AN ASSESSMENT OF PANS AS LANDSCAPE FEATURES IN THE NORTH WEST PROVINCE USING REMOTE SENSING TECHNIQUES

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DECLARATION

I declare that this report is my own, unaided work. It is being submitted in partial fulfilment of the requirements for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any other degree or examination in any other University.

Signed:

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ABSTRACT

Pans are unique as wetlands in that they are shallow endorheic basins which display marked fluctuations in water depth and duration. They are significant sites of local ecological diversity and particularly, an essential habitat for aquatic avifauna. In a review of pans as landscape features, pan morphology, initiation and propagation mechanisms and functioning as wetlands are discussed

The first step in building an inventory and classification of wetlands is the location of sites. Satellite imagery is ideally suited to mapping broadlevel landcover and landuse. In this study Landsat TM data and image processing techniques are employed to locate pans of differing sizes, morphology and vegetation structure in a pan-field in the North West province.

With the Landsat TM data available for this study it was possible to determine the location and type, the surface extent of pans, whether or not they contained vegetation and to what extent across their surfaces, and whether they contained water. It was not possible with the vintage of Landsat TM data used to determine the plant communities associated with the pans from spectral signatures of the vegetation.

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1 INTRODUCTION AND OBJECTIVES

The first step in building up an inventory and classification of wetlands is the location of sites. A technique or combination of techniques which can facilitate this process and contribute to management in southern Africa accurately, cost effectively, with the available manpower needs to be determined and implemented. Aerial photographs are presently the primary tool for operational wetland mapping and inventory programmes. Numerous, widely separated groups of investigators are attempting to take advantage of satellite repetitive wide-area coverage to meet the current needs for inventory and monitoring of natural resources, including wetlands.

Satellite imagery is ideally suited to mapping broad level land cover or landuse and was, in terms of terrestrial monitoring, developed primarily for this application. The type of classes that can be identified are directly dependent on the landscape in terms of size, form, and vegetation cover and the spectral and spatial resolution of the imagery. Current Landsat studies have provided many basic techniques for both manual and digital interpretations, with a shifting emphasis from wetland mapping to determination of wetland hydrology and quantification of wetland functional values.

Remote sensing is defined as the technique of obtaining information about objects through analysis of data collected by specialised instrumentation not in physical contact with the objects of investigation. As such, remote sensing can be regarded as reconnaissance from a distance. The present study is aimed at applying remote sensing methods and techniques to the detection and quantification of pans as landscape features in the North West province to obtain a reference site in a semi-arid, anthropogenically influenced landscape.

The type of remote sensing data used in this study is governed by financial constraints and data aquisition availability. The hypothesis on which this study is based is that Landsat TM has the spectral and spatial resolution to detect changes in vegetation and open water on a medium scale.

There exists an extensive literature on pans and related deposits (Harmse *et al* 1990), however, the fundamental reasons for the presence of pans in a particular landscape have been poorly understood. Furthermore, geological location, soil mineralisation and climatic factors have a fundamental bearing on the vegetation of pans. The following overview is aimed at providing a basic background to pans as features in the South African Landscape and enhancing the interpretation and understanding of the Landsat TM data presented in this study.

2 PANS AS FEATURES OF THE SOUTH AFRICAN LANDSCAPE (Fig 2 Map Pocket)

Shallow, basin-like depressions, either permanently or periodically inundated with water are an important landscape component of large areas of southern Africa and many of the world's arid zones.

Typical locations are the Texas High Plains of North America, western Australia, the Pampas of Argentina, the Pantanal of the Brazilian Mato Grosso (Klammer 1982), the fringes of the Indus Plain in Pakistan (Shaw and Thomas 1989). Terminology applied to these closed depressions include *sebkhas* of North Africa (Alia 1959), *playas* and *playa lakes* of North America and Australia (Cooke and Warren 1973), *plains* in Zambia (Williams 1982), *pans* in southern Africa. Shaw and Thomas (1989:185) give a broad geomorphological definition of pans and playas as:

'......arid zone basins of widely varying size and multivariate origin which, although generally above the present groundwater table, are subject to ephemeral surface water inundation, though periodicity and extent of inundation is highly variable. Their basal and marginal sediments often display evidence of evaporite accumulation, deflation and aeolian accumulation, and/or lacustrine activity.......'

Pans, in some areas can be extensive features such as those in the Lake Eyre basin in South Australia, the Makgadigadi pans complex of Botswana and Itundu Plain in Western Zambia. More commonly, individual pans occupy a small area of the landscape ranging from less than a hectare to a few hectares in extent but may occur in large numbers such as on the Southern High Plains of Texas and New Mexico, U.S.A., where there are over 25,000 playa lakes with an average size of just over 6 hectares (Shaw and Thomas 1989).

In southern Africa pans continue to be enigmatic as a feature of the landscape. They are widespread but not ubiquitous and occur on a large variety of surfaces and in diverse climatic conditions. Some pans are permanently inundated and others occur as ephemeral shallow water bodies. The water in these pans may range from shallow fresh ground water up to hypersaline brines. Pans are generally concentrated in areas which receive an annual rainfall less than 550mm and have a mean annual free surface evaporation loss of more than 1000mm (Le Roux 1978; Goudie and Thomas 1985), with notable exception of those in the Carolina-Ermelo area of the Eastern Transvaal, of which the permanent Lake Chrissie is probably the best known. These perennial water bodies, recognised as pans, extend into an area where the mean annual rainfall is about 750mm. At the other end of the continuum are the immense surface depressions of the Makgadigadi and Etosha pans which only occasionally contain water, and then on very limited parts of their total present-day extent (Verhagen 1991).

There are some major concentrations of pans in South Africa. In the western Free State there is a pan-field which extends southwards from Kroonstad, Wesselbron, Boshof and Dealesville to the south of Kimberly, with a pan density exceeding 1 per km² near Bultfontein (Figure 2, map pocket). North of this belt is another pan-field in the North West Province and Northern Cape Province where pan densities reach 1 per 0.5 km² are reached along the axis from Vryberg to Delareyville and Wolmaranstad (Shaw 1988). Two other groups occur in the Northern Cape Province: a belt to the south of the Orange River between Kenhardt and Brandvlei and a belt running northwestwards from Upington across the Molopo Valley into Namibia to the east of Keetmanshoop (Goudie and Thomas 1985) and the and in the Eastern Transvaal, the Lake Chrissie panfield.

2.1 Pan Morphology

Variability of pan morphology seems to be the norm but they do have some common features (Shaw and Thomas 1989):

1. Pans are features associated with areas of low topographic relief.
2. They lack surface water outflows (endorheic basins).
3. The basins are occupied, normally, by ephemeral water bodies.
4. Pans generally have flat surfaces.
5. Hydrologically, pan evaporation exceeds inputs of water.
6. Pan surfaces are either vegetation-free or characterised by distinctive, sometimes 'zoned' plant communities.

Pans and surface drainage tend to be mutually exclusive and Jaeger (1939) observed that a higher density of pans are often found on watersheds, in the early beginnings of surface drainage. Most pans in South Africa are sited on bedrock or on thin alluvium cover and consist of depressions in the underlying rock strata and contain argillaceous pan floor deposits (Versfeld and van Deventer 1992). Towards the west of the country the pan floors are calcareