14915	57.0
86	2	21	22	41	841	889	.888	14915	57.0
86	2	22	11	74	2553	3177	2.440	17183	59.1
86	2	22	22	73	2533	3177	2.440	17183	59.1
86	3	3	11	18	404	724	.447	13882	56.6
86	3	3	22	16	393	724	.447	13882	56.6
86	3	6	11	32	469	401	.424	13351	58.1
86	3	6	22	30	460	401	.424	13351	58.1
86	3	10	11	116	3531	2271	2.160	15897	61.1
86	3	12	11	30	741	583	.650	15336	60.3
86	3	12	22	30	740	583	.650	15336	60.3
86	3	13	11	10	368	461	.537	14149	60.2
86	3	13	22	10	368	461	.537	14149	60.2
86	3	14	11	40	1099	2170	1.086	16224	58.3
86	3	14	22	39	1087	2170	1.086	16224	58.3
86	3	24	11	91	1532	787	.885	12625	55.9
86	3	24	22	81	1480	787	.674	12625	55.9

86	10	27	11	97	2837	2091	2.000	14511	64.3
86	11	18	11	31	1266	2947	2.627	15472	56.1
86	11	22	11	11	131	222	.161	11009	57.9
86	11	24	11	7	316	463	.473	11079	58.3
86	11	25	11	25	478	297	.526	10196	58.8
86	11	26	11	46	1331	901	.779	13959	61.0
86	11	27	11	18	1302	1630	.786	15681	65.0
86	12	1	11	28	1039	815	.835	14746	63.1
86	12	2	11	44	1359	1072	.998	14224	60.9
86	12	3	11	41	709	930	1.430	13982	70.2
86	12	19	11	44	3373	3005	2.772	13992	70.5
87	1	7	11	8	504	2783	1.699	15324	62.1
87	1	13	11	25	1049	1928	1.481	16704	59.8
87	1	16	11	75	980	427	.456	13456	56.2
87	1	19	11	68	3773	5870	5.365	20128	67.8
87	1	21	11	29	1647	3676	2.194	17222	62.6
87	1	22	11	13	639	1347	.798	16753	60.0
87	1	23	11	20	371	672	.687	14506	57.1
87	1	28	11	23	1269	4687	5.338	18202	57.1
87	1	29	11	8	145	505	.831	14998	56.4
87	1	30	11	41	2852	8931	5.079	18271	69.5
87	2	2	11	27	1630	2366	1.740	16641	64.4
87	2	3	11	100	5311	4817	6.579	16688	67.0
87	2	4	11	50	987	848	1.255	16406	63.2
87	2	6	11	14	290	624	.684	17322	60.2
87	2	20	11	45	900	766	.801	14896	57.4
87	2	27	11	76	2857	5841	4.713	16840	69.5
87	3	5	11	4	217	1221	.708	15695	59.7
87	3	6	11	24	2232	3544	3.799	16236	63.0
87	3	9	11	46	2329	5648	3.290	15622	68.7
87	3	13	11	38	1583	2045	1.536	16323	70.7
87	3	19	11	27	980	590	.787	15262	66.0
87	3	24	11	31	663	552	.727	12042	65.9
88	3	16	11	6	73	815	1.035	14826	48.6
88	3	17	11	17	318	467	.764	13787	50.5
88	4	7	11	26	382	278	.362	10857	56.7
88	4	8	11	23	317	274	.234	9941	49.8
88	10	17	11	77	2416	2942	2.866	15486	59.7
88	11	3	11	68	3550	3189	2.816	15987	65.9
88	11	9	11	56	4365	4728	4.729	14416	62.0
88	11	26	11	43	1050	764	.530	14102	66.0
88	11	28	11	108	3909	4081	4.194	16004	64.8
88	12	2	11	89	2035	1500	2.394	13955	57.0
88	12	5	11	49	3942	3514	2.080	13769	60.5
88	12	12	11	92	3244	1446	1.474	12855	62.8
88	12	15	11	91	2752	1762	1.801	19635	63.4
88	12	20	11	35	778	1591	1.420	14662	58.6
88	12	21	11	138	5196	4882	6.637	16349	63.8
89	1	9	11	153	5201	2722	1.918	14871	61.3
89	1	10	11	45	1467	1267	.679	14477	63.0
89	1	11	11	61	1600	1042	1.082	13686	60.4
89	2	14	11	263	3836	3020	1.709	22080	60.6
89	3	1	11	37	998	925	.766	13614	60.3
89	3	2	11	135	2916	1457	1.596	15172	58.7
89	3	13	11	62	1659	2366	1.368	15551	54.2

END OF DATA

PROPOSED PILOT TARGET AREAS FOR DESK STUDIES



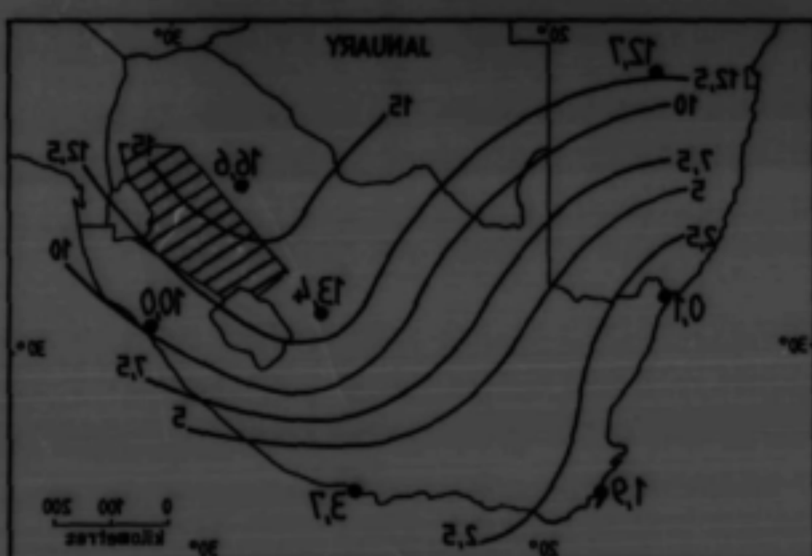


MEAN PRECIPITABLE DAILY WATER VAPOUR (cm) : JANUARY VALUES

(AFTER McGEE, 1982)

TARGET ZONE

FIGURE 6.5



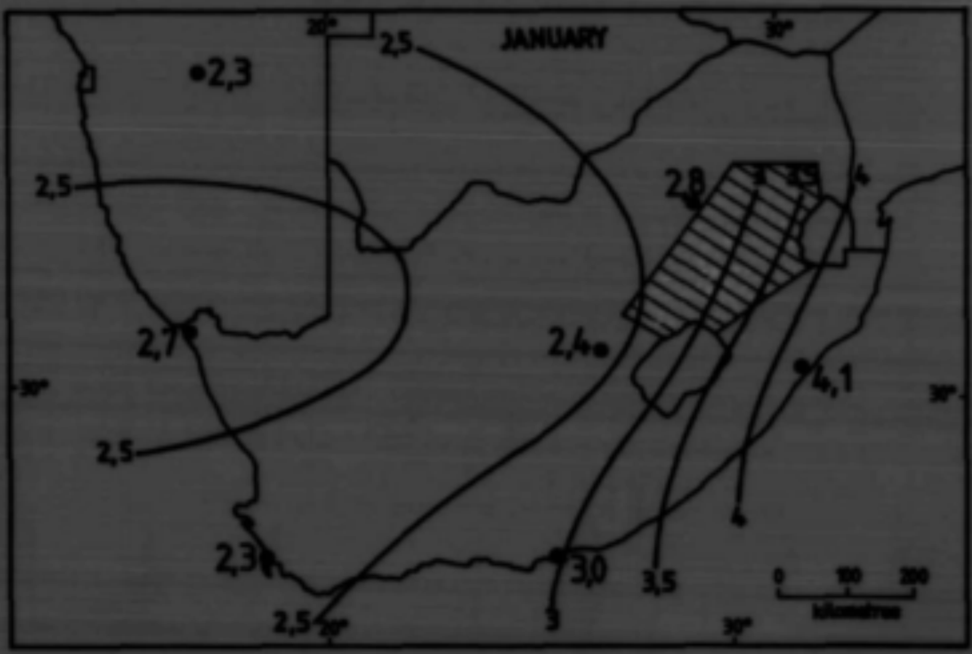
FRACTION (%) OF MEAN PRECIPITABLE DAILY WATER VAPOUR

ACTUALLY BECOMING RAIN

(AFTER McGEE, 1982)

TARGET ZONE

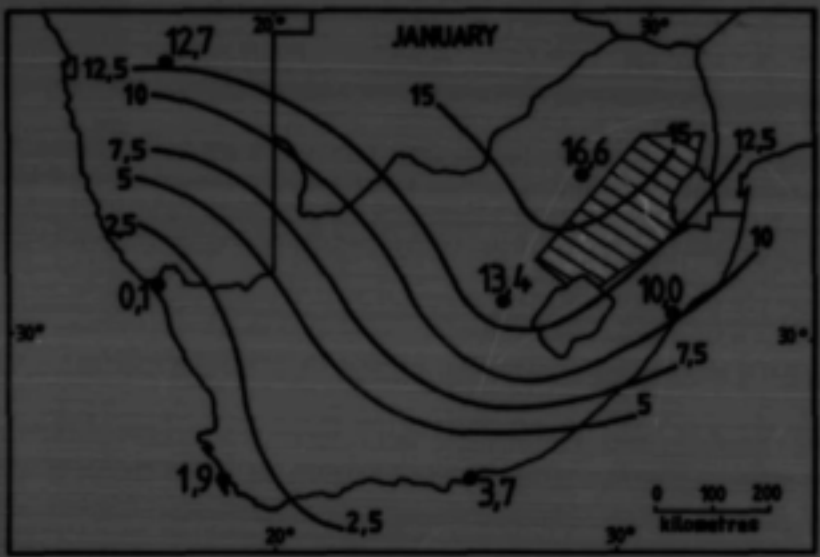
FIGURE 6.6



MEAN PRECIPITABLE DAILY WATER VAPOUR (cm): JANUARY VALUES
(AFTER McGEE, 1982)

TARGET ZONE

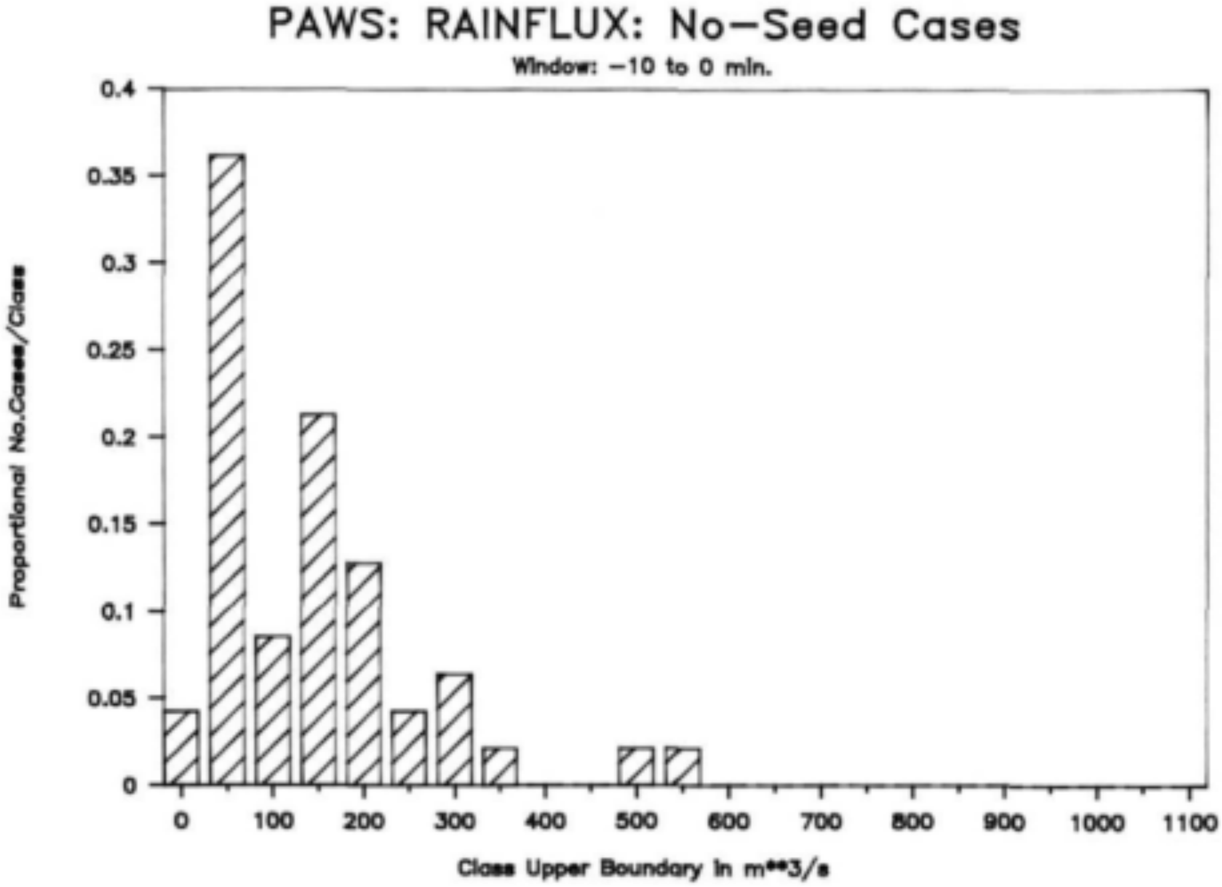
FIGURE 6.5



FRACTION (%) OF MEAN PRECIPITABLE DAILY WATER VAPOUR
ACTUALLY BECOMING RAIN
(AFTER McGEE, 1982)

TARGET ZONE

FIGURE 6.6


PAWS: RAINFLUX: No-Seed Cases
Window: -10 to 0 min.
Proportional No.Cases/Class
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

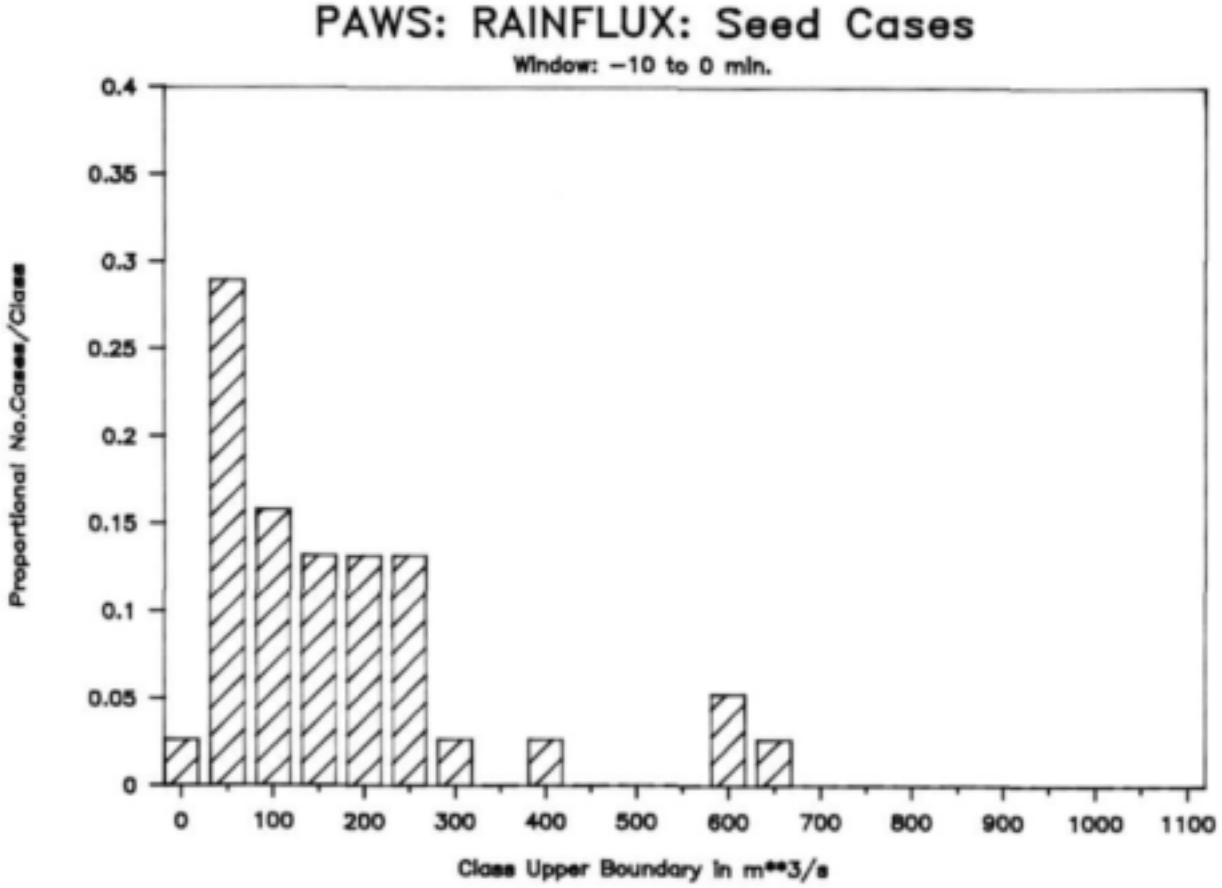
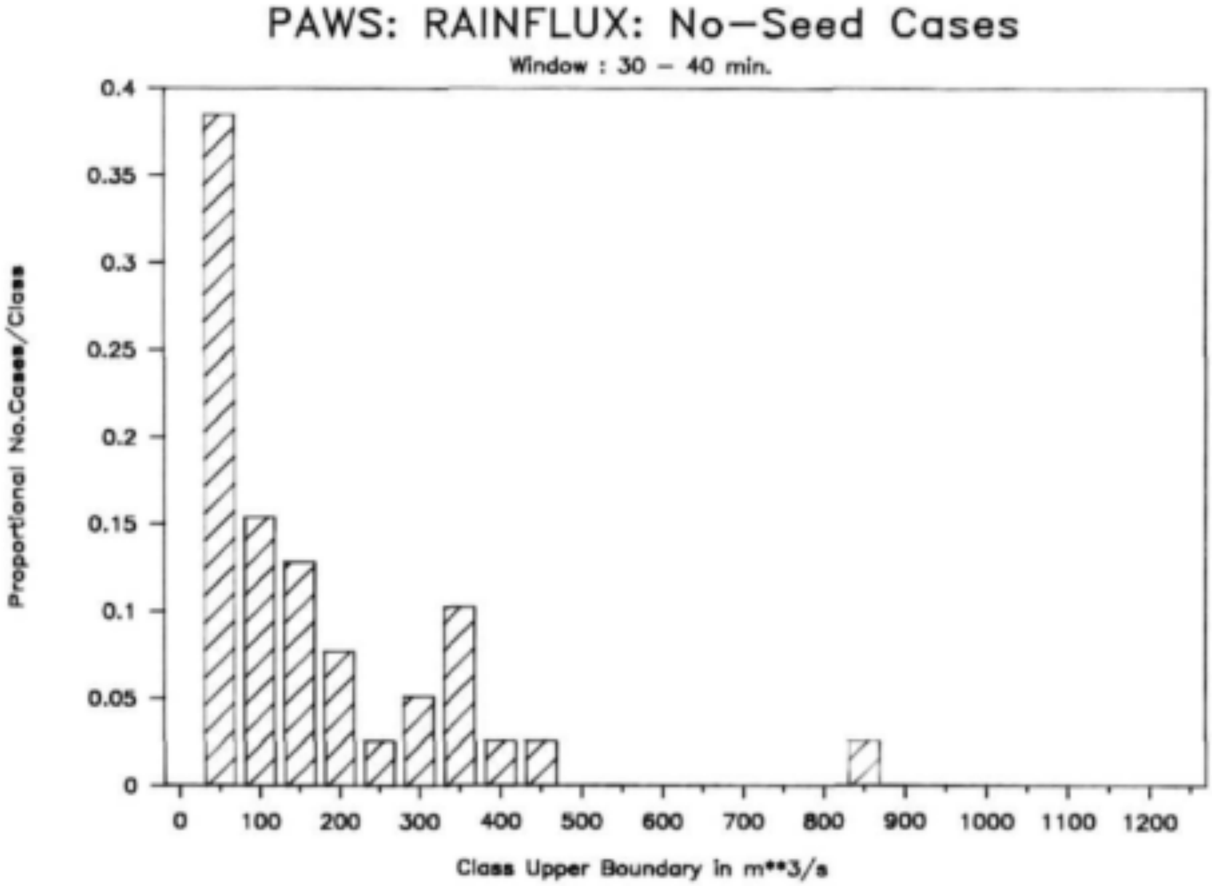

PAWS: RAINFLUX: Seed Cases
Window: -10 to 0 min.
Proportional No.Cases/Class
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

FIGURE 5.1


PAWS: RAINFLUX: No-Seed Cases
Window : 30 – 40 min.
Proportional No.Cases/Class
Class Upper Boundary in m**3/s
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200

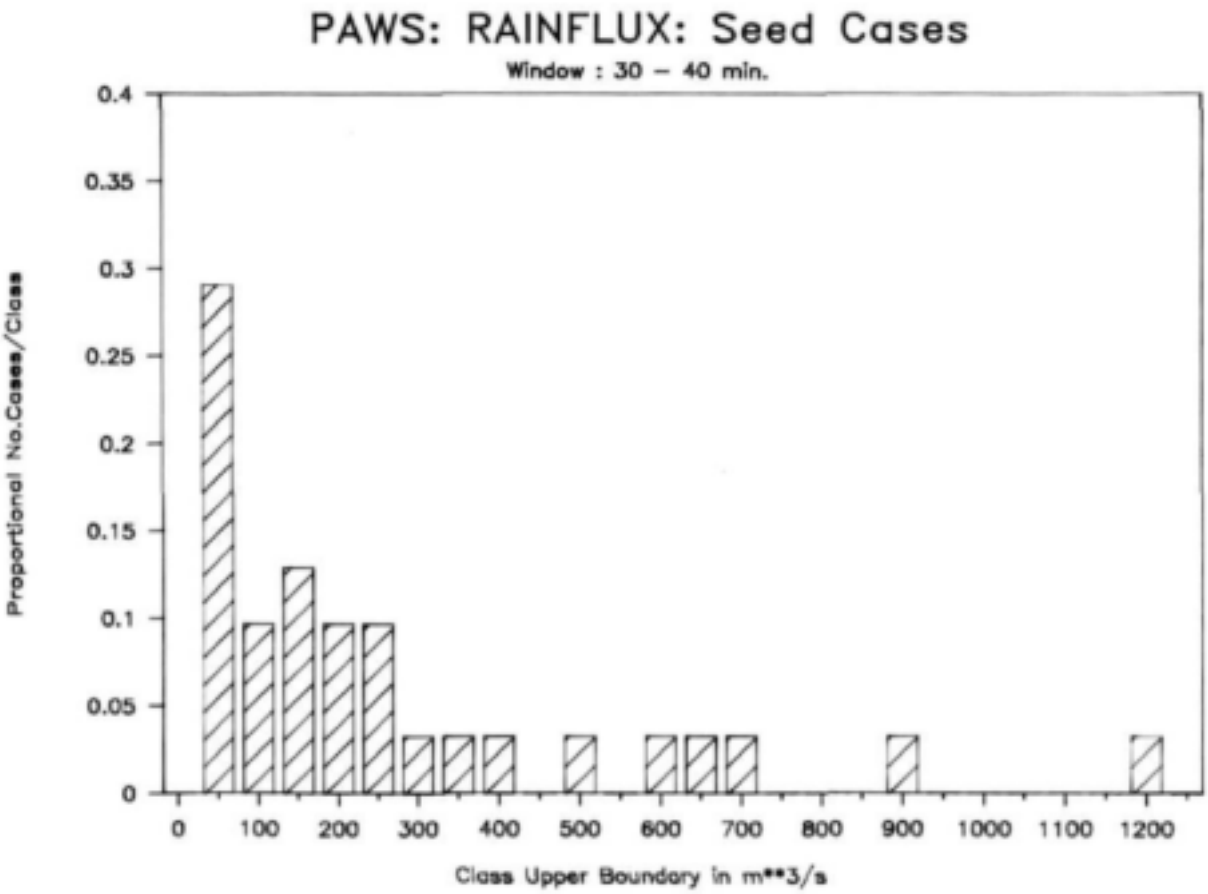
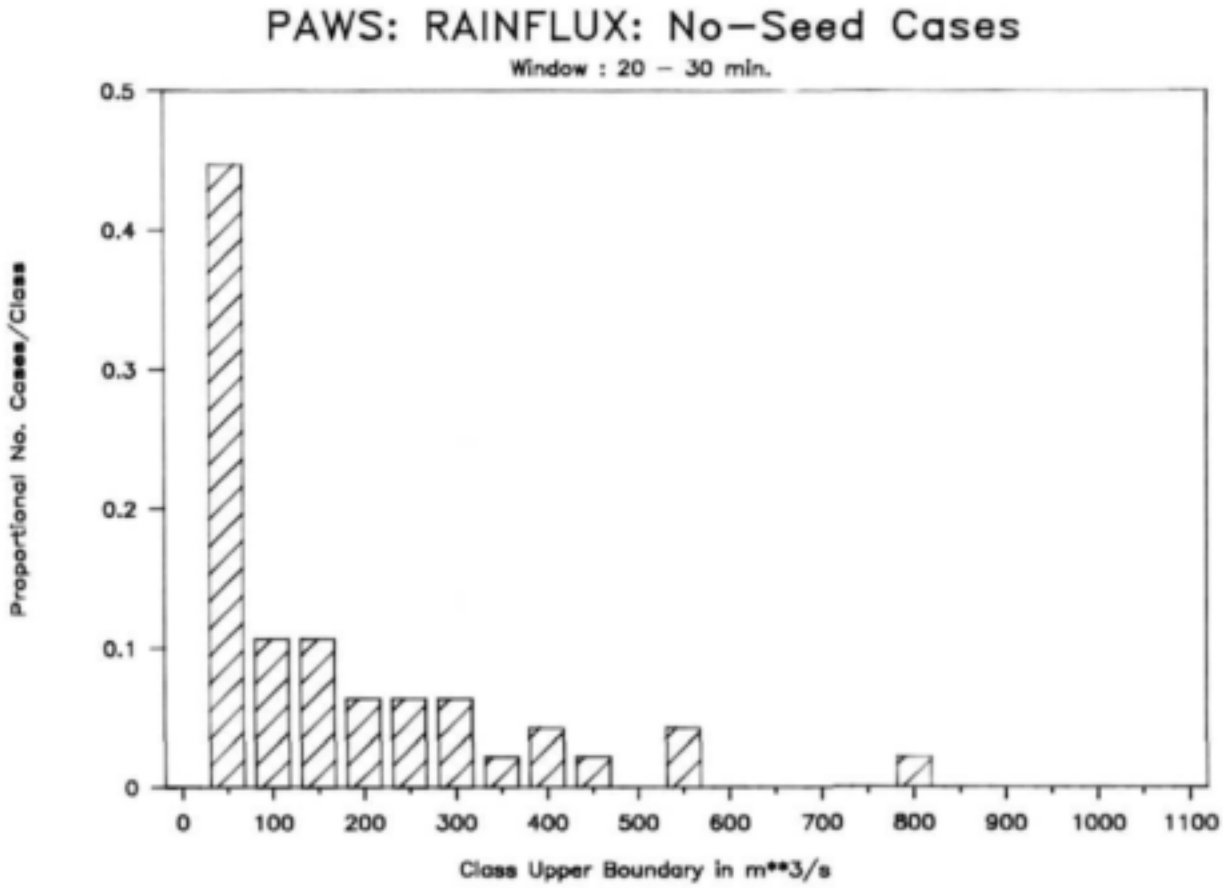

PAWS: RAINFLUX: Seed Cases
Window : 30 – 40 min.
Proportional No.Cases/Class
Class Upper Boundary in m**3/s
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200

FIGURE 5.3


PAWS: RAINFLUX: No-Seed Cases
Window : 20 – 30 min.
Proportional No. Cases/Class
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

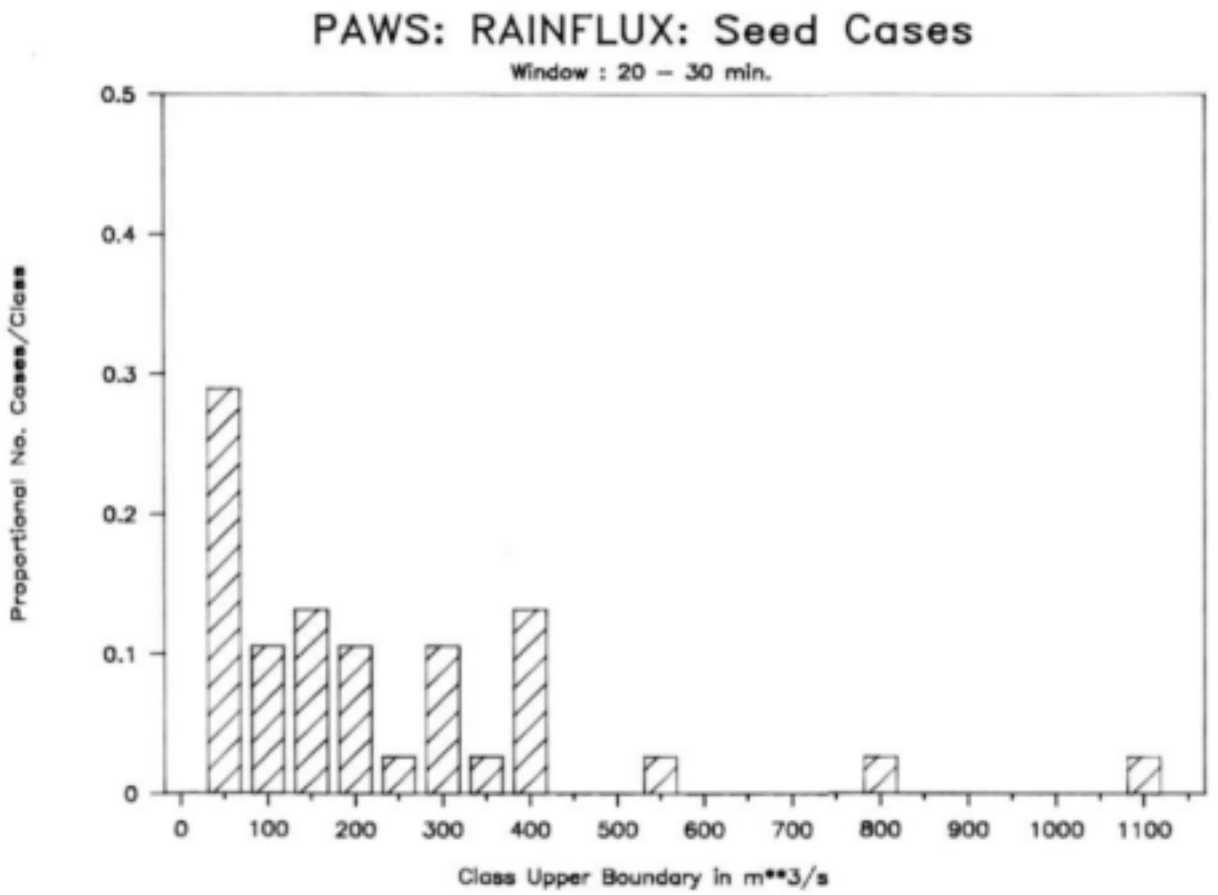
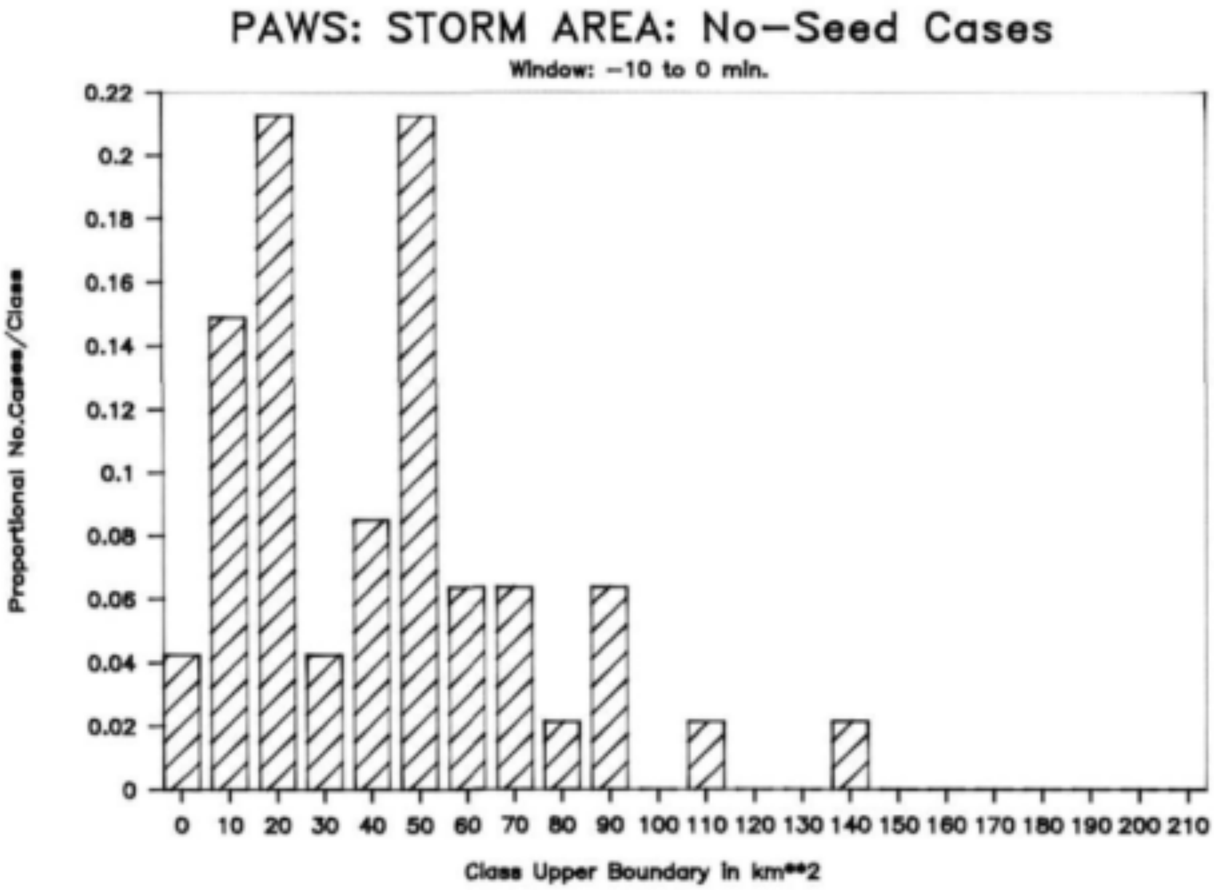
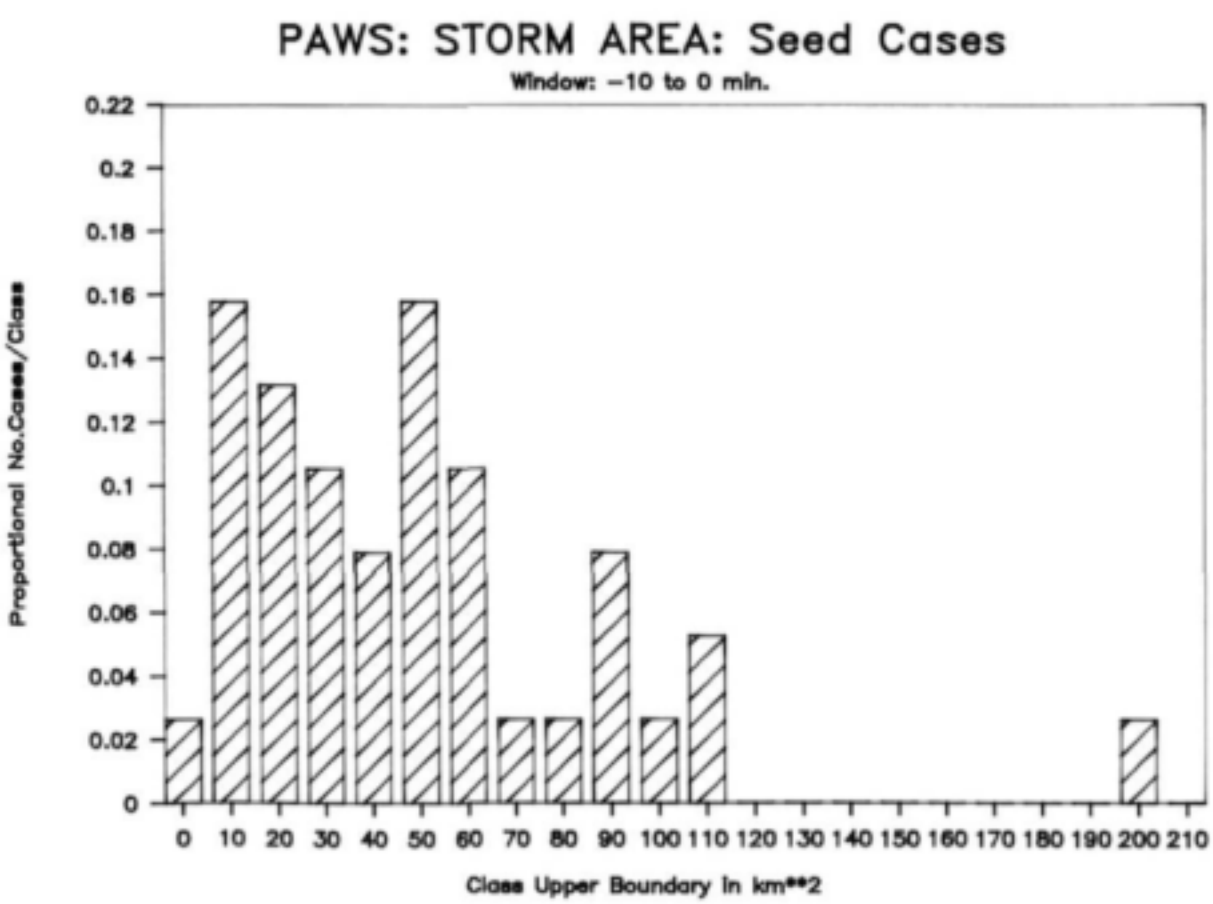

PAWS: RAINFLUX: Seed Cases
Window : 20 – 30 min.
Proportional No. Cases/Class
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
700
800
900
1000
1100
Class Upper Boundary in m**3/s

FIGURE 5.2

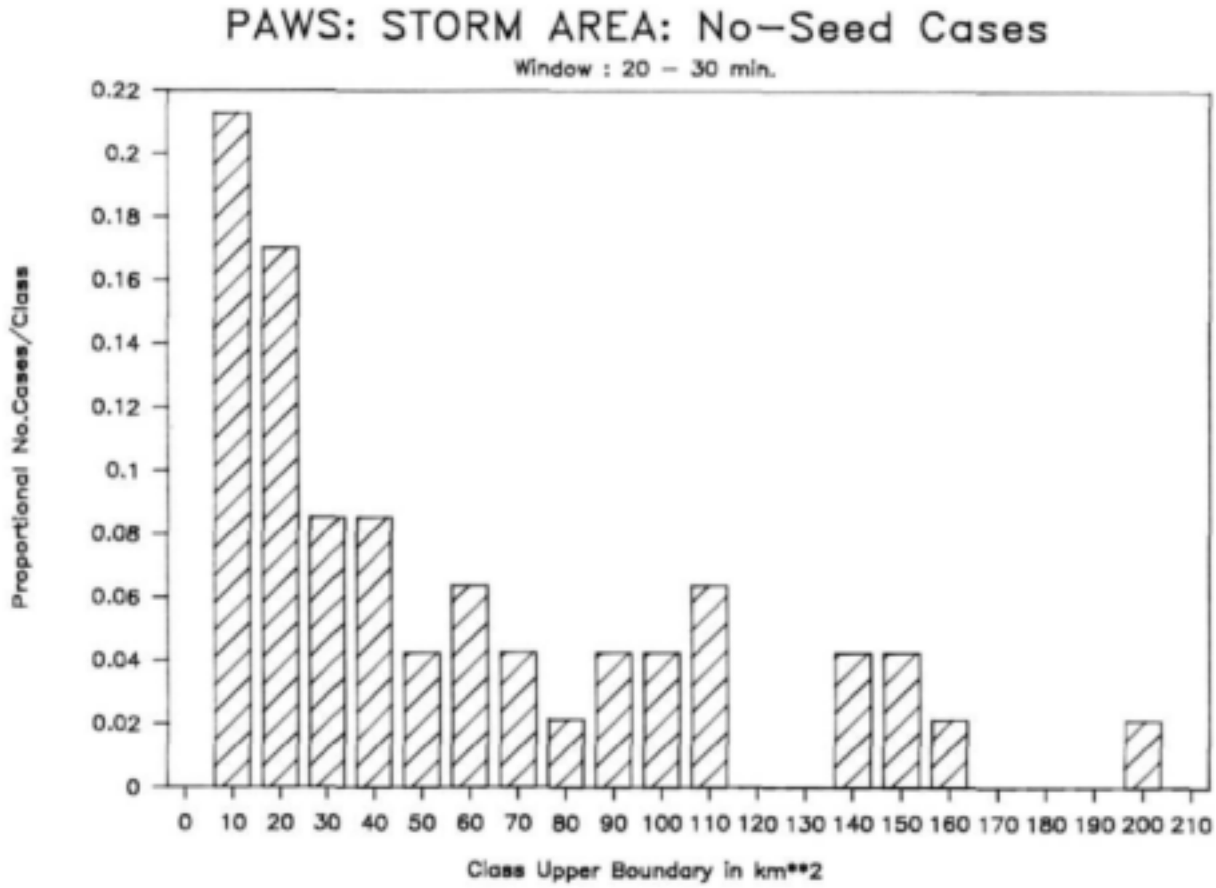


PAWS: STORM AREA: No-Seed Cases
Window: -10 to 0 min.
Proportional No.Cases/Class
Class Upper Boundary in km**2
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22



PAWS: STORM AREA: Seed Cases
Window: -10 to 0 min.
Proportional No.Cases/Class
Class Upper Boundary in km**2
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22

FIGURE 5.4


PAWS: STORM AREA: No-Seed Cases
Window : 20 - 30 min.
Proportional No.Cases/Class
Class Upper Boundary in km**2

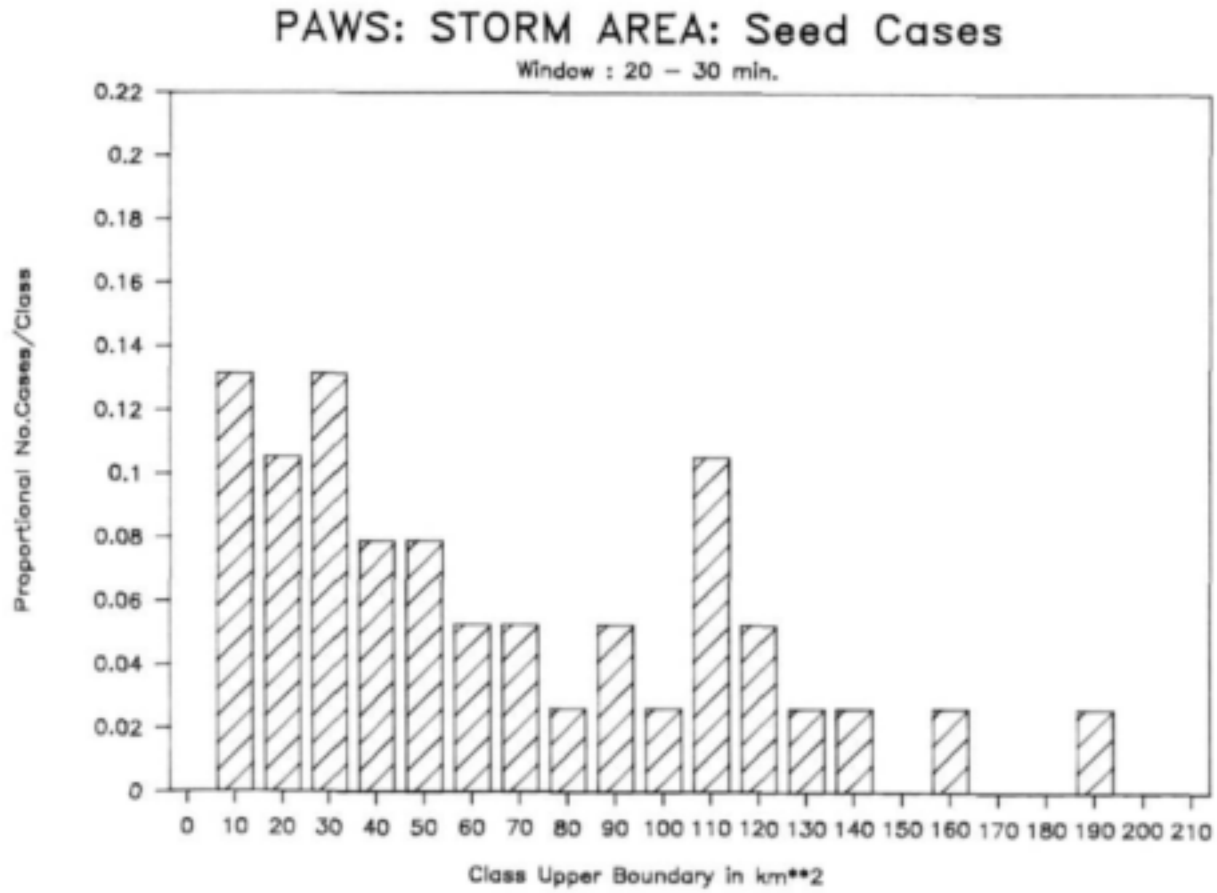
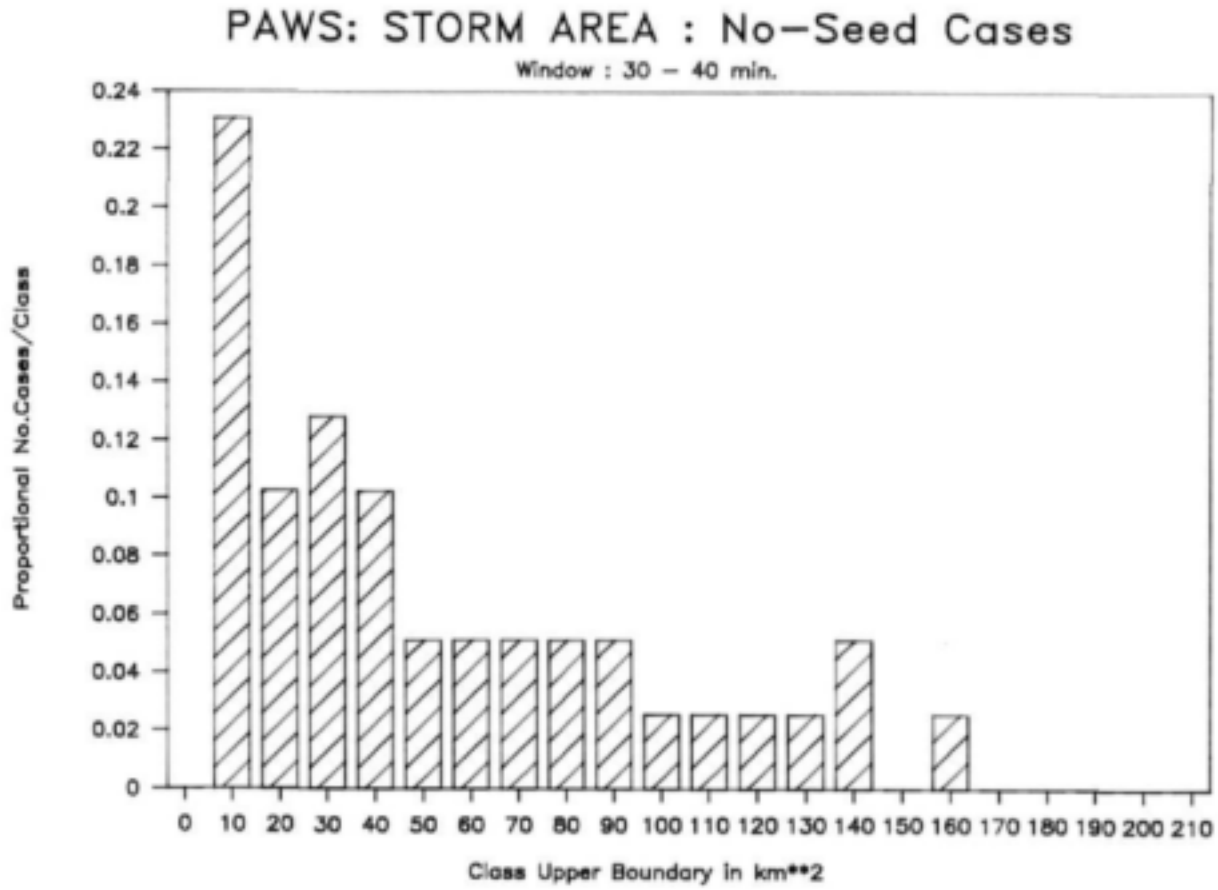

PAWS: STORM AREA: Seed Cases
Window : 20 - 30 min.
Proportional No.Cases/Class
Class Upper Boundary in km**2

FIGURE 5.5


PAWS: STORM AREA : No–Seed Cases
Window : 30 – 40 min.
Proportional No.Cases/Class
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22 0.24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

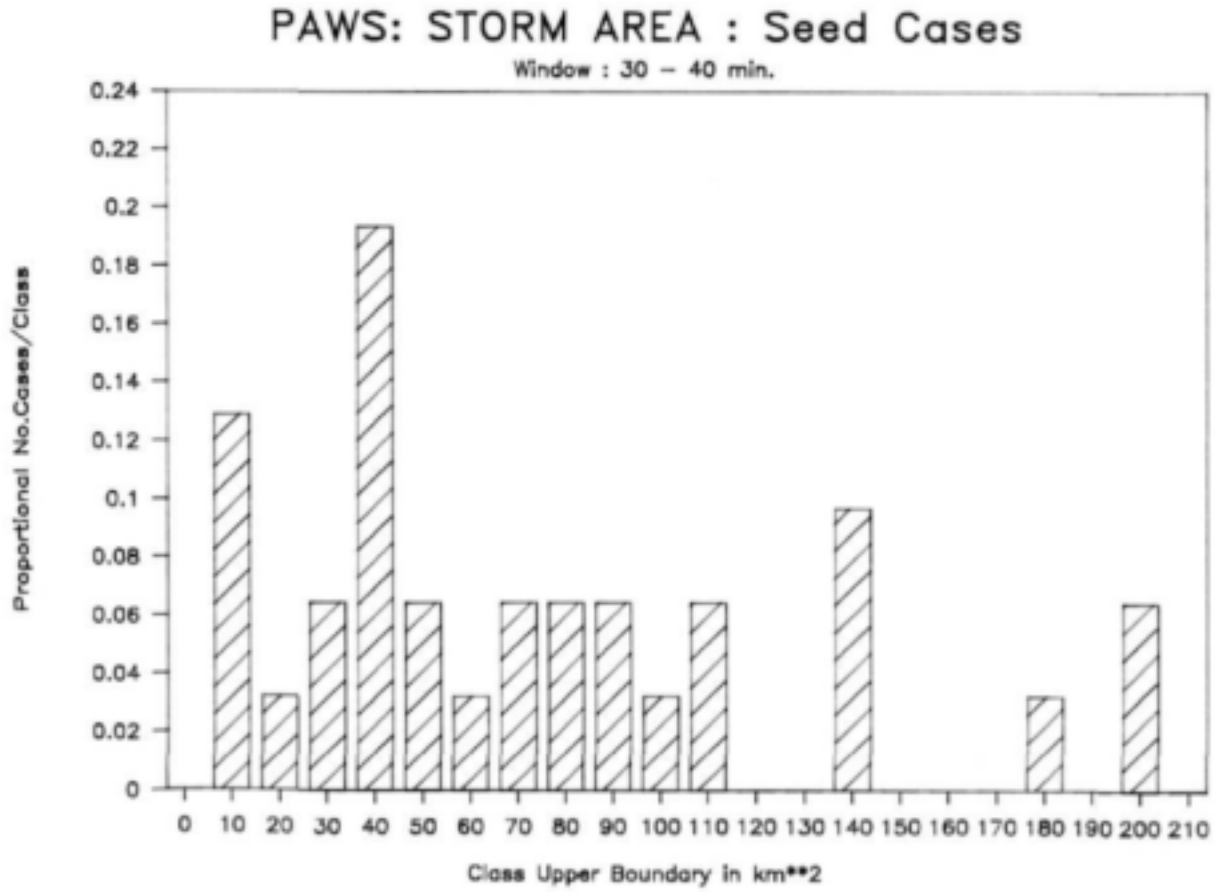
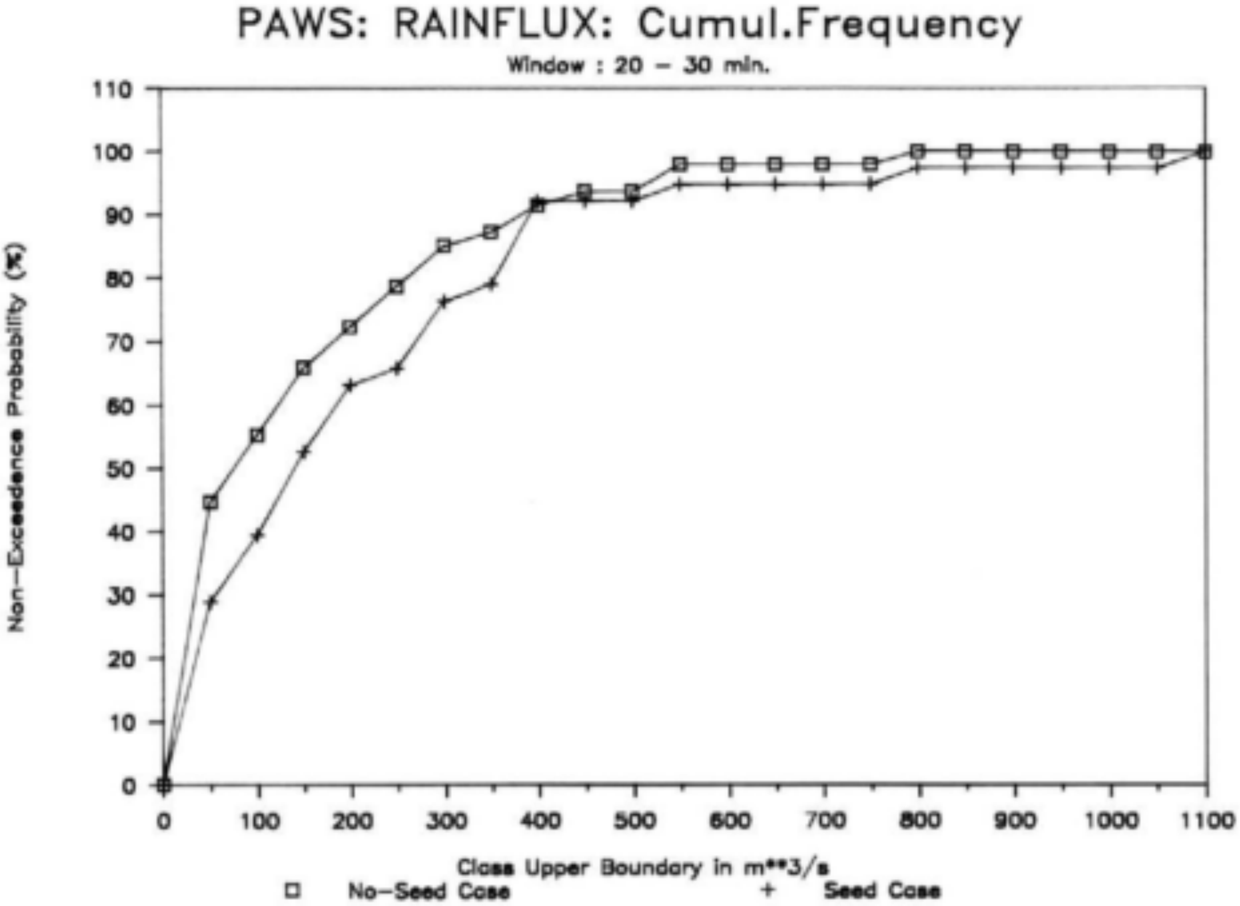

PAWS: STORM AREA : Seed Cases
Window : 30 – 40 min.
Proportional No.Cases/Class
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22 0.24
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210
Class Upper Boundary in km**2

FIGURE 5.6


PAWS: RAINFLUX: Cumul.Frequency
Window : 20 – 30 min.
Non-Exceedence Probability (%)
Class Upper Boundary in m**3/s
No-Seed Case
Seed Case

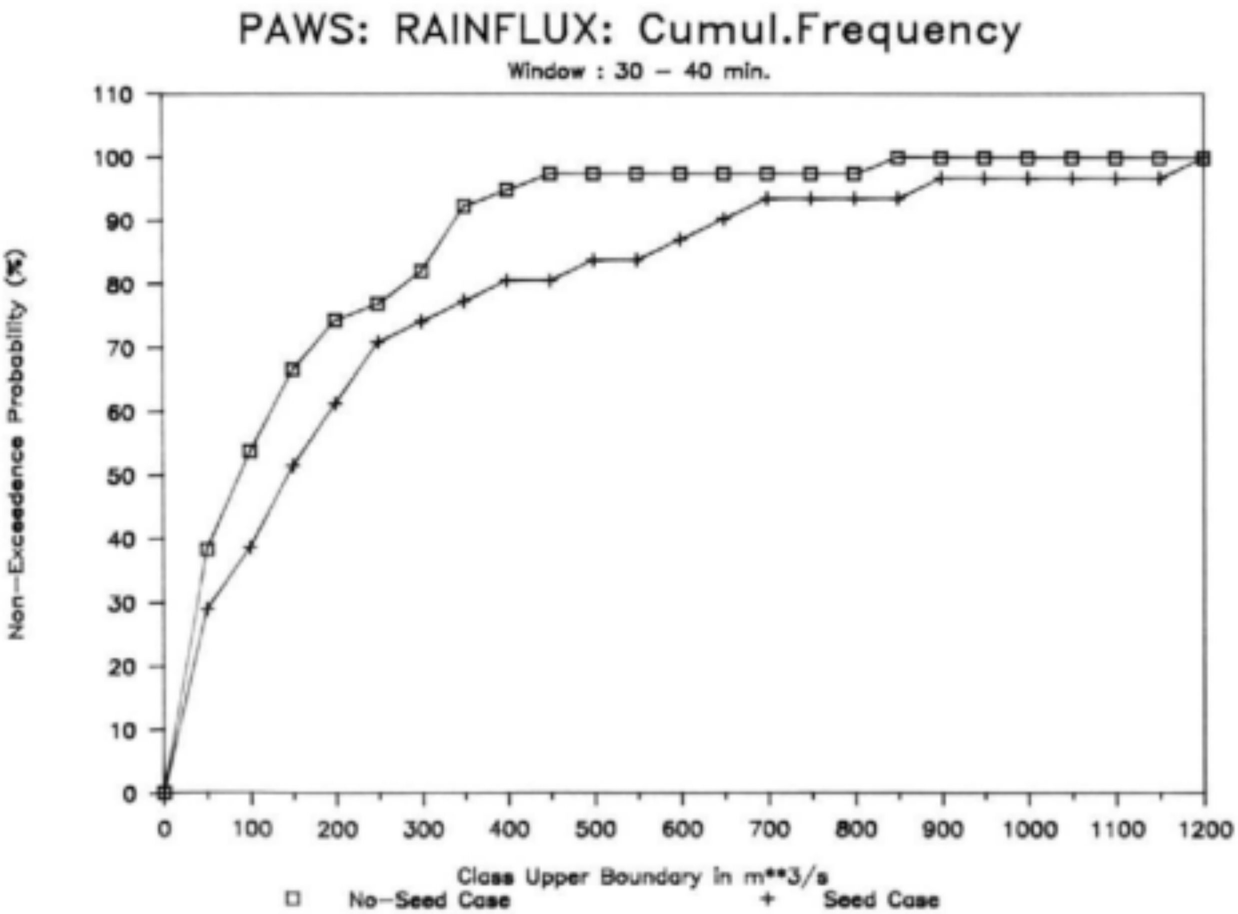

PAWS: RAINFLUX: Cumul.Frequency
Window : 30 – 40 min.
Non-Exceedence Probability (%)
Class Upper Boundary in m**3/s
No-Seed Case
Seed Case

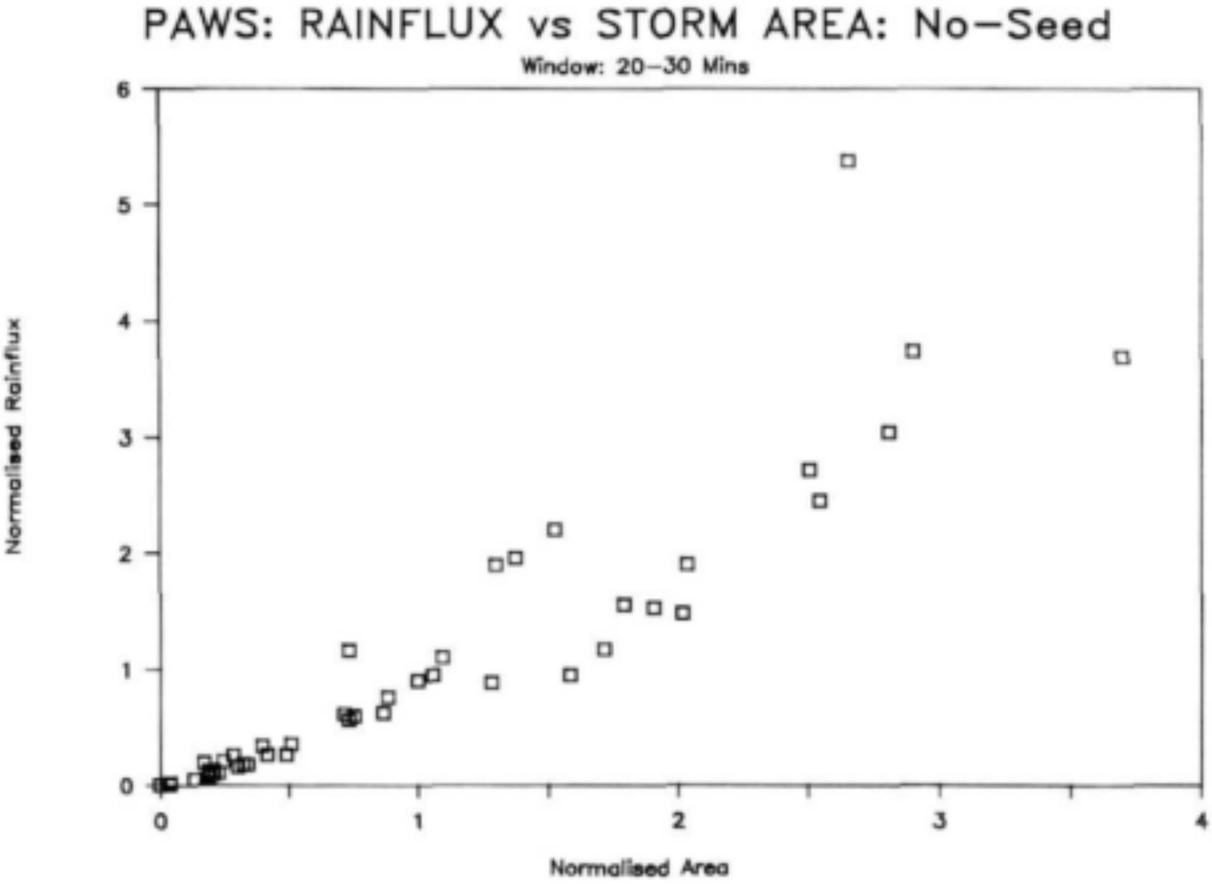
FIGURE 5.7

5.3.3 Outliers and the relationship between rainflux and storm area

The last observation in the previous sub-section raises both the spectre of "outlier" influences on the apparent seeding effects and the question of how to allow for outliers in the derivation of a modification scenario. To examine this provisionally, the paired values of rainflux and storm area for all cases were plotted on a normalised basis, i.e. each value divided by its corresponding mean, as shown in Figs. 5.8 and 5.9. Each set of paired values displays a strikingly linear relationship, which is to be expected as rainflux is a function of storm area (see 5.3.1), but which, for each of the four cases, is marred by a single "outlier". The seed case "outliers" relate to an event on 16/11/84 and the no-seed "outliers" to an event on 27/11/86.

A naïve, but plausible, interpretation of the "outliers" in Figures 5.8 and 5.9 is that they represent storms in which the rainfall mechanisms achieved a much greater efficiency than the norm for PAWS convective clouds. A glance at the data in Appendix A reveals that the no-seed rainflux "outliers" for the event on 27/11/86 are also accompanied by storm volume "outliers". In contrast, the storm volumes associated with the seed rainflux "outliers" for the event on 16/11/84 are not unduely large. This contrast might be indicative of an extraordinary seeding effect on 16/11/84. However, mindful of the nature of the rainflux calculation (as outlined in 5.3.1 above) which makes rainflux a function of storm area, we thought it might be more informative to look at mean rainfall intensity for pointers to outliers and individual seeding effects.

Average rainfall intensity values were derived as the quotient of every pair of rainflux and storm area values and used to produce scatterplots of average intensity versus storm area. These are shown as Figs. 5.10 and 5.11 for the two post-seeding windows of interest. No useful relationships are evident in these scatterplots, except, perhaps, a mere intimation of lower and upper envelopes - upper envelopes in the region of 20 mm/h, regardless of seeding and lower envelopes for storms larger than about 20 km^2 of approximately 5 mm/h. What does stand out,


PAWS: RAINFLUX vs STORM AREA: No-Seed
Window: 20-30 Mins
Normalised Rainflux
Normalised Area
0
1
2
3
4
5
6
0
1
2
3
4

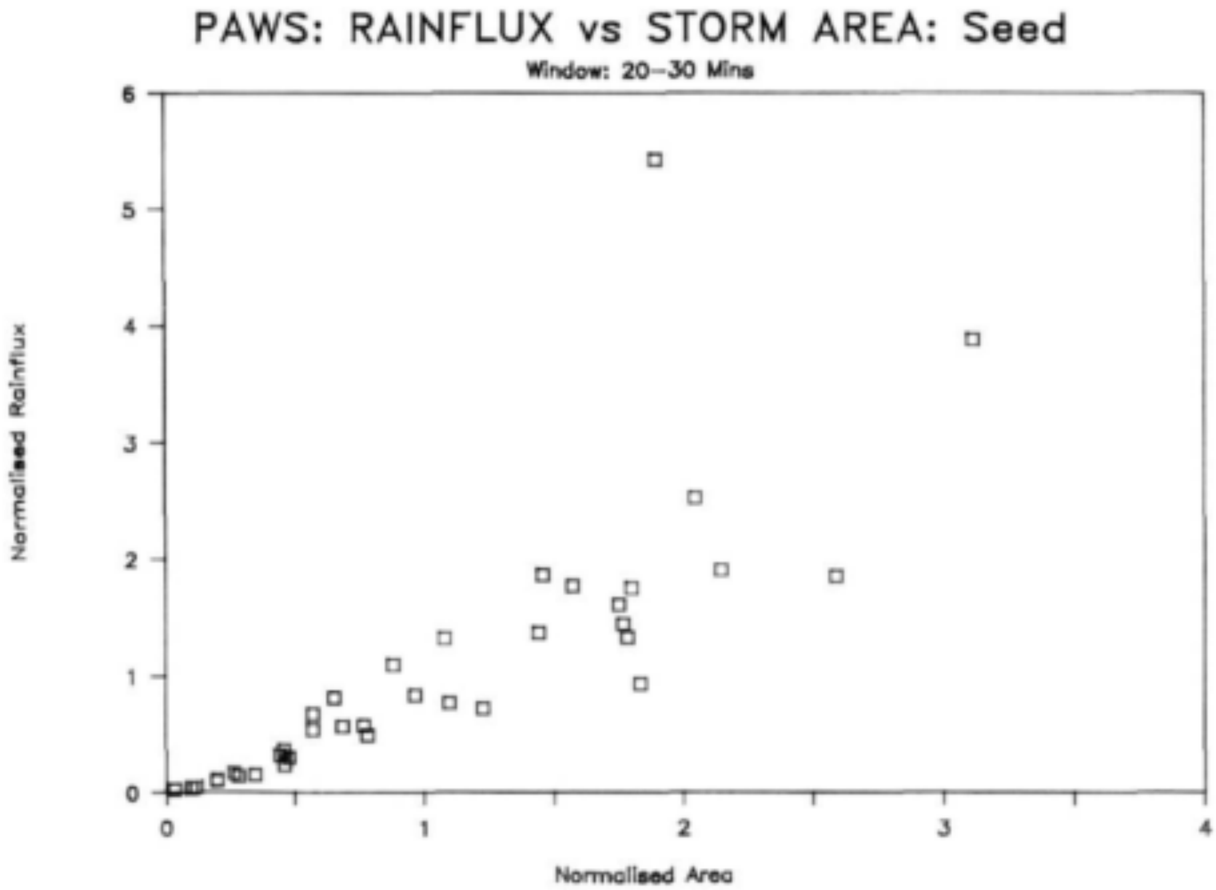
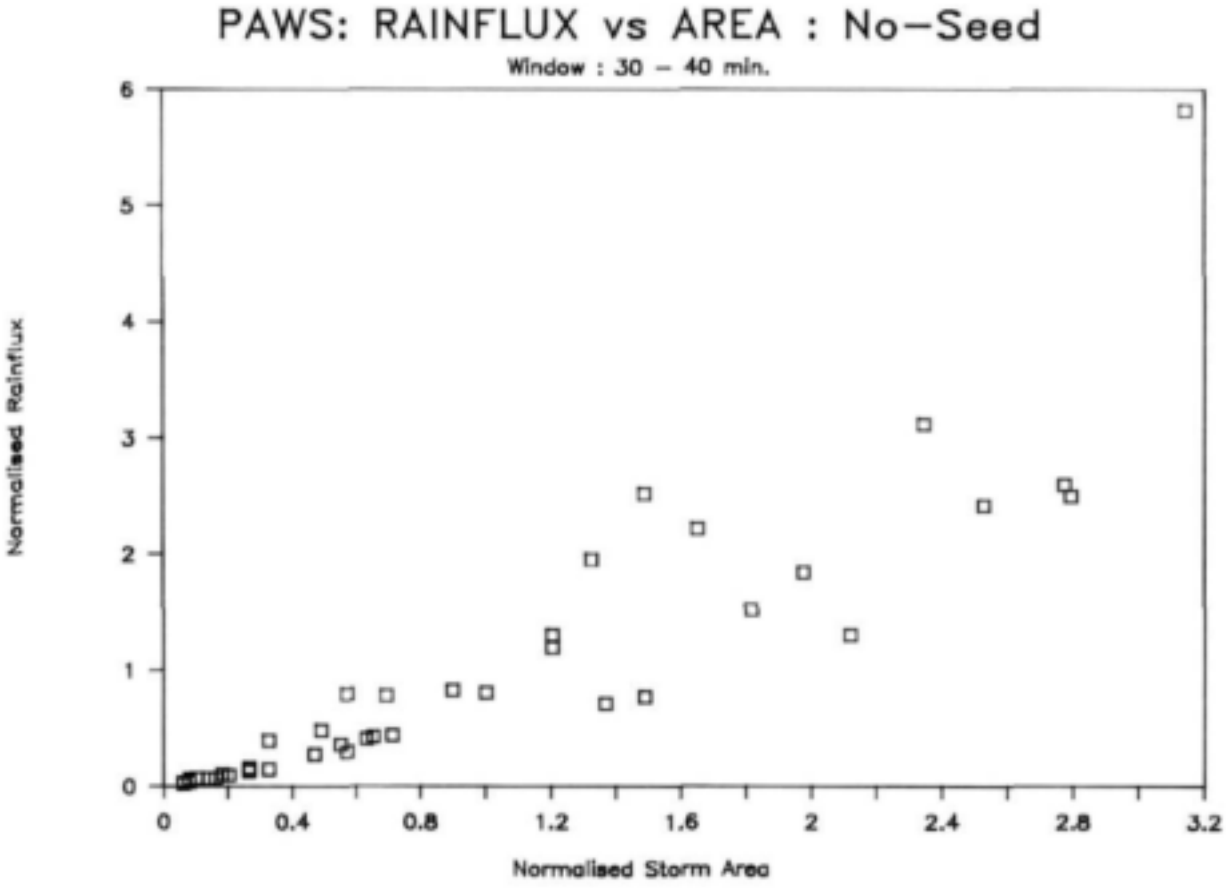

PAWS: RAINFLUX vs STORM AREA: Seed
Window: 20-30 Mins
Normalised Rainflux
Normalised Area
0
1
2
3
4
5
6
0
1
2
3
4

FIGURE 5.8


PAWS: RAINFLUX vs AREA : No−Seed
Window : 30 − 40 min.
Normalised Rainflux
Normalised Storm Area
0
1
2
3
4
5
6
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2

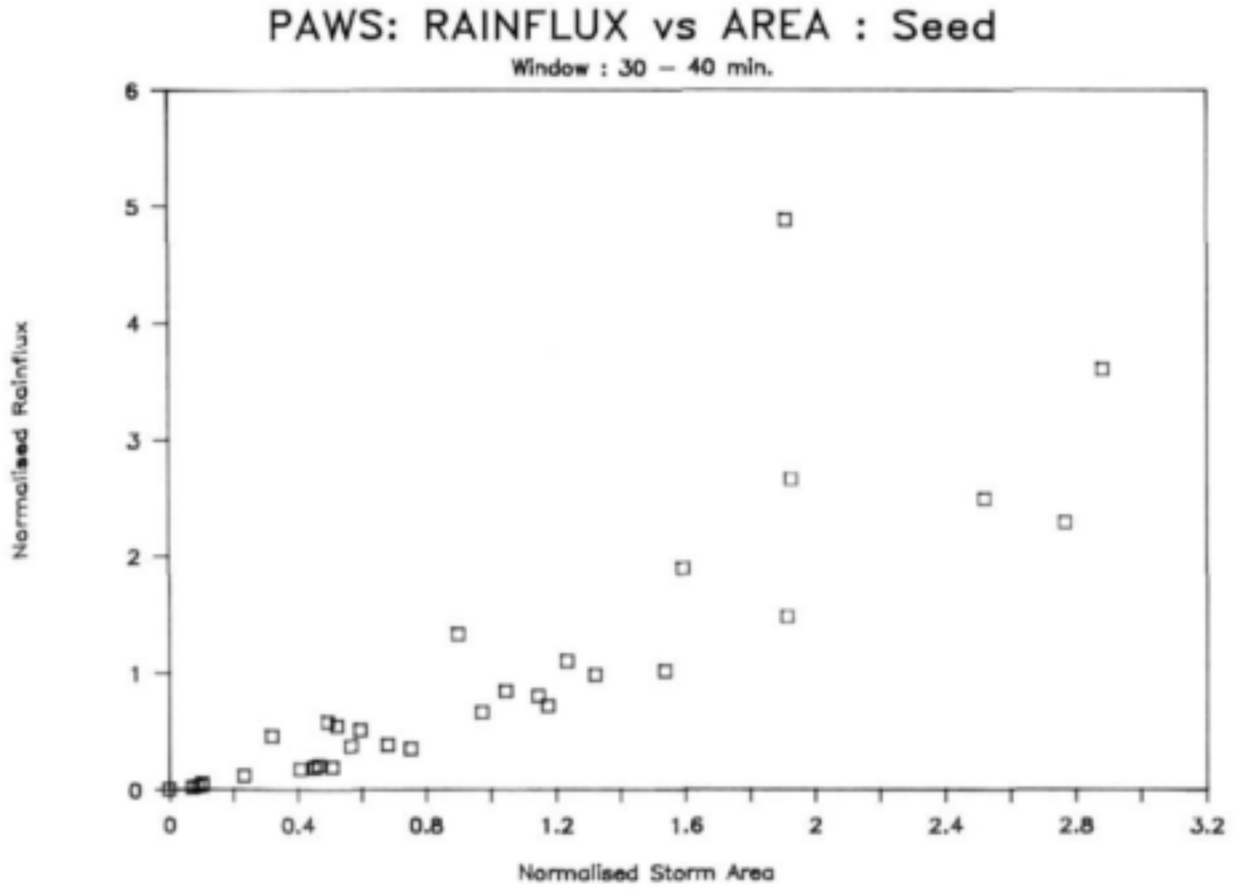
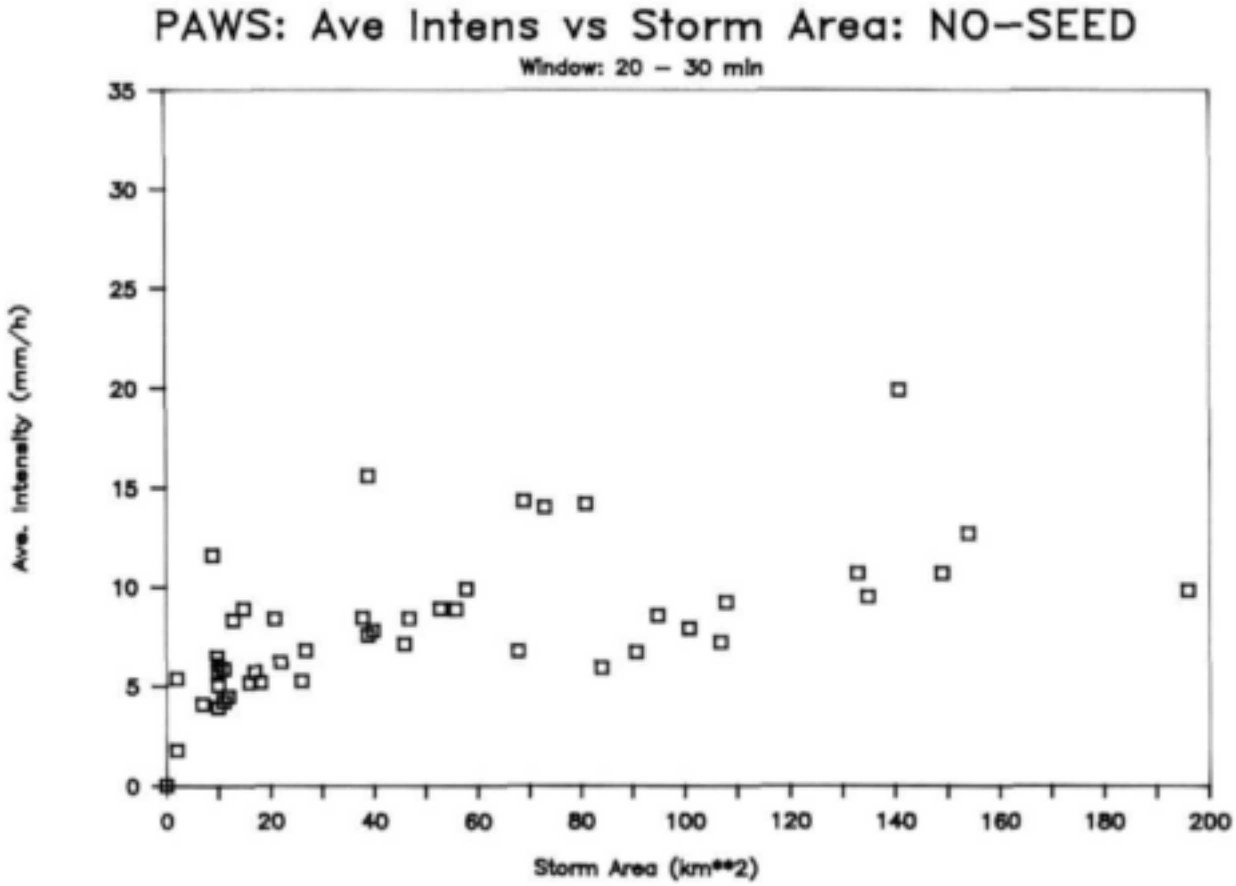

PAWS: RAINFLUX vs AREA : Seed
Window : 30 − 40 min.
Normalised Rainflux
Normalised Storm Area
0
1
2
3
4
5
6
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2

FIGURE 5.9


PAWS: Ave Intens vs Storm Area: NO-SEED
Window: 20 – 30 min
Ave. Intensity (mm/h)
Storm Area (km**2)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200

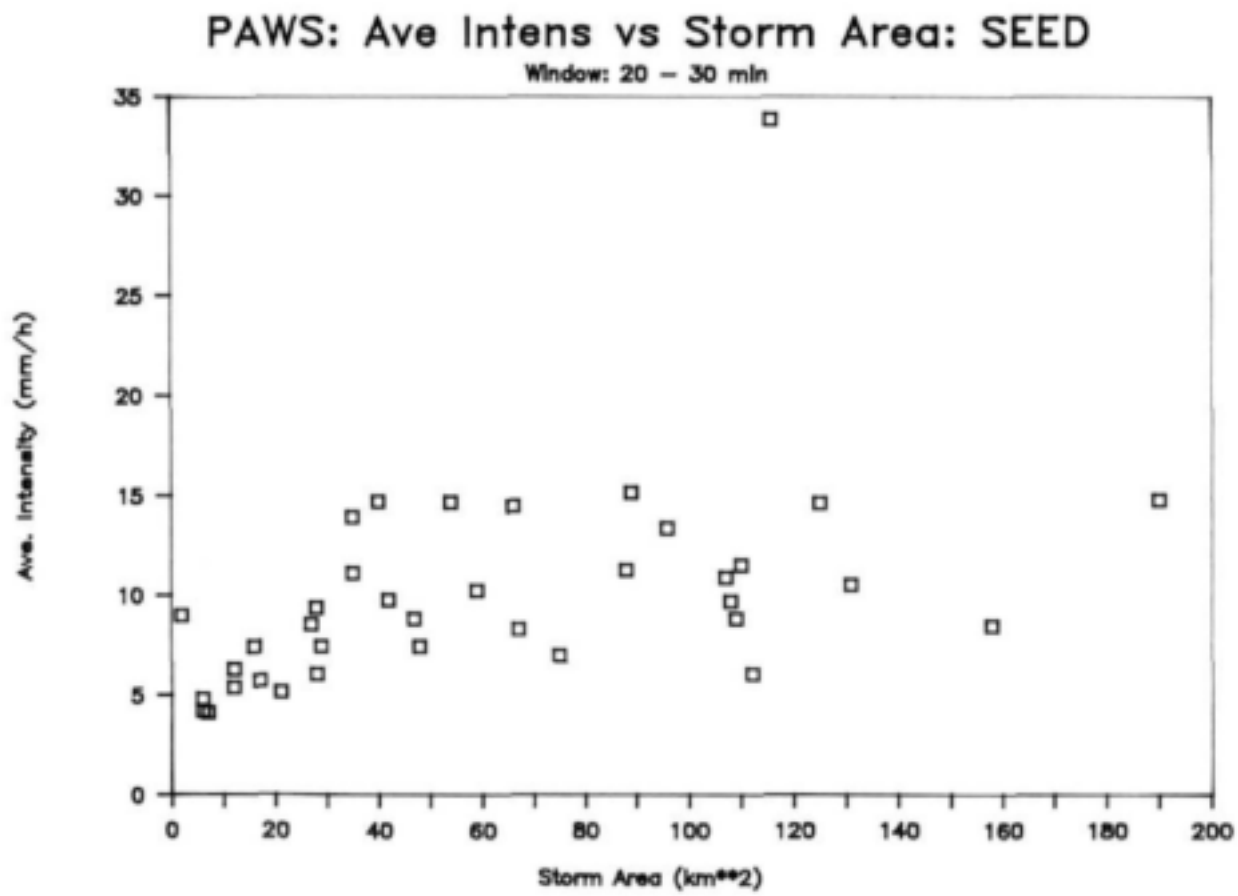
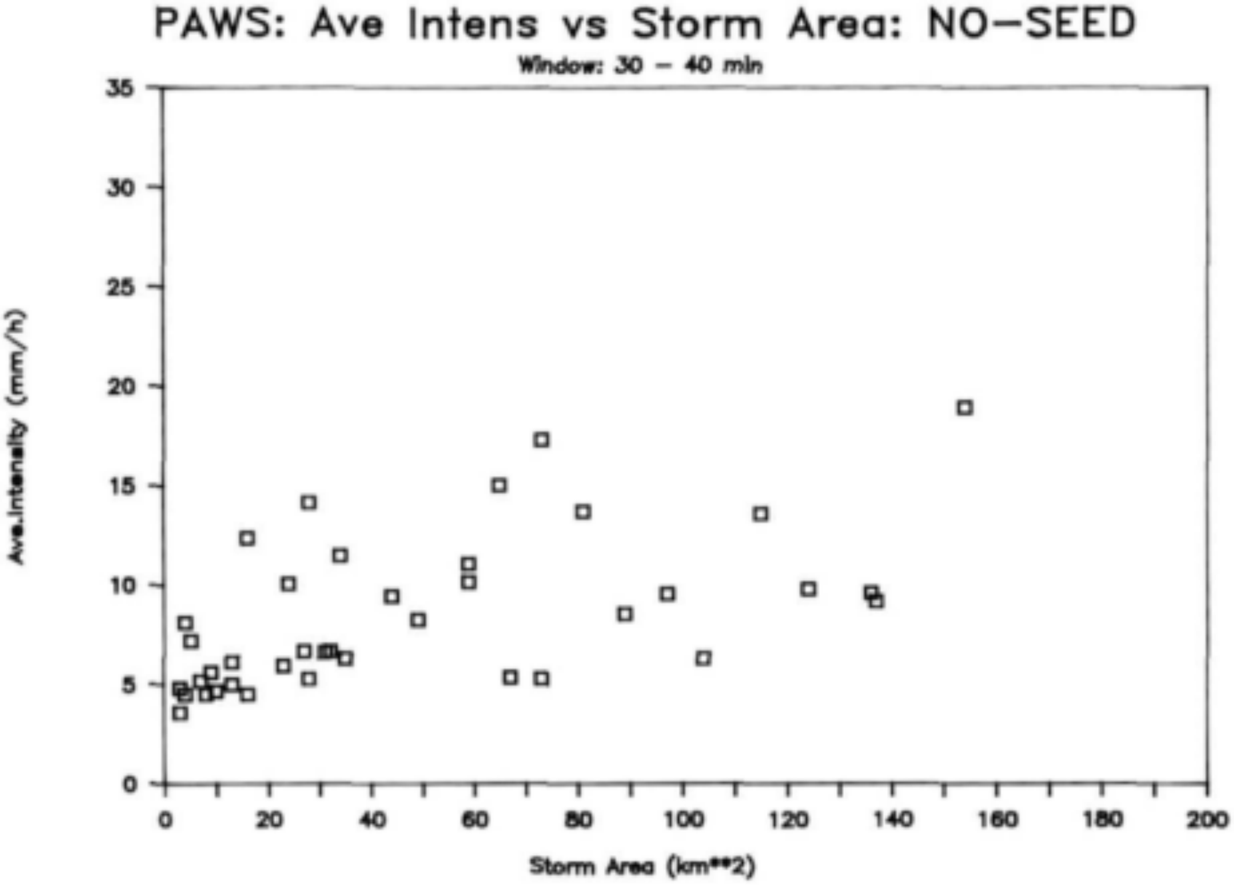

PAWS: Ave Intens vs Storm Area: SEED
Window: 20 – 30 min
Ave. Intensity (mm/h)
Storm Area (km**2)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200

FIGURE 5.10


0 20 40 60 80 100


PAWS: Ave Intens vs Storm Area: NO-SEED
Window: 30 - 40 min
Ave.Intensity (mm/h)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200
Storm Area (km**2)

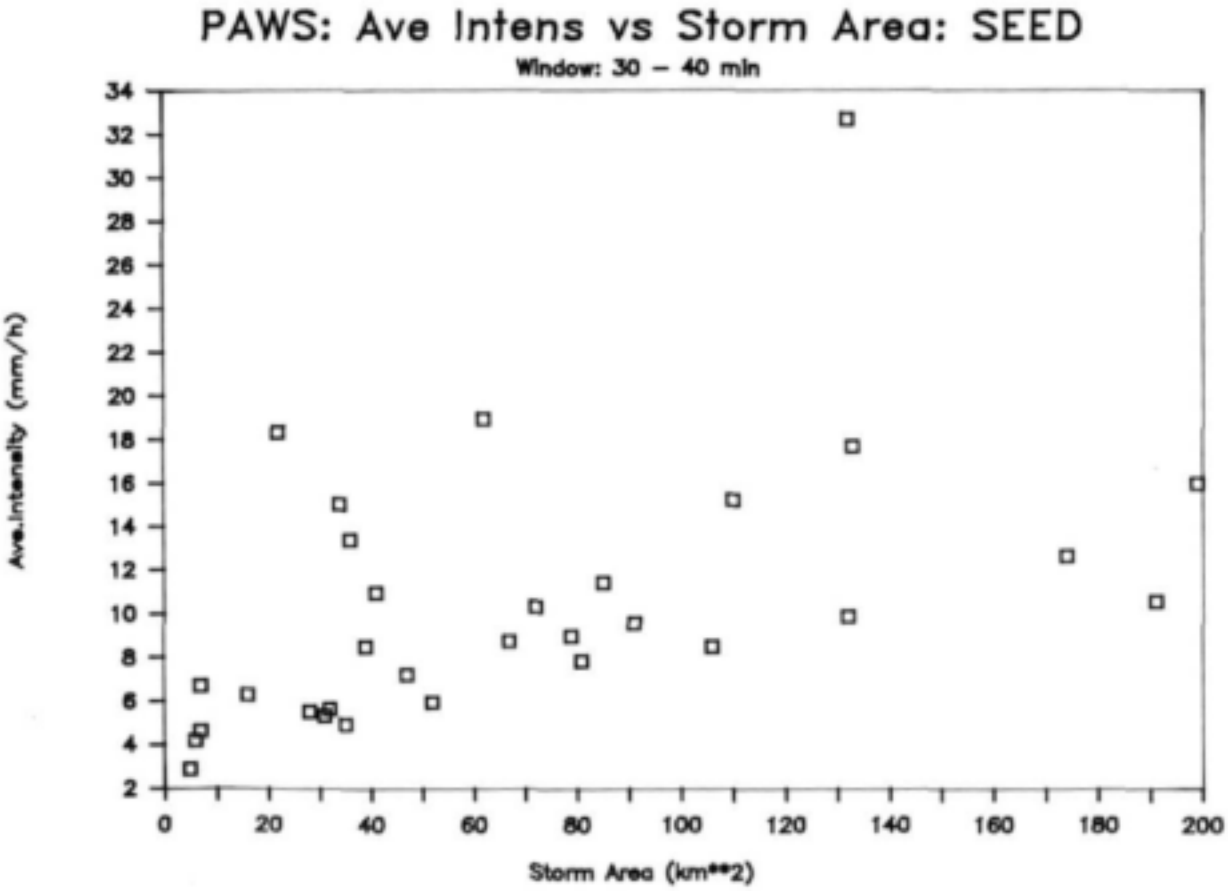

PAWS: Ave Intens vs Storm Area: SEED
Window: 30 - 40 min
Ave.Intensity (mm/h)
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
0
20
40
60
80
100
120
140
160
180
200
Storm Area (km**2)

FIGURE 5.11

however is a single seeded average intensity value well above 30 mm/h in each window - the 16/11/84 event. The apparent outlier no-seed event on 27/11/86 shown in Figs 5.8 and 5.9 does not feature in these scatterplots and is therefore considered to have been an artifact of a somewhat spurious juxtaposition of two sets of dependent variables.

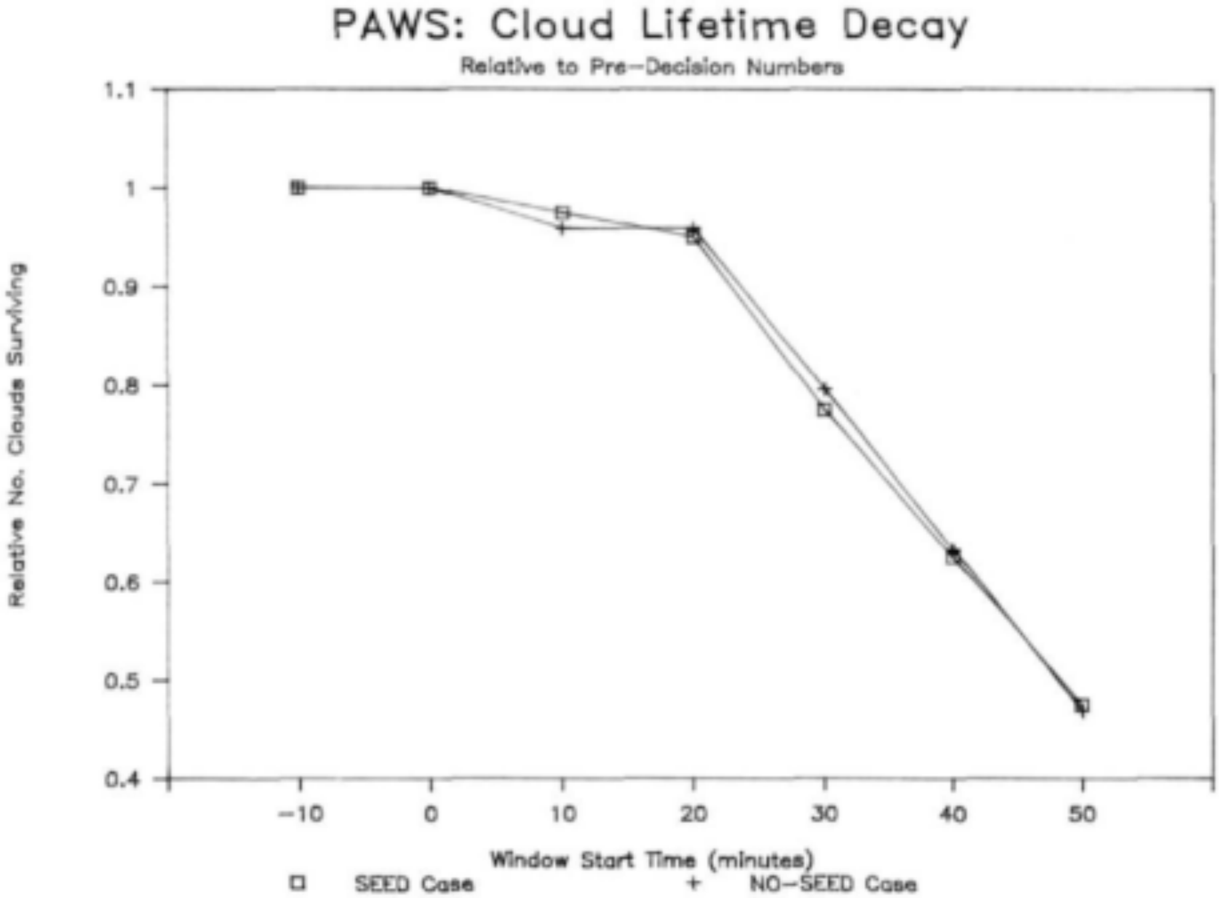
The scatterplot for the pre-seeding window shown in Fig. 5.12 reveals one reasonably high average intensity value (at 26,3 mm/h) in the seed sample - which happens to be the event of 16/11/84. It seems therefore that the apparent outlier detected in the two post-seeding window samples started off prior to seeding as a near-outlier. Consequently, the possiblity of an extroardinary seeding effect on that date must be regarded as quite remote.

The task at hand here is not to prove seeding effects, but to distill from the PAWS results useful concepts and relationships that can be employed in impact studies. The concept of average rainfall intensity introduced in this section falls in this category. We therefore endorse average rainfall intensity as a derived cloud attribute, along with mean rainflux and mean storm area, applicable to the derivation of a provisional modified rainfall scenario for South Africa. Now the question remains whether the PAWS data exhibits any evidence for a seeding effect on rainfall intensity. Unfortunately, the seed/no-seed ratios reported in Table 5.2 do not signify a large seeding effect in terms of average rainfall intensity. These, and other considerations regarding "true" seeding effects, are explored in the subsequent section.

5.4 The anatomy of the average seeded storm

5.4.1 Seed/No-Seed ratios from PAWS

At this point the scene is set to postulate a storm-based average seeding effect for summer cumuli in South Africa that can be employed in impact studies. As stated above the physical attributes that seem most useful to describe the anatomy of the seeded storms, both in terms of the seeding effects indicated by PAWS and in terms of the data


PAWS: Cloud Lifetime Decay
Relative to Pre-Decision Numbers
Relative No. Clouds Surviving
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
-10
0
10
20
30
40
50
Window Start Time (minutes)
SEED Case
NO-SEED Case

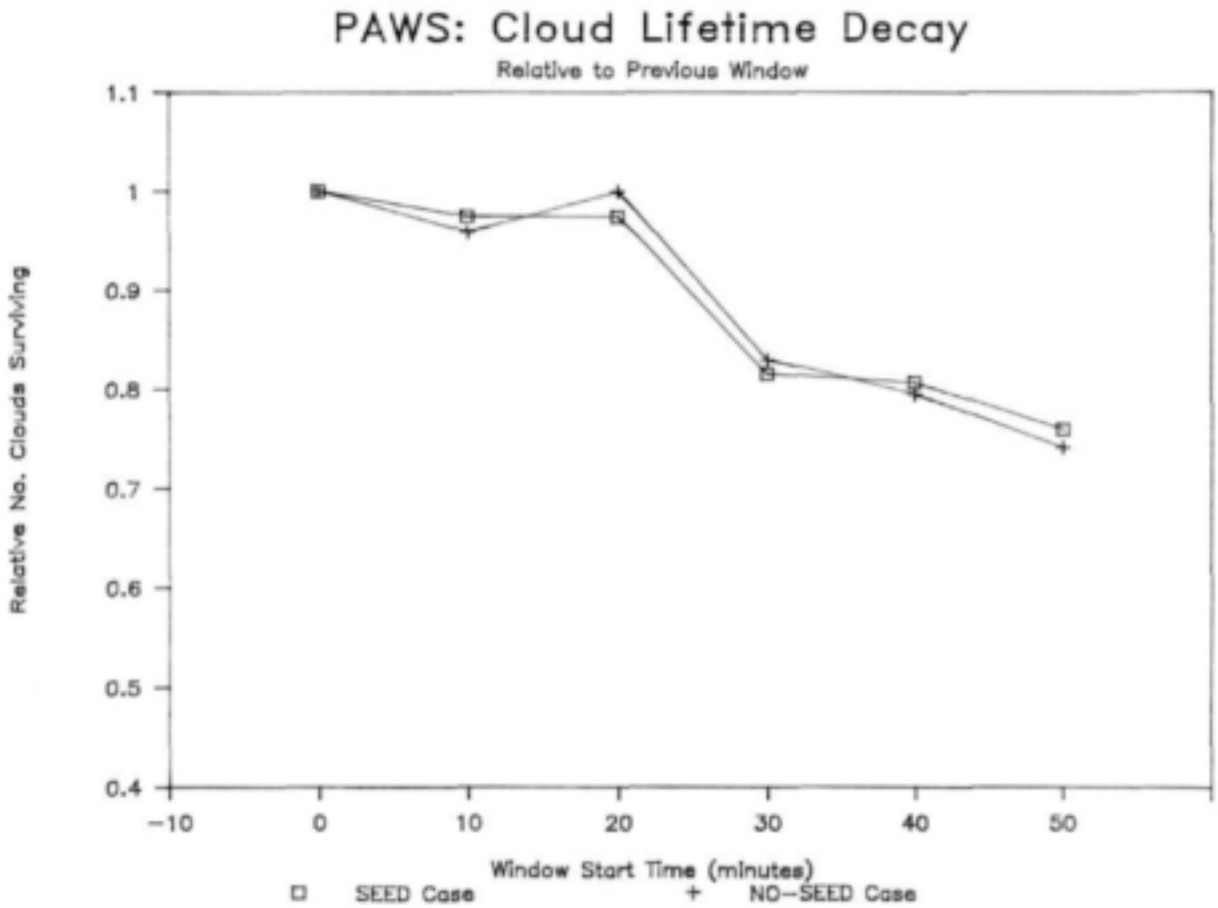
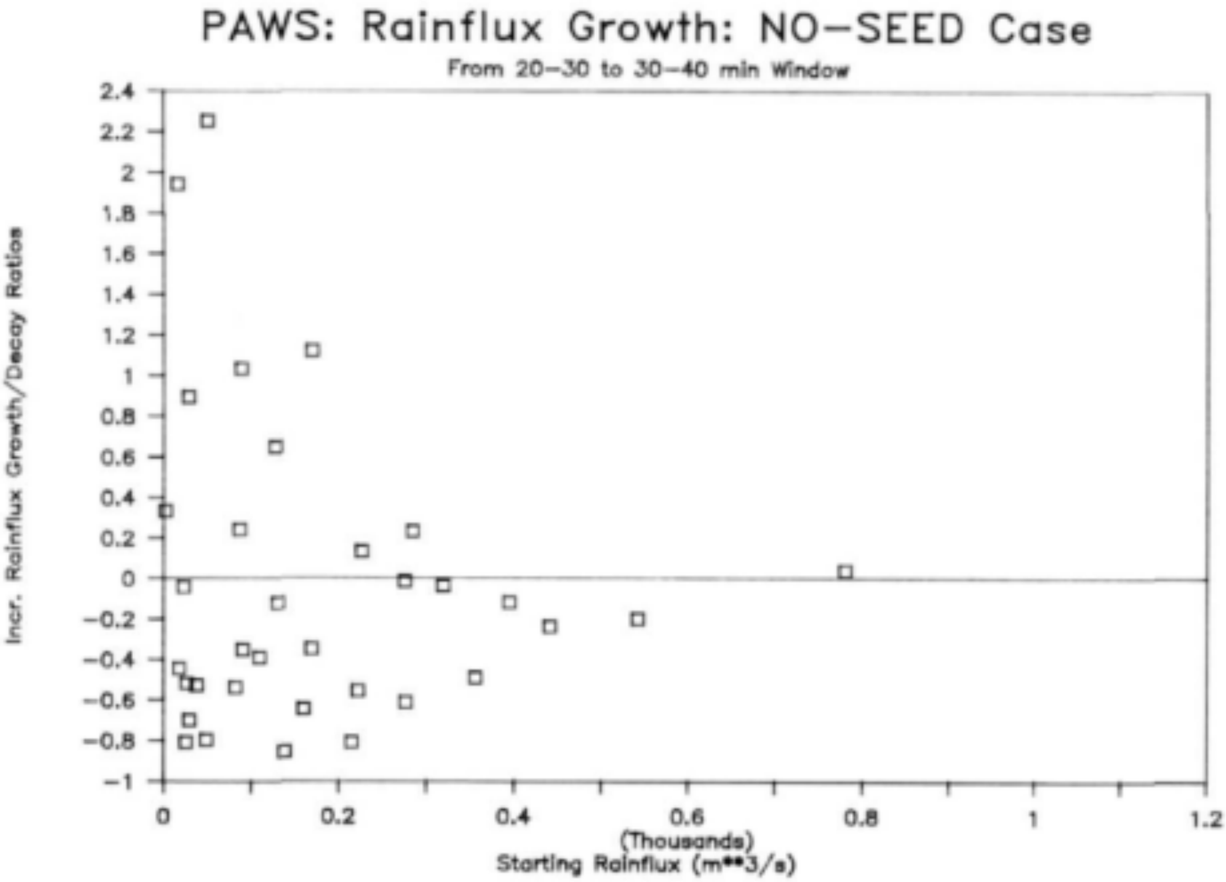

PAWS: Cloud Lifetime Decay
Relative to Previous Window
Relative No. Clouds Surviving
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
-10
0
10
20
30
40
50
Window Start Time (minutes)
SEED Case
NO-SEED Case

FIGURE 5.18


PAWS: Rainflux Growth: NO-SEED Case
From 20-30 to 30-40 min Window
Incr. Rainflux Growth/Decay Ratios
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

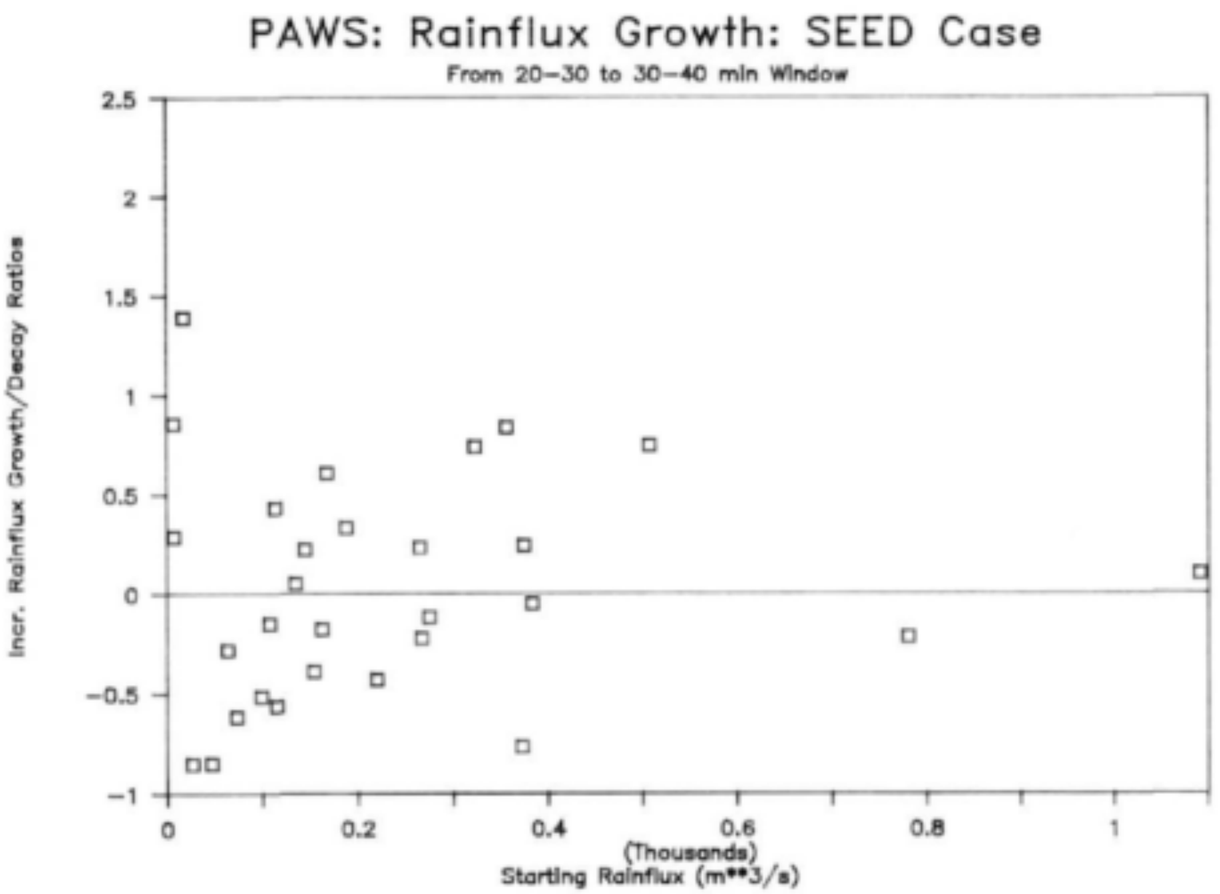
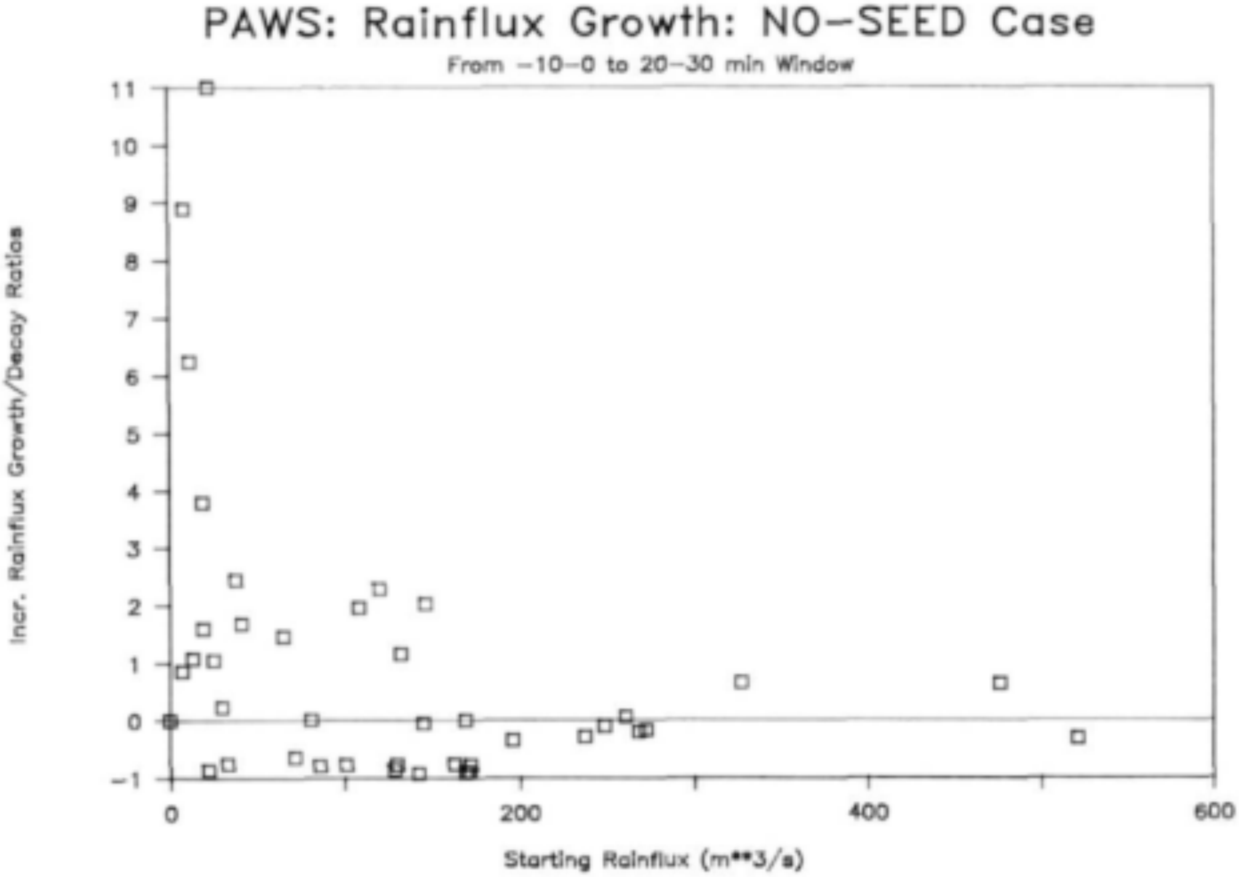

PAWS: Rainflux Growth: SEED Case
From 20-30 to 30-40 min Window
Incr. Rainflux Growth/Decay Ratios
2.5
2
1.5
1
0.5
0
-0.5
-1
0
0.2
0.4
0.6
0.8
1
(Thousands)
Starting Rainflux (m**3/s)

FIGURE 5.17B


PAWS: Rainflux Growth: NO-SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay Ratios
Starting Rainflux (m**3/s)

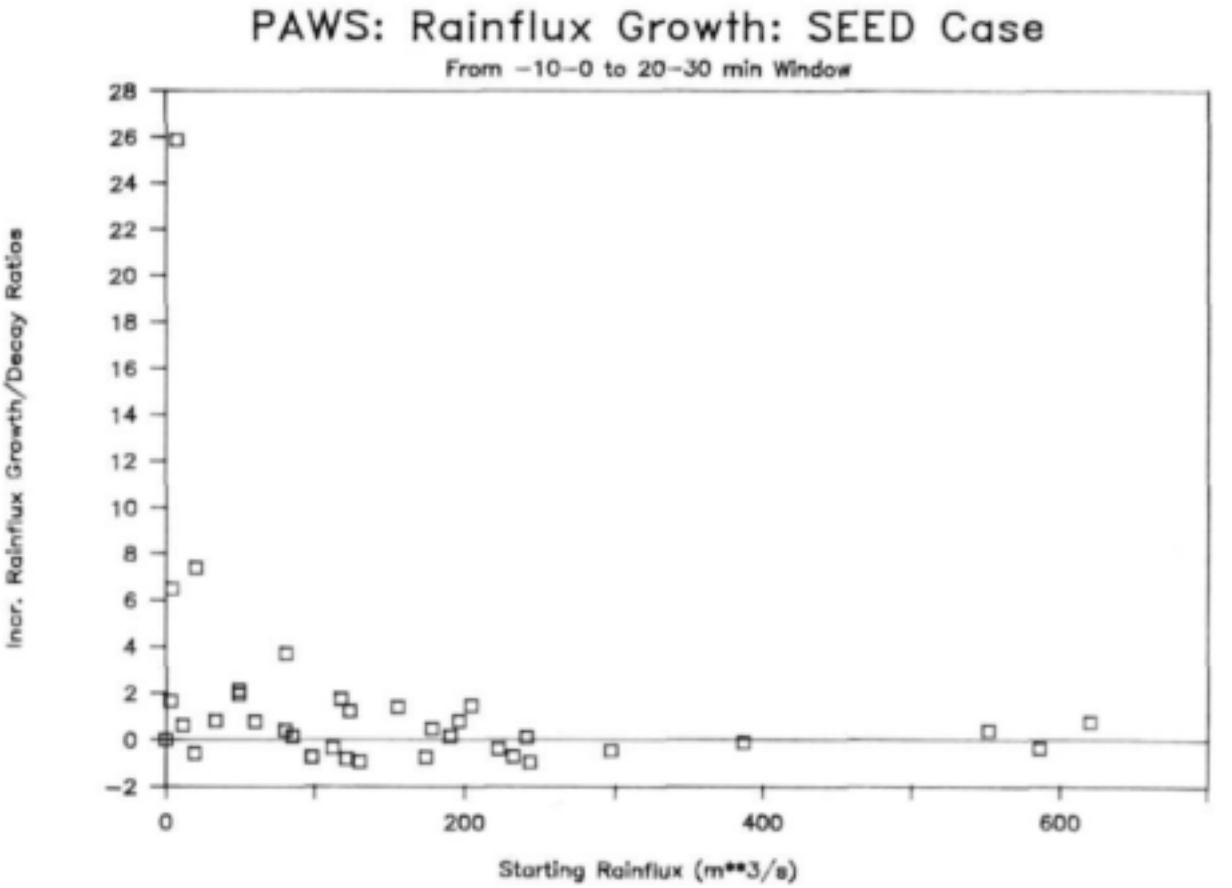
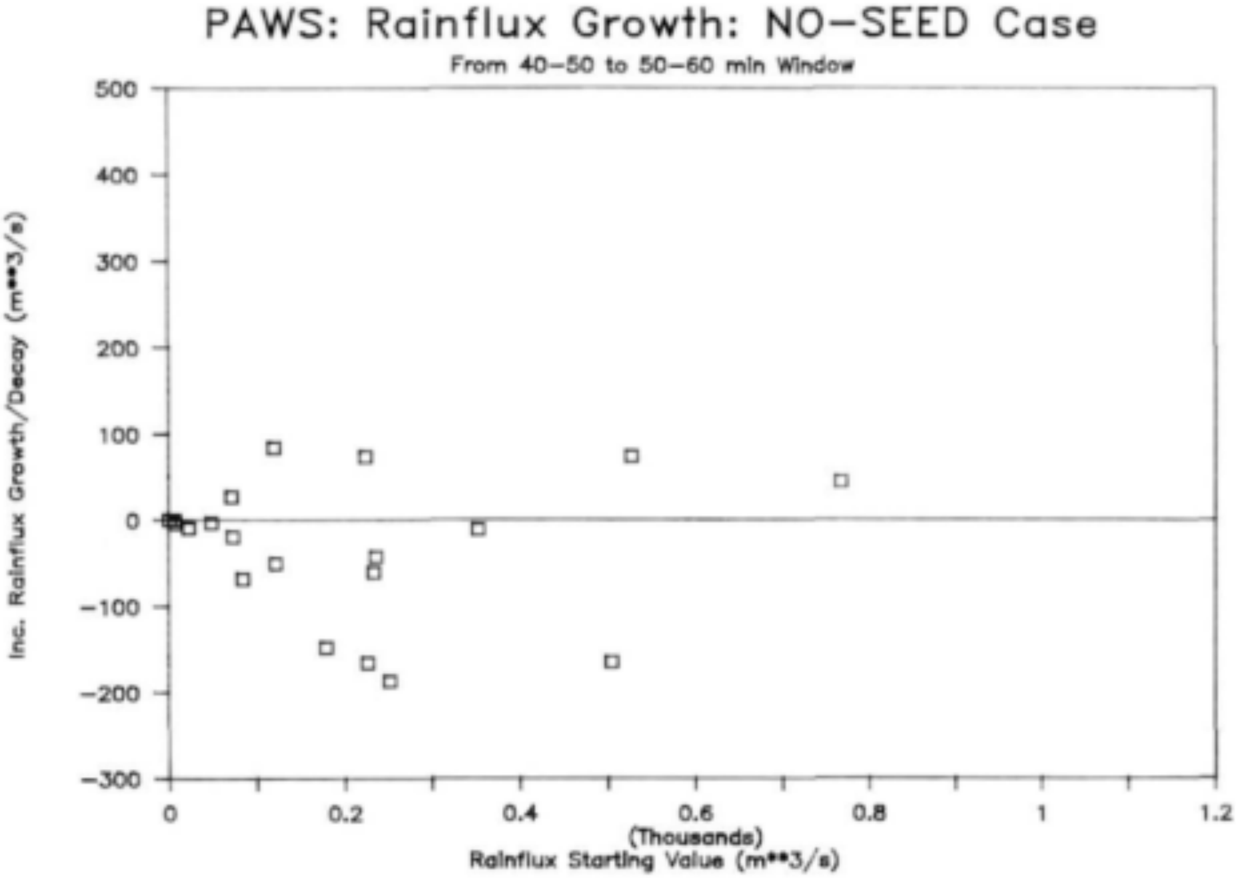

PAWS: Rainflux Growth: SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay Ratios
Starting Rainflux (m**3/s)

FIGURE 5.17A


PAWS: Rainflux Growth: NO-SEED Case
From 40-50 to 50-60 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

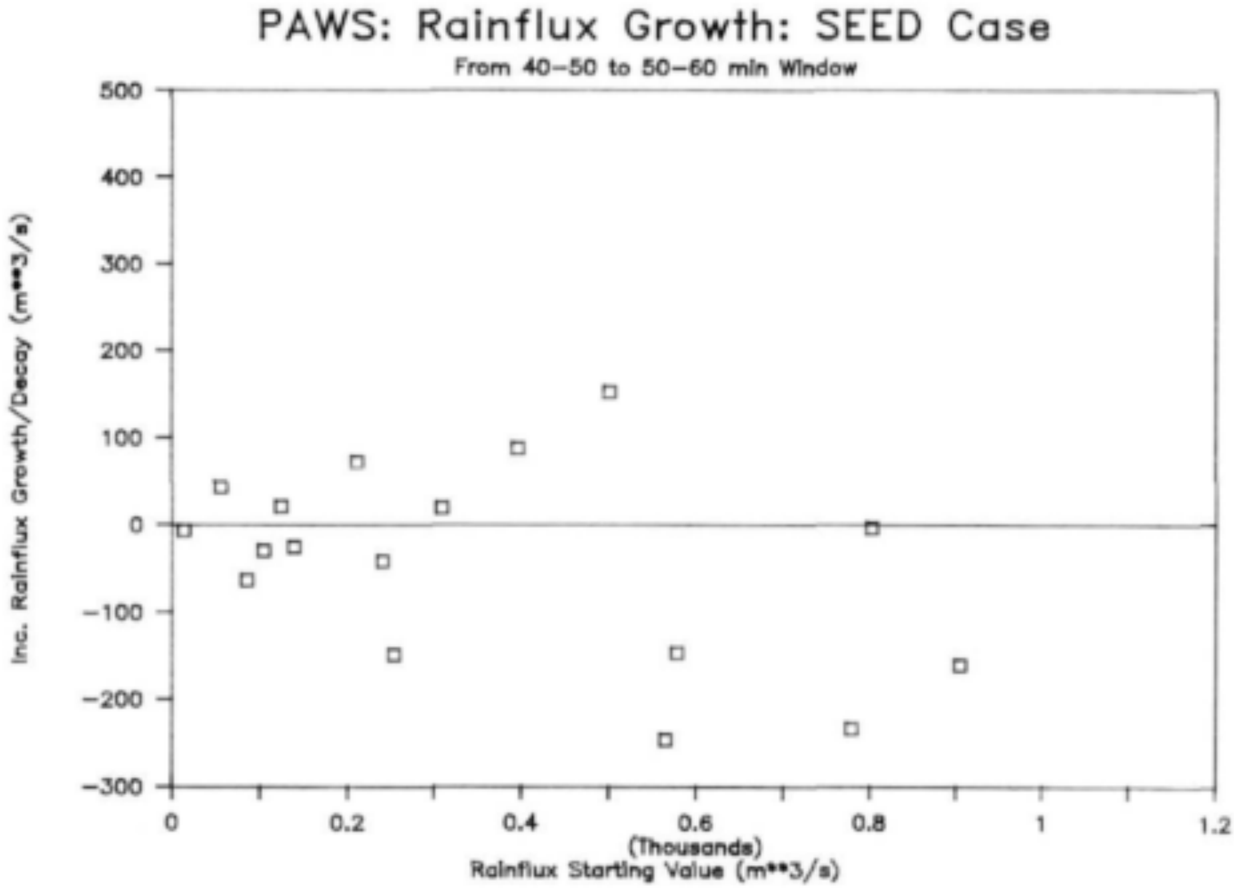
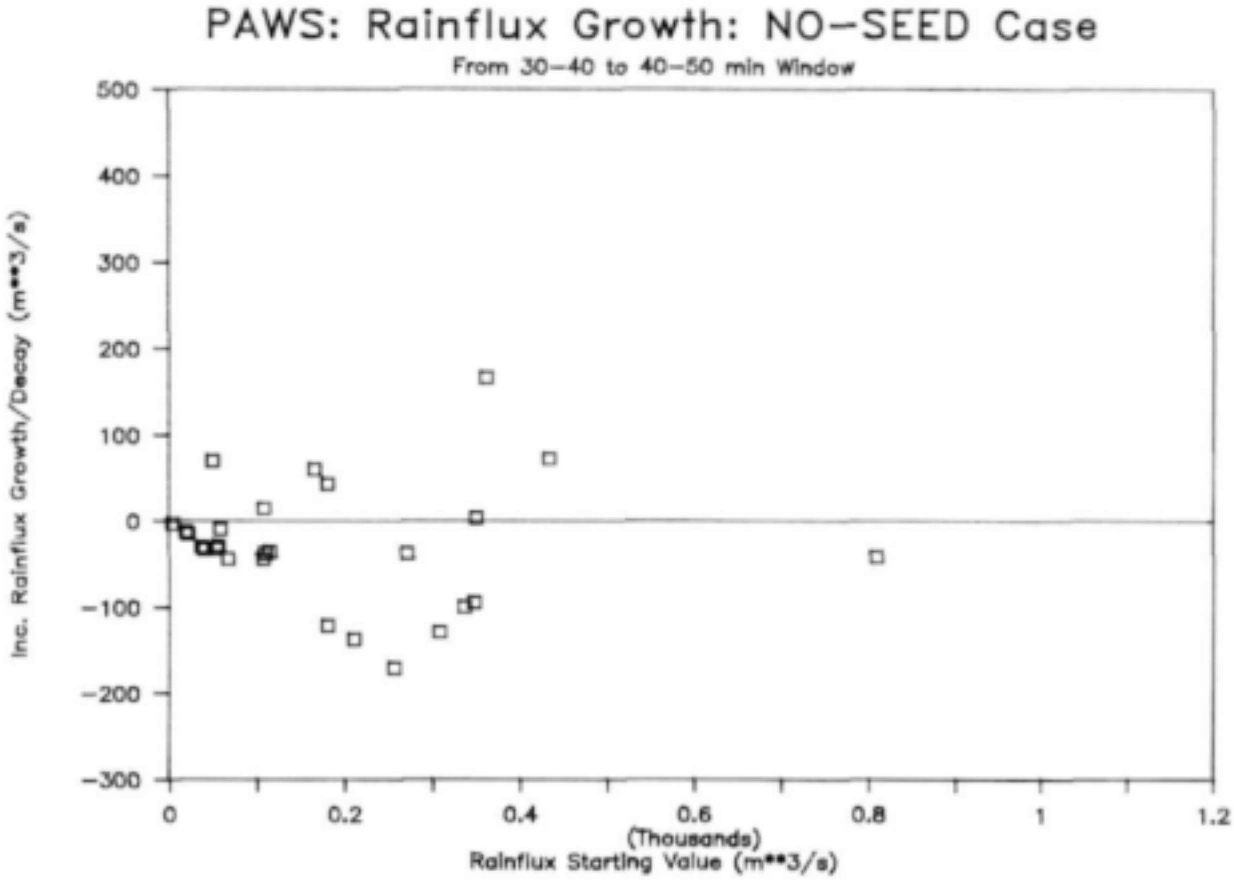

PAWS: Rainflux Growth: SEED Case
From 40-50 to 50-60 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

FIGURE 5.16 D


PAWS: Rainflux Growth: NO-SEED Case
From 30-40 to 40-50 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

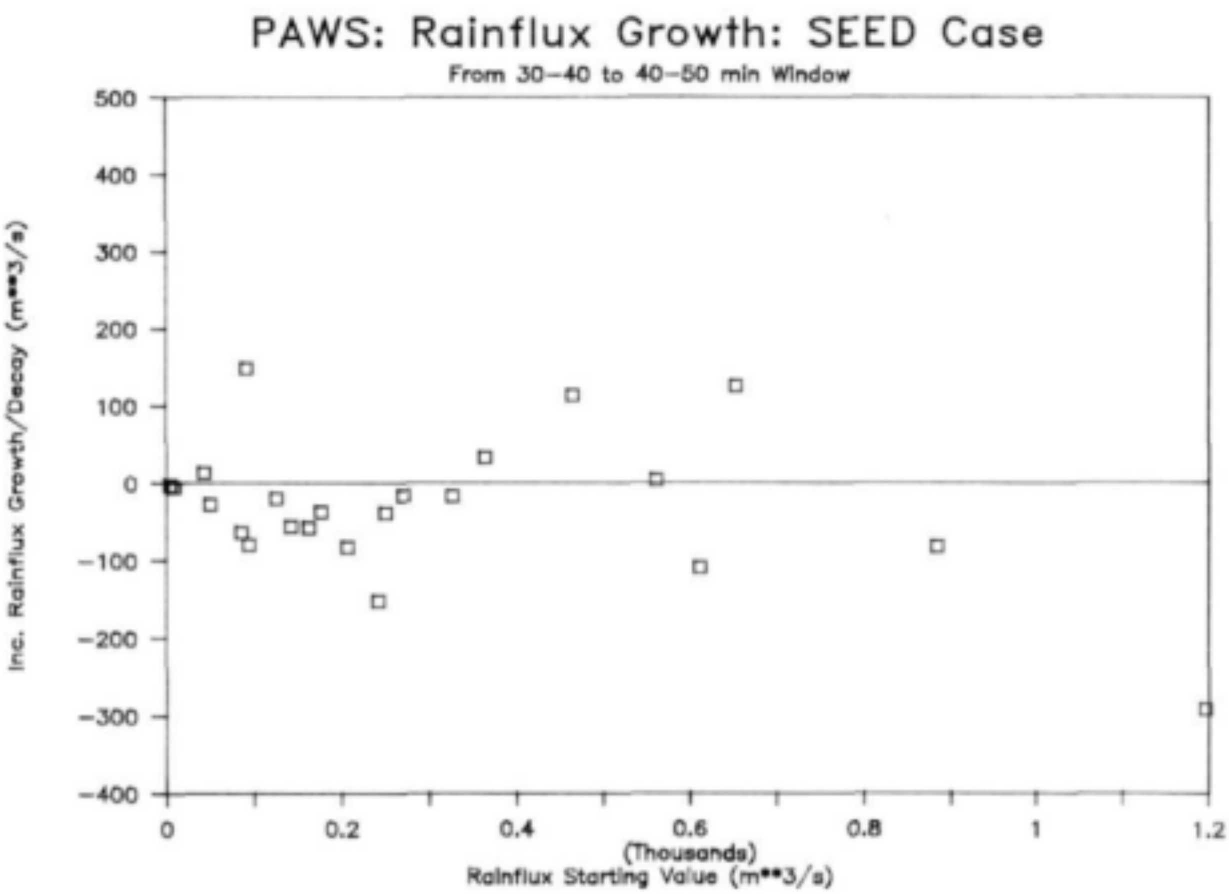
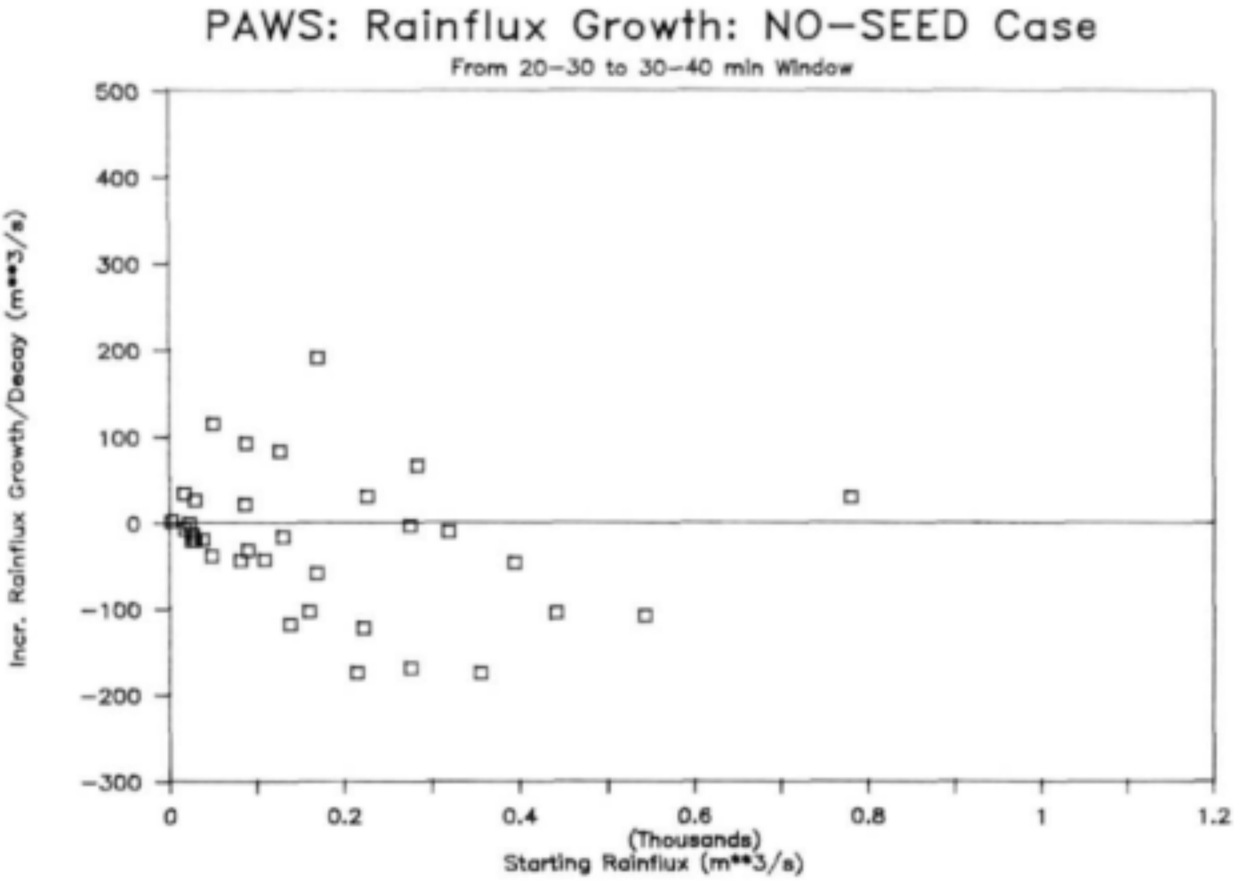

PAWS: Rainflux Growth: SEED Case
From 30-40 to 40-50 min Window
Inc. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
-400
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Rainflux Starting Value (m**3/s)

FIGURE 5.16 C


PAWS: Rainflux Growth: NO-SEED Case
From 20-30 to 30-40 min Window
Incr. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

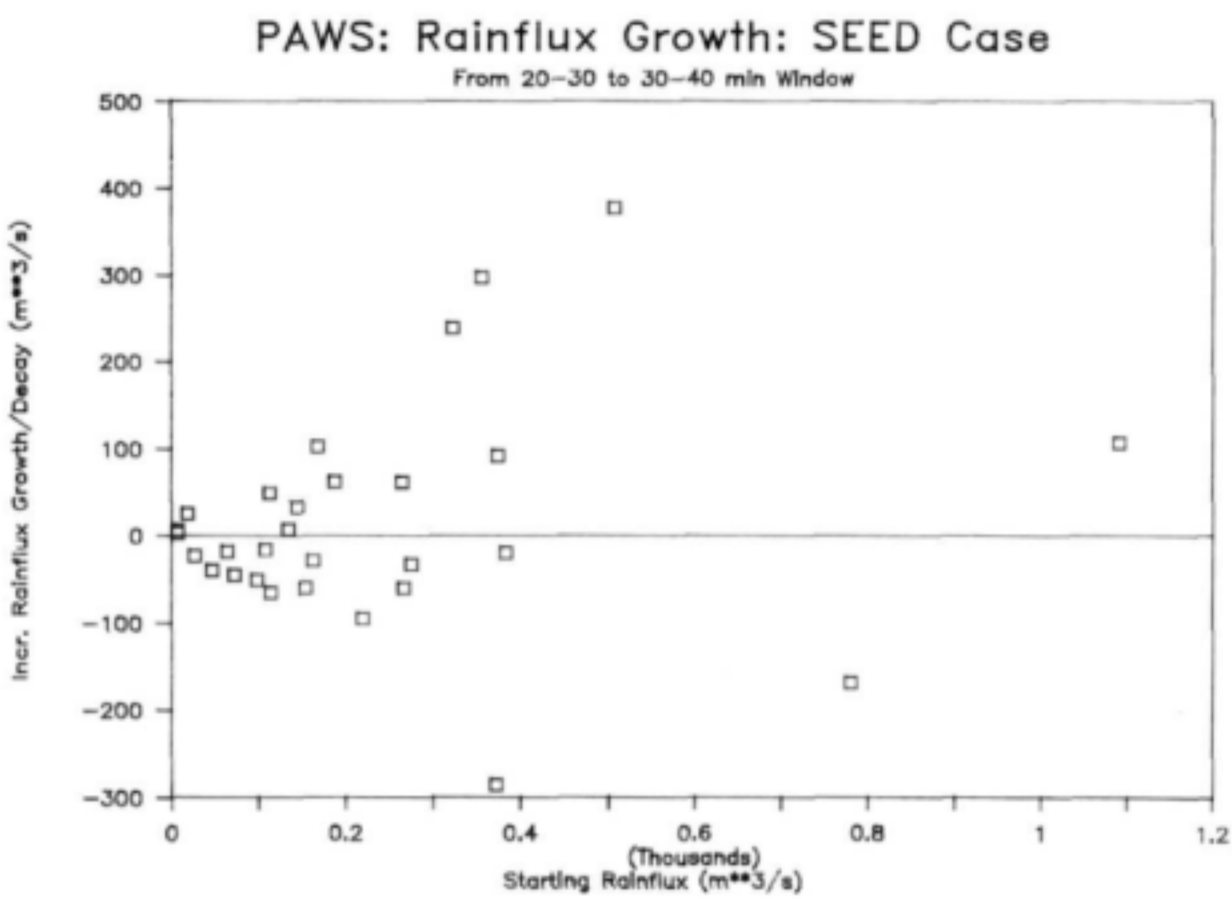
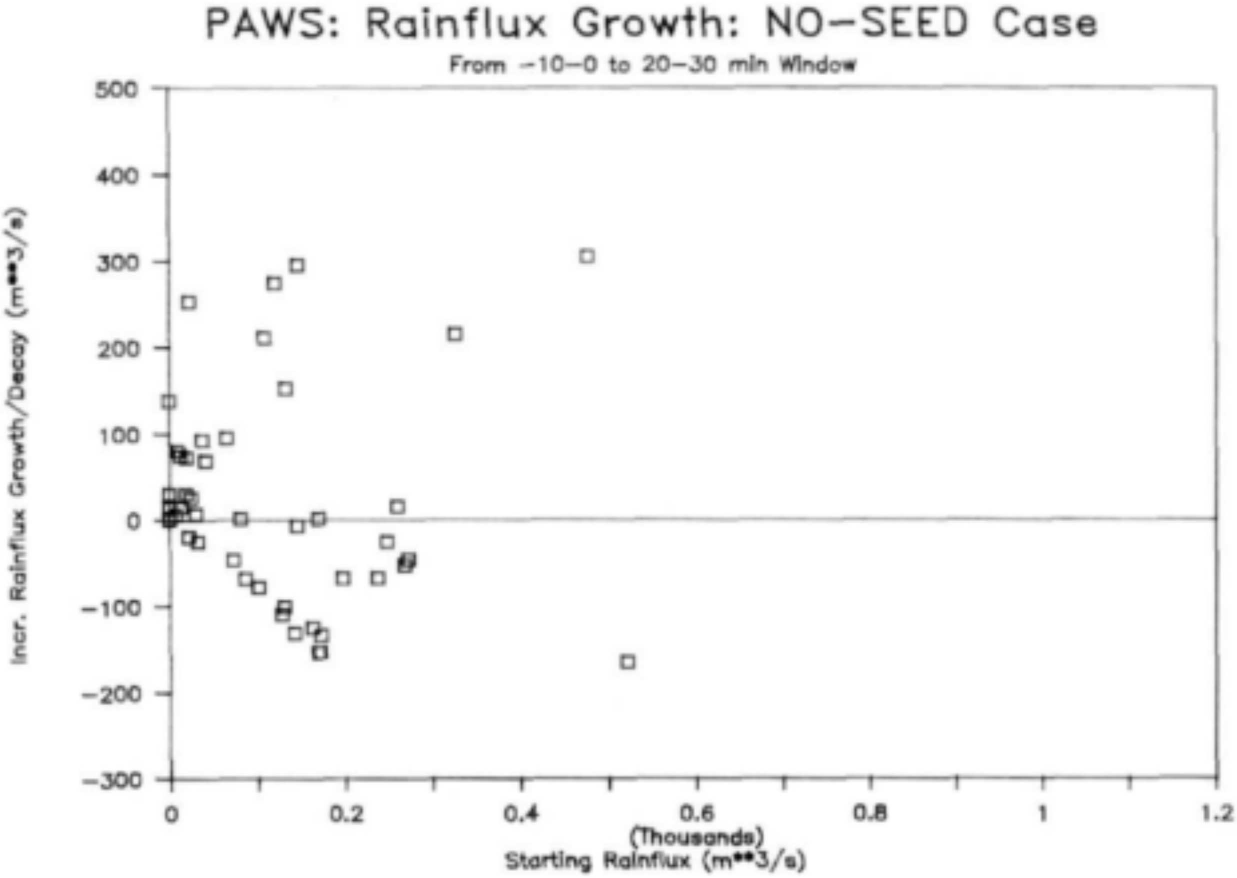

PAWS: Rainflux Growth: SEED Case
From 20-30 to 30-40 min Window
Incr. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

FIGURE 5.16B


PAWS: Rainflux Growth: NO-SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

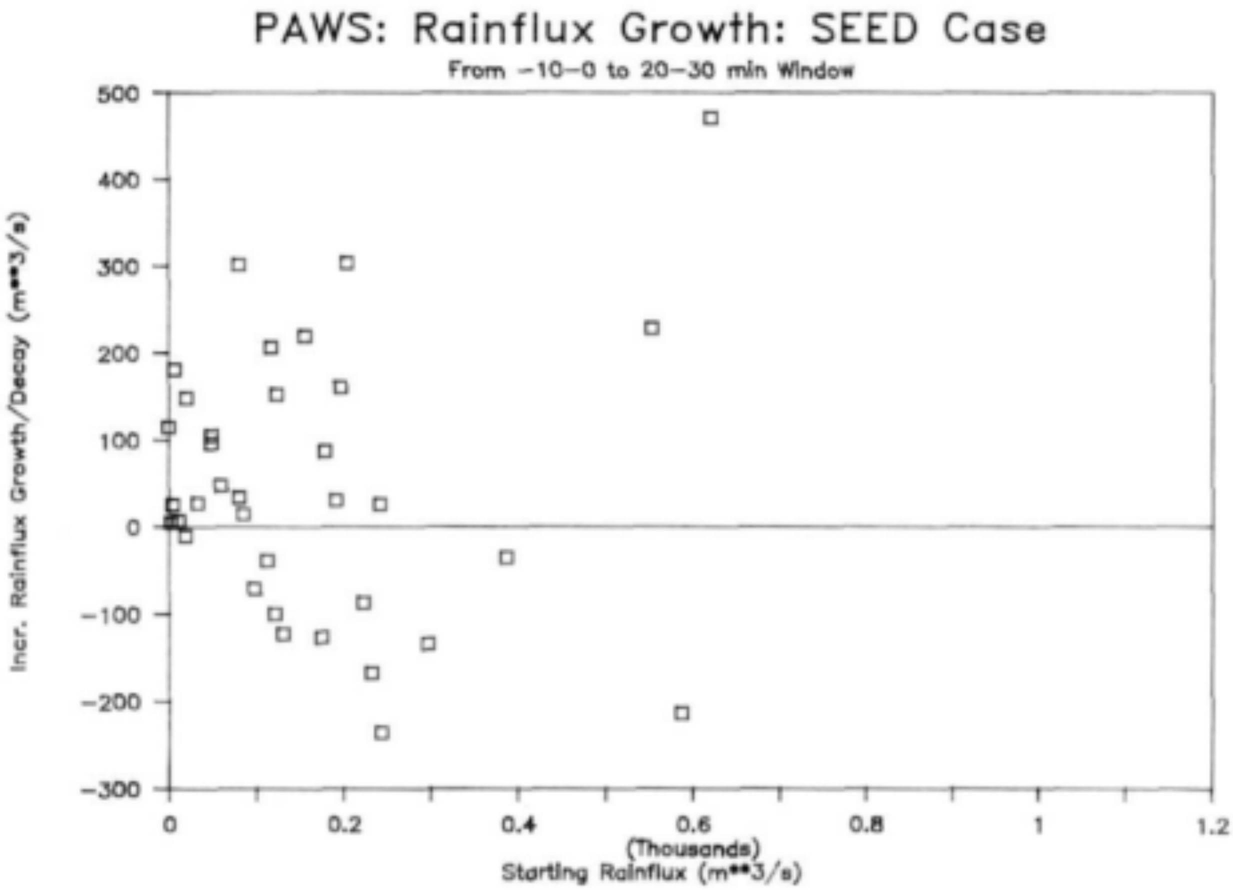

PAWS: Rainflux Growth: SEED Case
From -10-0 to 20-30 min Window
Incr. Rainflux Growth/Decay (m**3/s)
500
400
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
1.2
(Thousands)
Starting Rainflux (m**3/s)

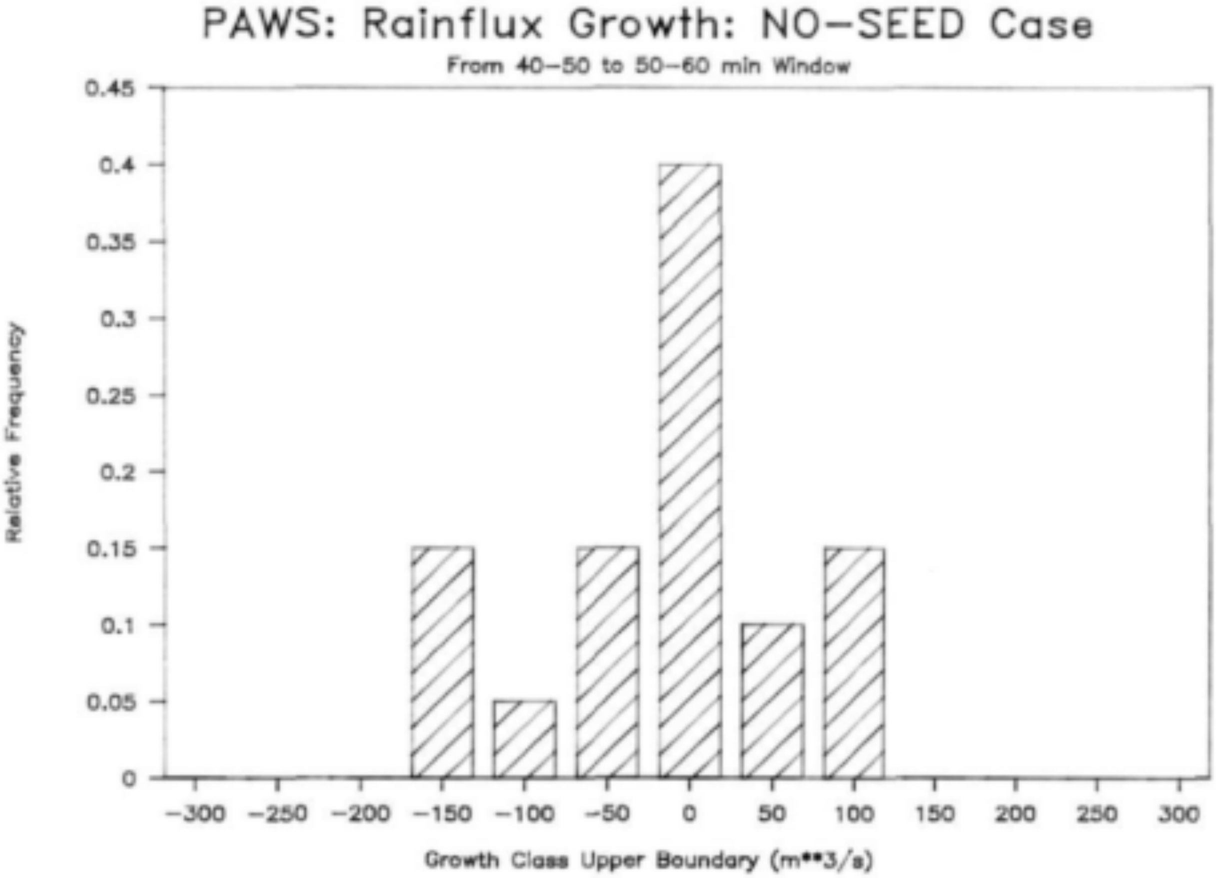
FIGURE 5.16 A

average, a fairly symmetrical distribution. Without having attempted distribution fitting tests, we believe that a truncated Normal distribution would be a reasonable working hypothesis for incremental rainflux growth/decay, regardless of seeding.

As an aid to the examination of the inter-storm variability of seeding responses we plotted incremental rainflux growth/decay against starting rainflux values for sequential window pairs. Figures 5.16 (a) to (d) depict the results. Rainflux decay is of course bounded by the 1:1 line, but suprisingly, rainflux growth for seed cases seem to have an upper envelope for window pairs beyond 20 minutes after decision time. Figures 5.17 (a) and (b) display similar information in terms of growth ratios. In general, however, the incremental growth/decay values show no systematic patterns and appear to be fairly random.

A further characteristic that might reveal a variable seeding response is that of cloud lifetime as measured by storm duration. Fig. 5.18 reveals that cloud lifetime decay/storm survival rates for seeded clouds are virtually indistinguishable from those of unseeded clouds.

On the whole this cursory examination did not produce an abundance of "hard" quantified information on the variability of seeding responses. We surmise that use of incremental rainflux growth data stratified by specific cloud attributes or by factors such as synoptic type, in conjunction with a study of each target storm's post-decision history, might produce further information useful to the development of augmented rainfall time series. However, this work falls outside the scope of our study and has to await appropriate attention at some future date.


PAWS: Rainflux Growth: NO-SEED Case
From 40-50 to 50-60 min Window
Relative Frequency
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300
Growth Class Upper Boundary (m**3/s)

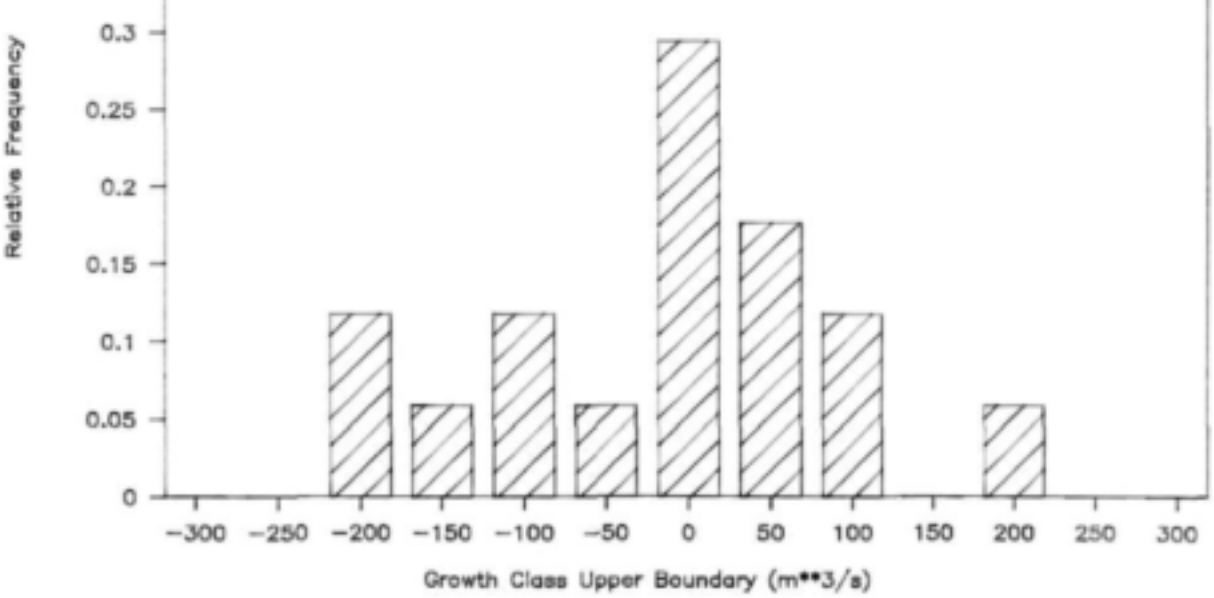
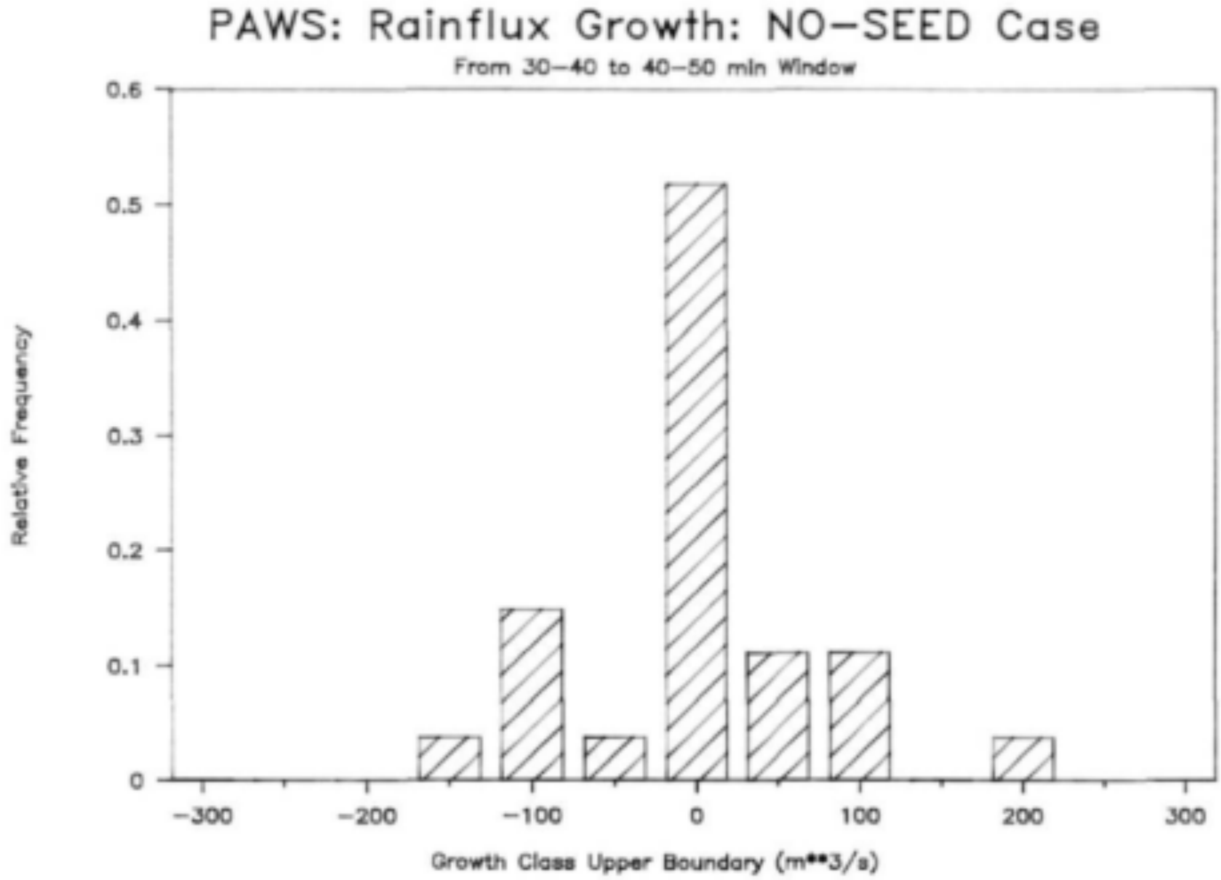

PAWS: Rainflux Growth: SEED Case
From 40-50 to 50-60 min Window
Relative Frequency
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300
Growth Class Upper Boundary (m**3/s)

FIGURE 5.15D


PAWS: Rainflux Growth: NO−SEED Case
From 30−40 to 40−50 min Window
Relative Frequency
0
0.1
0.2
0.3
0.4
0.5
0.6
−300
−200
−100
0
100
200
300
Growth Class Upper Boundary (m**3/s)

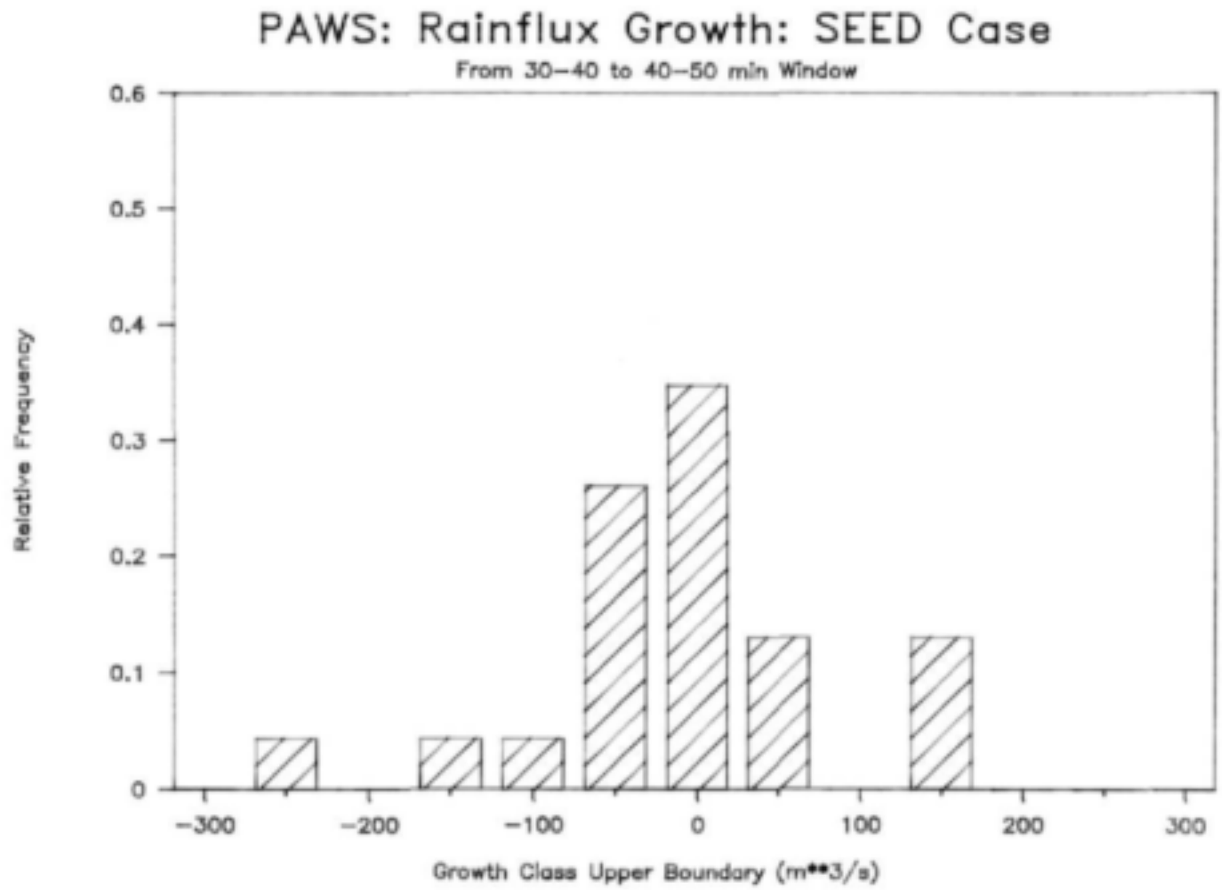
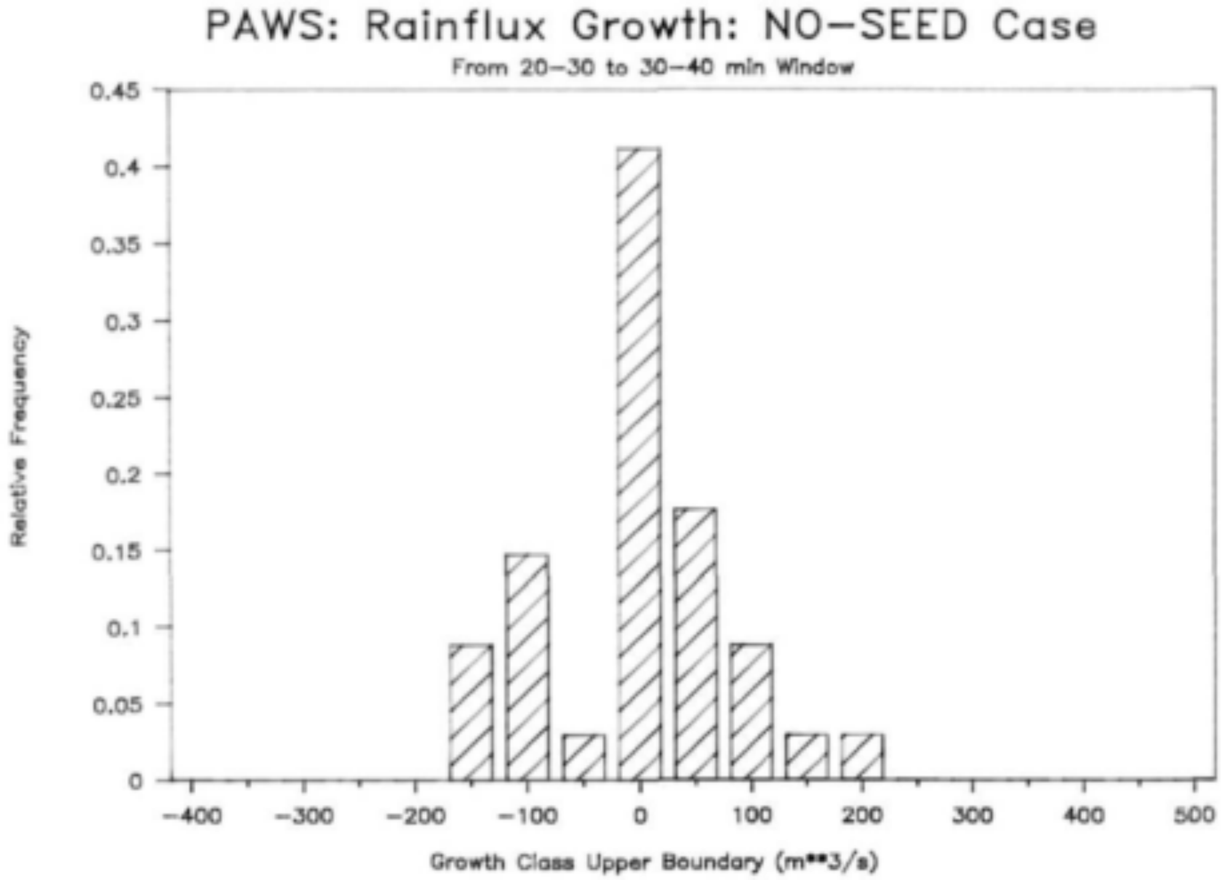

PAWS: Rainflux Growth: SEED Case
From 30−40 to 40−50 min Window
Relative Frequency
0
0.1
0.2
0.3
0.4
0.5
0.6
−300
−200
−100
0
100
200
300
Growth Class Upper Boundary (m**3/s)

FIGURE 5.15C


PAWS: Rainflux Growth: NO-SEED Case
From 20-30 to 30-40 min Window
Relative Frequency
Growth Class Upper Boundary (m**3/s)

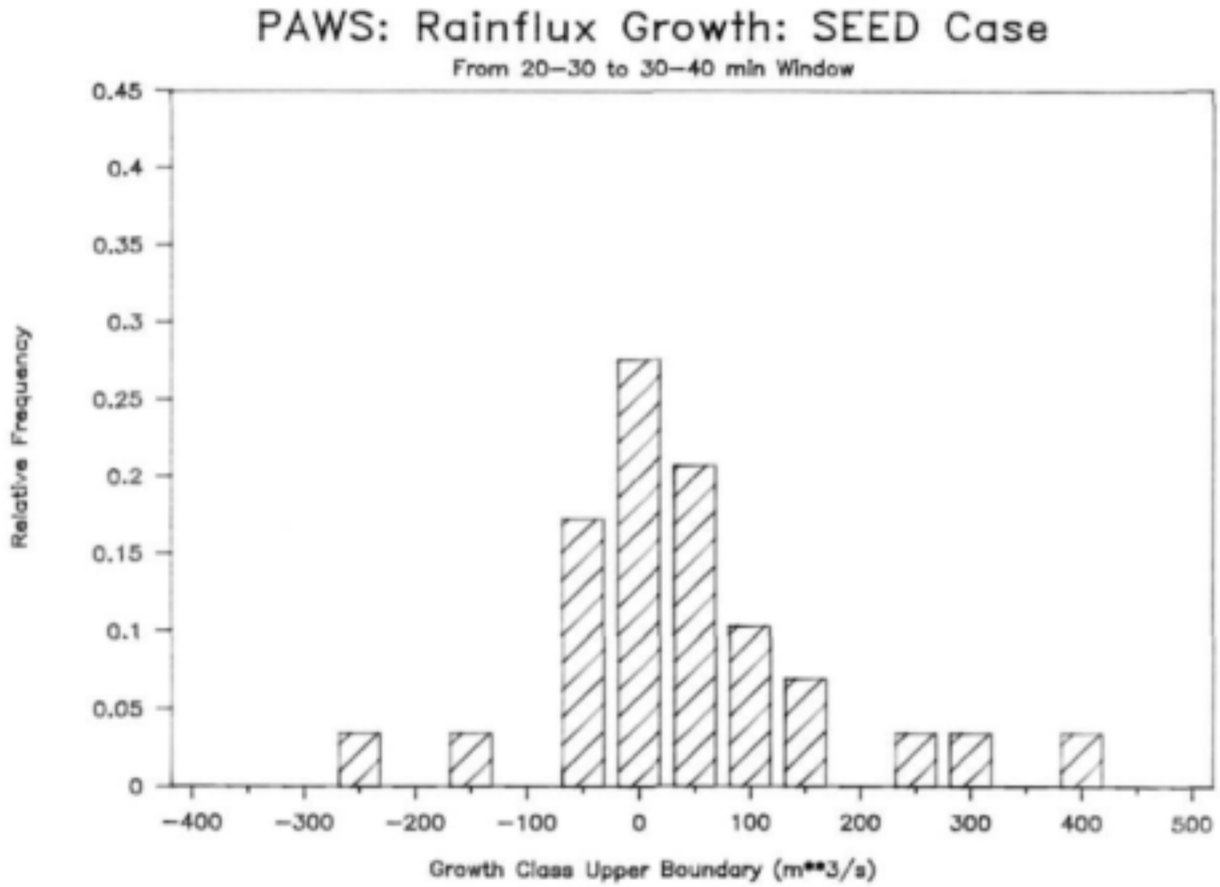
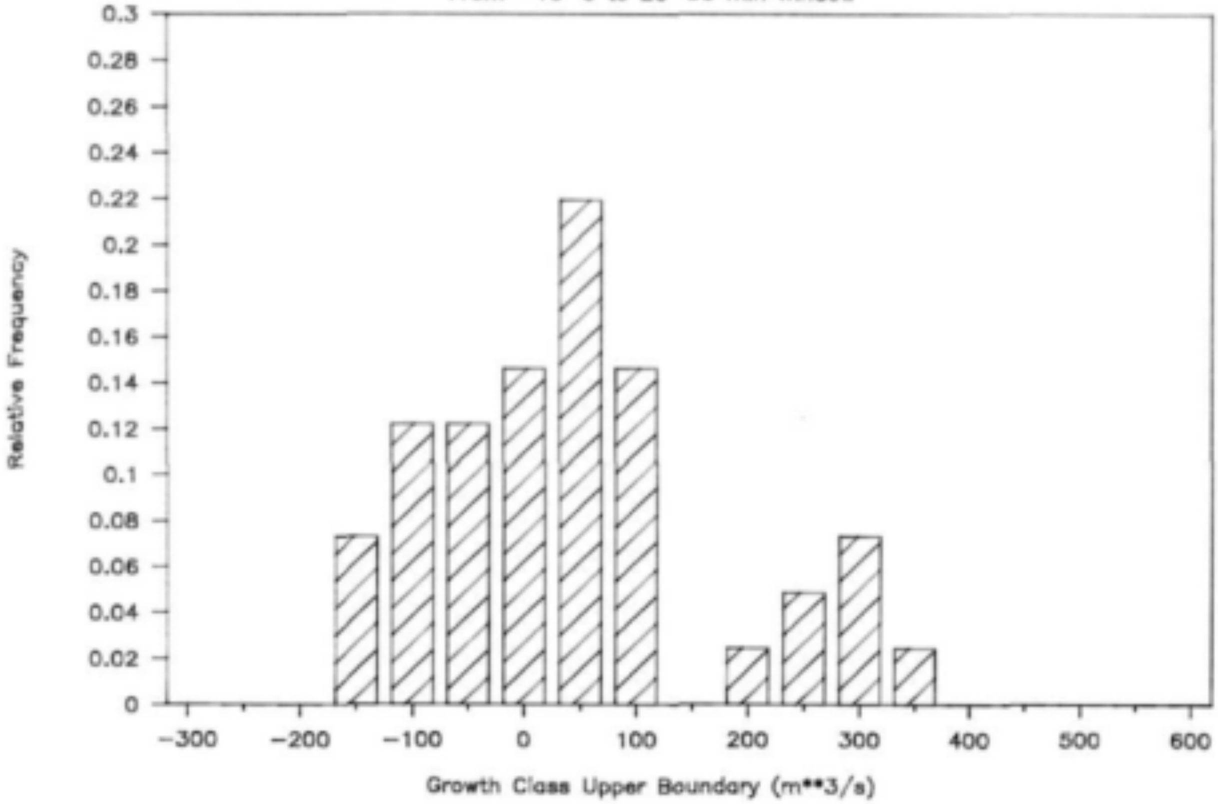

PAWS: Rainflux Growth: SEED Case
From 20-30 to 30-40 min Window
Relative Frequency
Growth Class Upper Boundary (m**3/s)

FIGURE 5.15B

PAWS: Rainflux Growth: NO-SEED Case

From -10-0 to 20-30 min Window



PAWS: Rainflux Growth: SEED Case

From -10-0 to 20-30 min Window

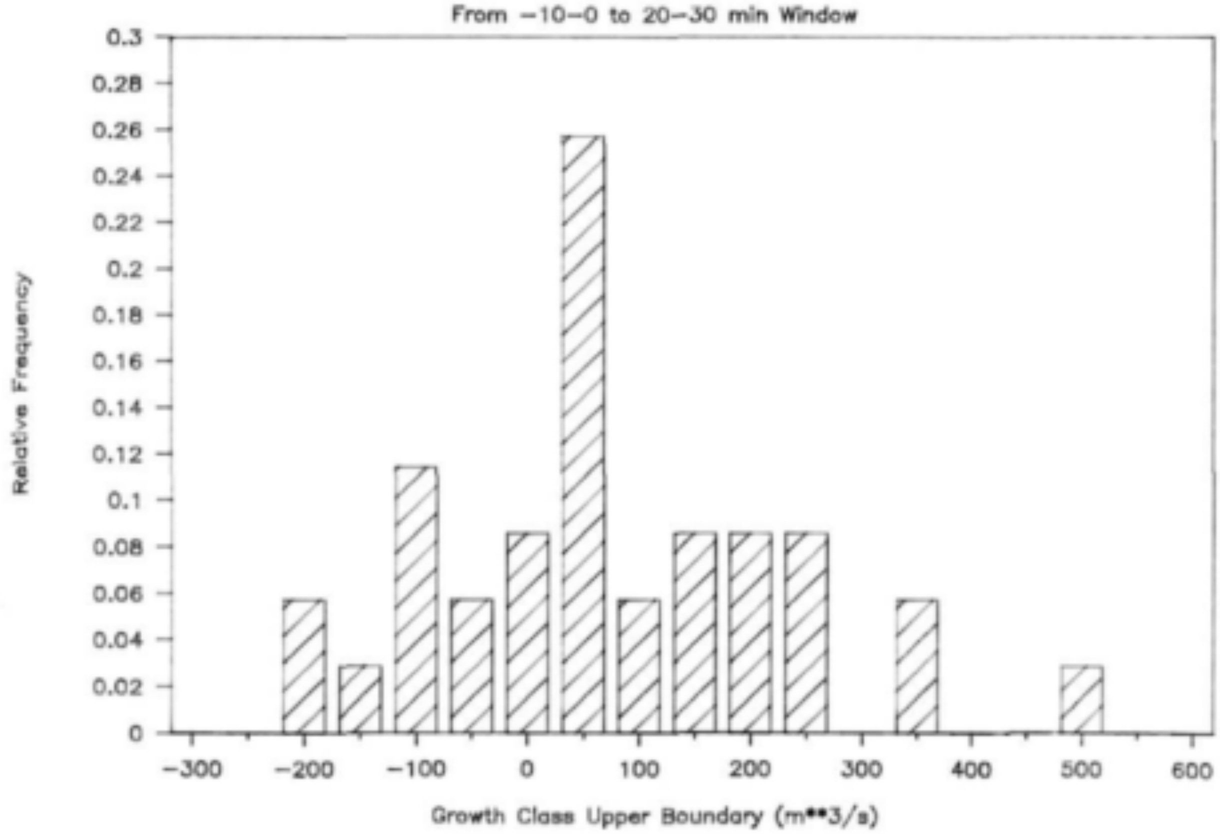


FIGURE 5.15A

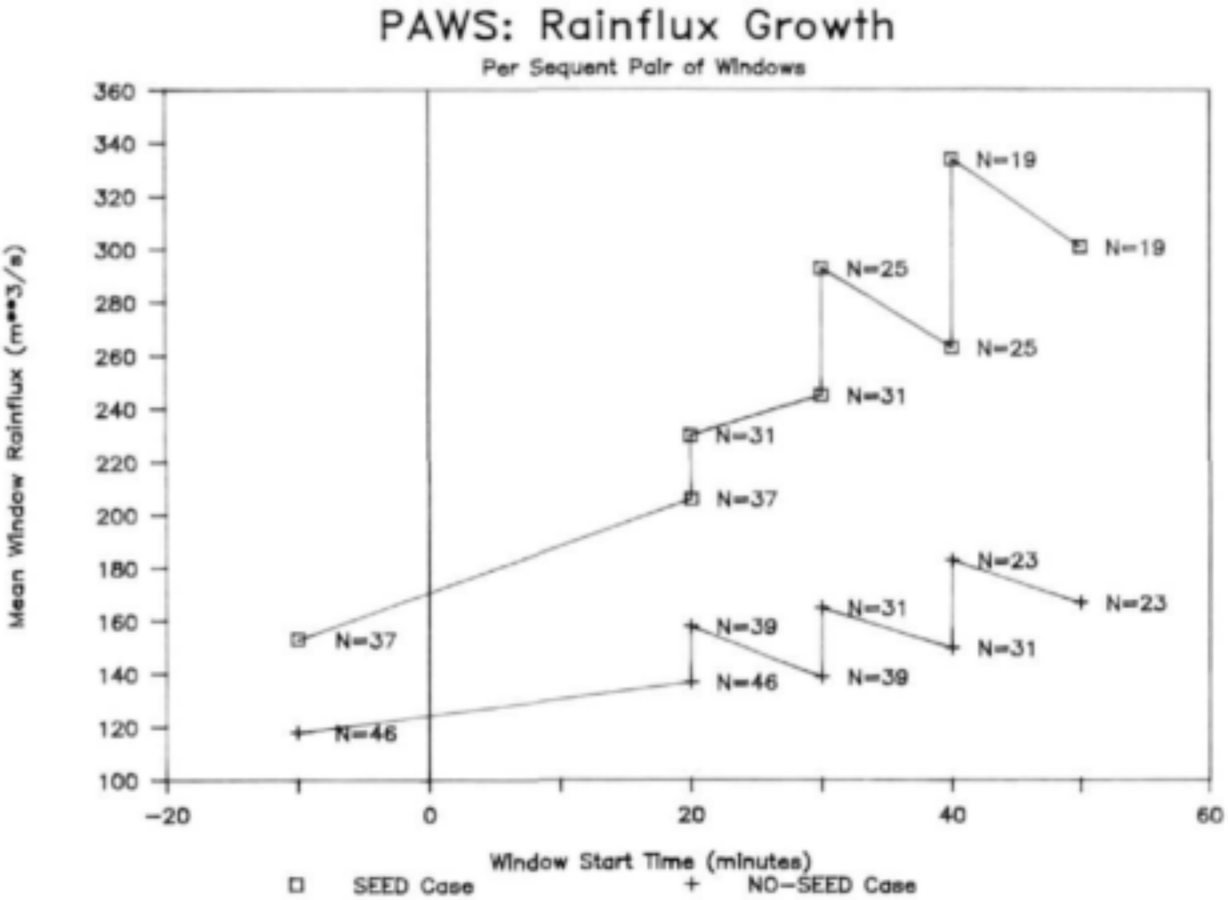
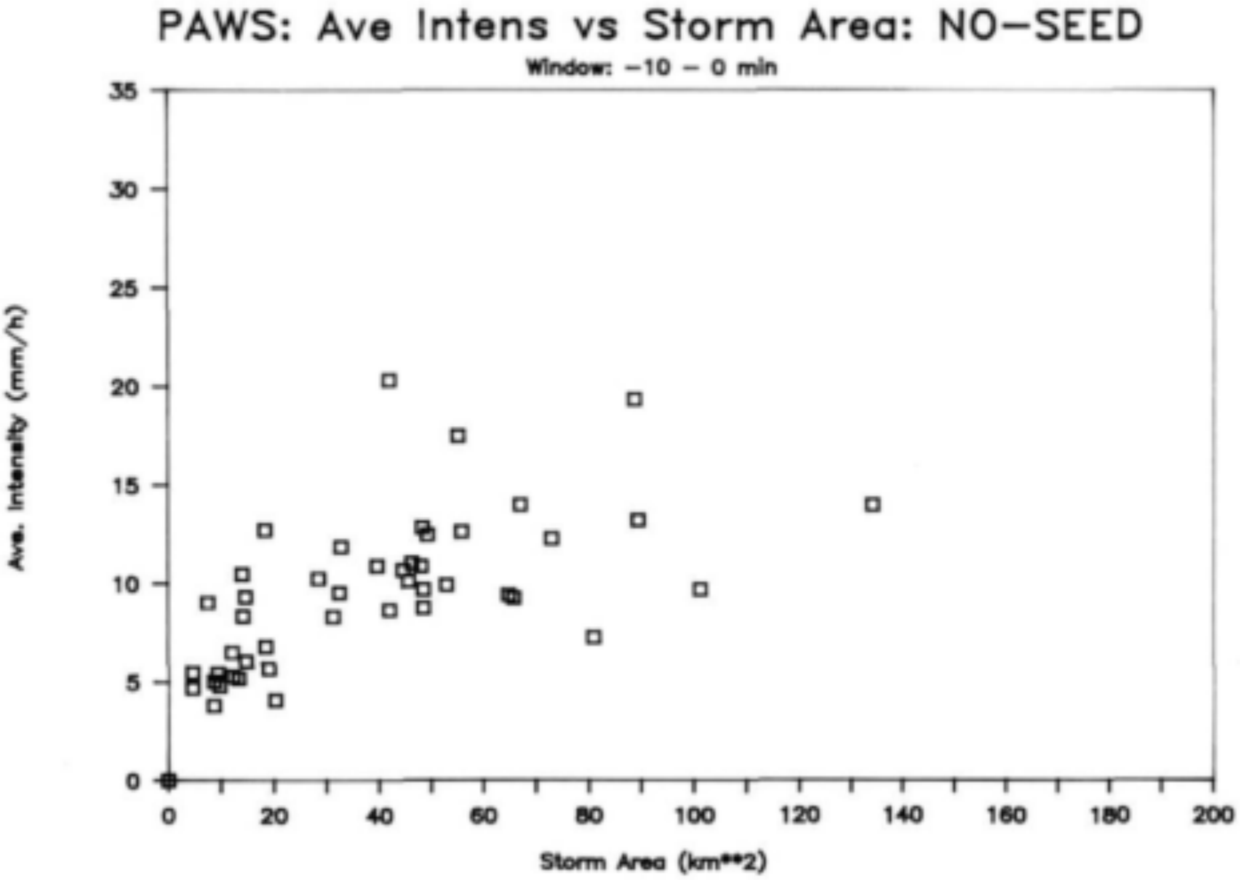

PAWS: Rainflux Growth
Per Sequent Pair of Windows
Mean Window Rainflux (m**3/s)
Window Start Time (minutes)
SEED Case
NO-SEED Case
N=37
N=37
N=31
N=31
N=25
N=25
N=19
N=19
N=46
N=46
N=39
N=39
N=31
N=31
N=23
N=23

FIGURE 5.14


PAWS: Ave Intens vs Storm Area: NO-SEED
Window: -10 - 0 min
Ave. Intensity (mm/h)
Storm Area (km**2)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200

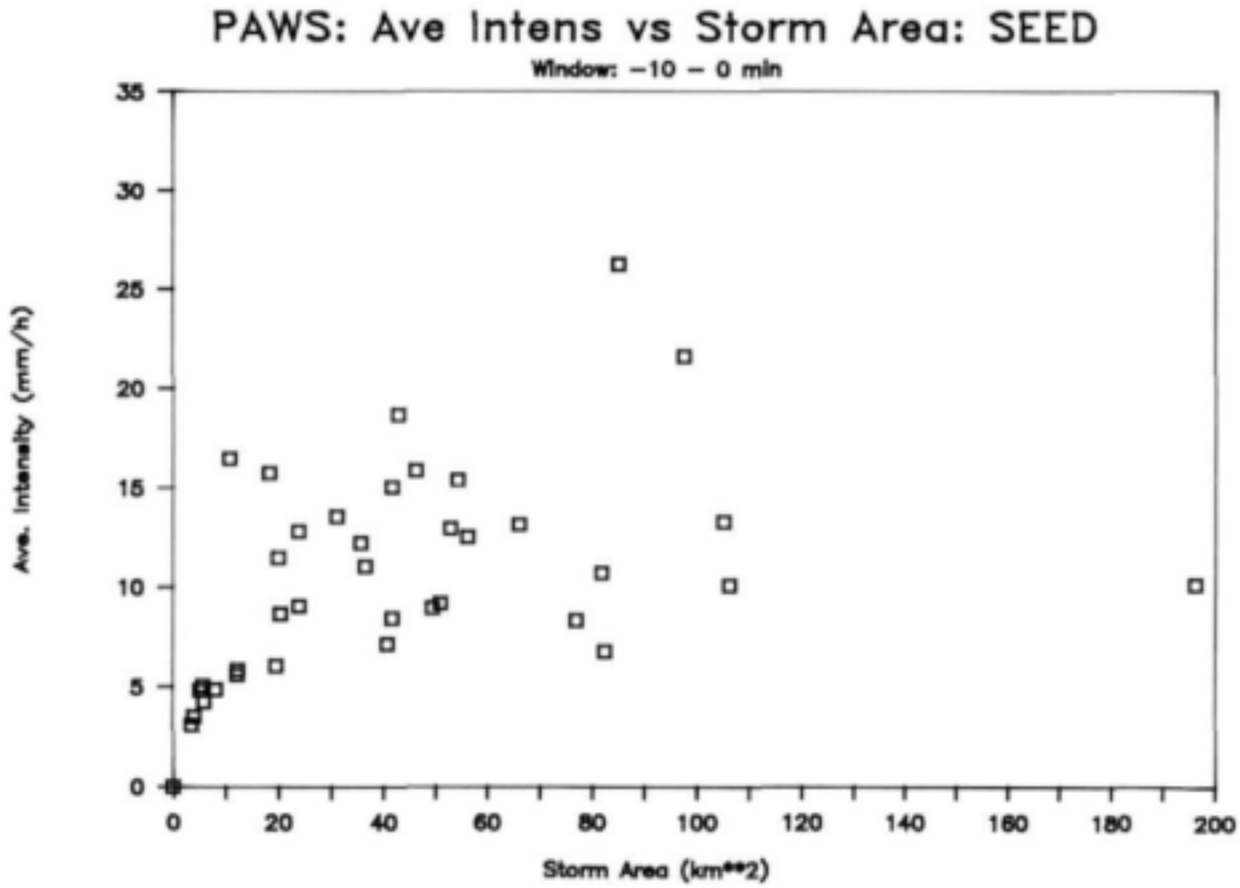

PAWS: Ave Intens vs Storm Area: SEED
Window: -10 - 0 min
Ave. Intensity (mm/h)
Storm Area (km**2)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140
160
180
200

FIGURE 5.12

TABLE 3.3 : CLOUD SELECTION CRITERIA FOR HIPLEX-1 (SILVERMAN, 1986)

Class A-1 Cloud Criteria

1. Average cloud liquid water concentration greater than 0.5 g m^{-3} over approximately a 1-km-long cloud region determined by 10 s of flight at approximately 100 m s^{-1}
2. Average ice crystal concentrations less than 1.0 L^{-1} in the 1-km-long (10 s of flight) cloud region of maximum average liquid water concentration
3. Maximum ice crystal concentration less than 5.0 L^{-1} for any 1-km-long (10 s of flight) cloud region (defined by FSSP liquid water concentration greater than 0.01 g m^{-3}) during the test pass
4. Vertical air velocity greater than −1.0 m s^{-1} in the region defined by item 1, but if the vertical velocity is greater than 10.0 m s^{-1} and the buoyancy is greater than 1°C, reject the candidate
5. Length of the test penetration more than 2 km and less than 8 km as defined by an FSSP liquid water concentration greater than 0.01 g m^{-3}
6. No radar echo detectable on the aircraft weather radar
7. Cloud-top temperature lower than −6°C but higher than −12°C
8. Cloud-base temperature higher than 0°C
9. Minimum separation between the current test cloud and previous test clouds greater than 15 km to insure the meteorological independence of the clouds

Class A-2 Cloud Criteria

1. Items 1 through 9 of Class A-1 Cloud Criteria
2. An average wind direction between the surface and 800 kPa from 250° to 040° true
3. A 30-kPa-thick stable layer present with its base between 0° and −10°C and its top temperature at least 1.5°C higher than the temperature extrapolated from the base of the layer to the top using pseudoadiabatic ascent
4. A 10°C dewpoint depression present somewhere within the 30-kPa layer of B.3 above

Class B Cloud Criteria

1. Items 1, 2, 3, 5, 6, 8 and 9 of Class A-1 Cloud Criteria
2. Cloud-top temperature lower than −6°C but higher than −20°C
3. Vertical air velocity greater than −1.0 m s^{-1} in the region defined by Item A.1, but no other vertical velocity or buoyancy restrictions

TABLE 3.4 : HIPLEX-1 PRIMARY RESPONSE VARIABLES (SILVERMAN, 1986)

1.	CIC2	Cloud ice concentration, 2 min after treatment
2.	CIC5	Cloud ice concentration, 5 min after treatment
3.	CCR5	Concentration of crystals rimed, 5 min after treatment
4.	PIC8	Precipitating ice number concentration, 8 min after treatment
5.	MVD8	Mean volume diameter of precipitating ice particles, 8 min after treatment
6.	AWC8	Average liquid water concentration, 8 min after treatment
7.	TFPI	Time to first precipitating ice (particles with diameters >0.6 mm in concentrations >0.1 L^{-1})
8.	TFE	Time to first SWR-75 radar echo (15 dBZ)
9a.	TIPA	Time to initial precipitation at +10°C level, aircraft measurement
b.	TIPR	Time to initial precipitation at +10°C level, SWR-75 radar (15 dBZ)
10a.	RERC	Radar-estimated rainfall at +10°C level, using a constant Z–R relationship
b.	AER	Aircraft-estimated rainfall at +10°C level

TABLE 9.3 **PROPOSED PRELIMINARY RESEARCH PROJECTS IN PRIMARY END-USER AND IMPACT FIELDS**

End-user/impact	Project leader(s)	Organisation(s)	Model(if any)	Field study details	Duration	Approximate budget (in R1000's) by years 1991	1992	1993	1994	1995
Modified rainfall time series	Dr A Seed	Hyd. Res. Institute Dept. Water Affairs	N/A	N/A	1 yr	130	-	-	-	-
Dryland maize and Wheat production	Prof J M de Jager	Dept. of Agrometeorology, U.O.F.S.	PUTU	Soil and crop surveys; monitor crop development using satellite data to verify model results	5 yrs	70	77	85	95	95
Dryland maize production	Dr J B Mallett	Grain Crops Research Institute, Cedara	CERES	Low budget : No field study Med.budget : Soil and crop surveys High budget : As for medium, but with test plots to verify model results	3-6 mths 12-18 mths 3 yrs	20 50 90	- 25 60	- - 75	- - -	- - -
Dryland pasture production	Prof O J H Bosch and Dr J Booysen	Dept. of Plant Sciences, Potchefstroom University	PUK (modified)	Species composition surveys along transects; habitat definitions; degradation gradient quantification; surveys to verify model results; target area divided into 3 zones	3 yrs(Zone I) or 4 yrs(I+II+III)	17 29 49	29 84 147	32 92 160	- 65 160	(Zone I) (I, II) (I, II,III)
Reservoir system yield (preliminary assessment)	Prof W J R Alexander	University of Pretoria and Sigma Beta	Pitman +1 reservoir system model	No field work	6 mths	50	-	-	-	-
Water resources and timber production	Dr A Görgens Prof R Schulze Dr J Bosch	Ninham Shand, University of Natal, Foresttek, CSIR	ACRU	No field work	24 mths	110	125	-	-	-
Socio-Economic	Prof M F Viljoen	Dept. Agr. Econ. U.O.F.S.	N/A	Interviews with relevant persons and institutions	3 yrs	-	50	90	90	-
Social attitudes	Ms M Pretorius and Dr J Schnetler	Human Sciences Research Council	N/A	Interviews with relevant persons; two alternative proposals	6-12 mths	- -	95(personal:180;telephonic;1200 people) 160(personal:1380; no telephonic)			

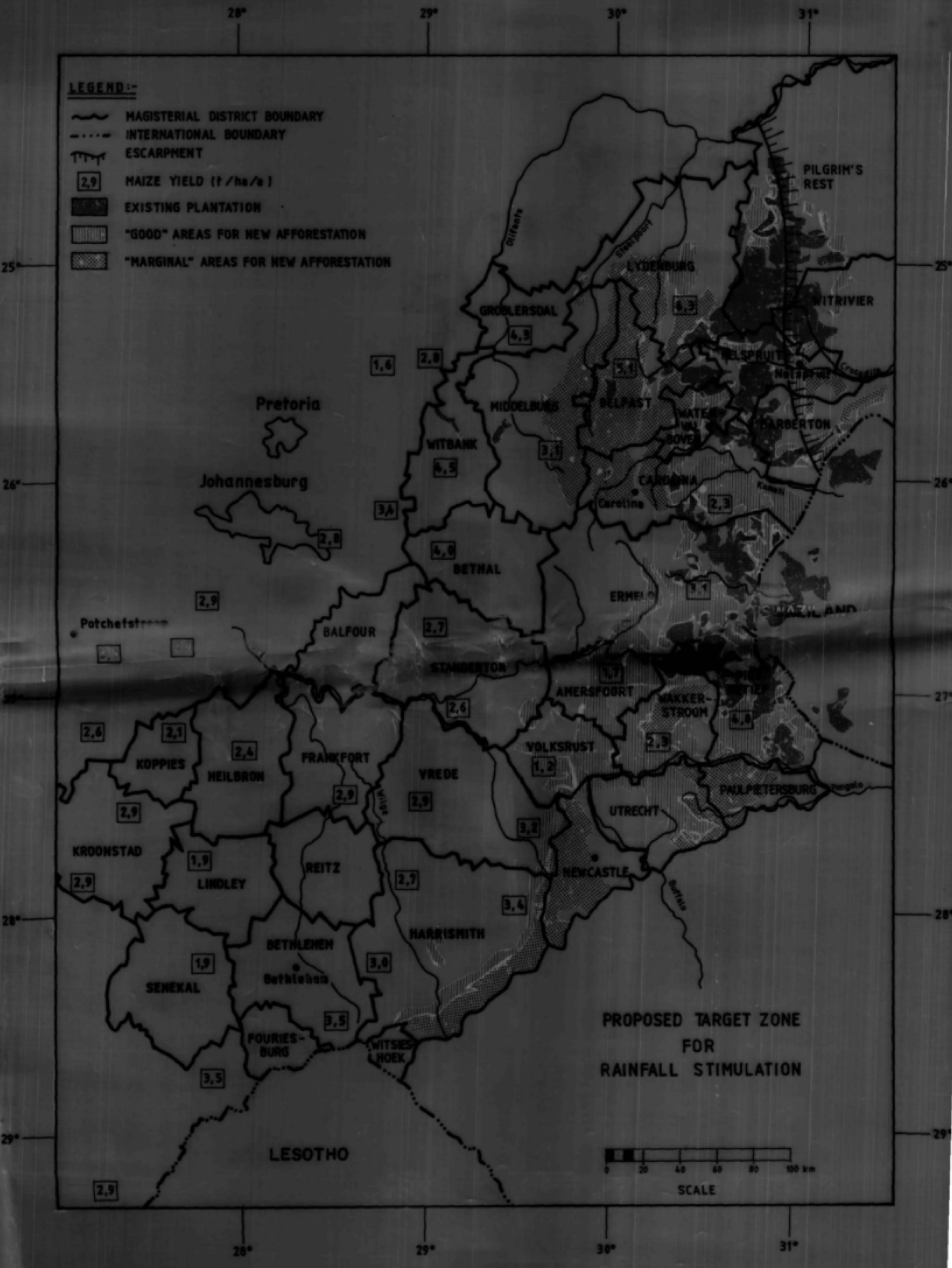

LEGEND:-
MAGISTERIAL DISTRICT BOUNDARY
INTERNATIONAL BOUNDARY
ESCARPMENT
2,9 MAIZE YIELD (t/ha/a)
EXISTING PLANTATION
"GOOD" AREAS FOR NEW AFFORESTATION
"MARGINAL" AREAS FOR NEW AFFORESTATION
PILGRIM'S REST
LYDENBURG
GROBLERSDAL
WITRIVIER
NELSPRUIT
MIDDELBURG
BELFAST
WATERVAL BOVEN
BARBERTON
Pretoria
Johannesburg
WITBANK
CAROLINA
Carolina
BETHAL
ERMELO
SWAZILAND
BALFOUR
Potchefstroom
STANDERTON
AMERSFOORT
WAKKERSTROOM
KOPPIES
HEILBRON
FRANKFORT
VREDE
VOLKSRUST
PAULPIETERSBURG
UTRECHT
KROONSTAD
LINDLEY
REITZ
NEWCASTLE
HARRISMITH
BETHLEHEM
Bethlehem
SENEKAL
FOURIESBURG
WITSIESHOEK
LESOTHO
PROPOSED TARGET ZONE FOR RAINFALL STIMULATION
SCALE
0 20 40 60 80 100 km

FIGURE 6.3

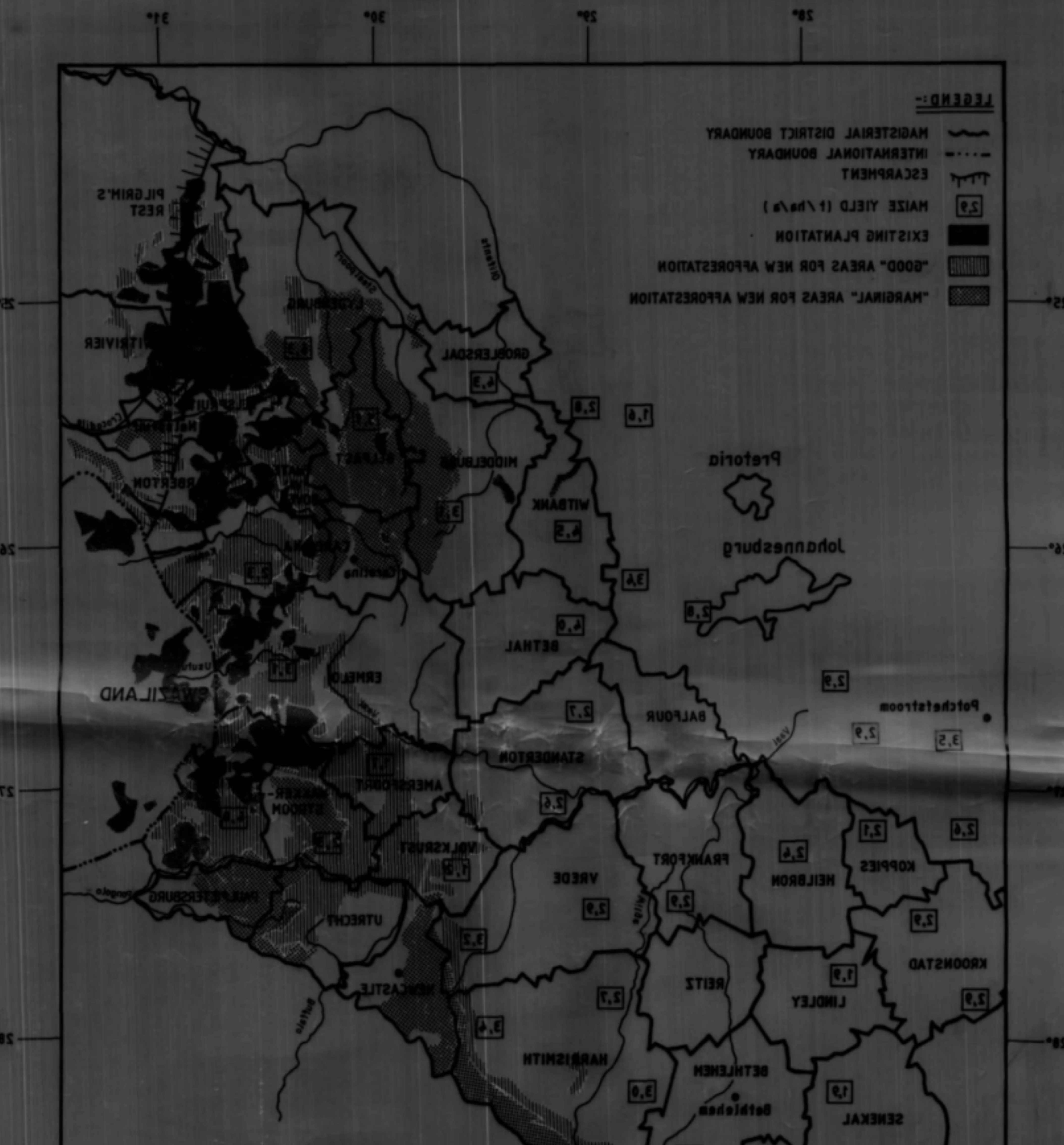

LEGEND:-
MAGISTERIAL DISTRICT BOUNDARY
INTERNATIONAL BOUNDARY
ESCARPMENT
MAIZE YIELD (t/ha/a)
EXISTING PLANTATION
"GOOD" AREAS FOR NEW AFFORESTATION
"MARGINAL" AREAS FOR NEW AFFORESTATION
PROPOSED TARGET ZONE
FOR
RAINFALL STIMULATION
PILGRIM'S REST
LYDENBURG
GROBLERSDAL
BELFAST
MIDDELBURG
WITBANK
CAROLINA
BETHAL
ERMELO
BALFOUR
STANDERTON
AMERSFOORT
WAKKERSTROOM
VOLKSRUST
PAULPIETERSBURG
UTRECHT
NEWCASTLE
VREDE
FRANKFORT
HEILBRON
KOPPIES
KROONSTAD
REITZ
LINDLEY
HARRISMITH
BETHLEHEM
Bethlehem
SENEKAL
FOURIES-BURG
WITSIES-HOEK
SWAZILAND
LESOTHO
Pretoria
Johannesburg
Potchefstroom
Carolina
Vaal
Wilge
Buffalo
Olifants
SCALE
31°
30°
29°
28°
25°
26°
27°
28°
29°

FIGURE 6.3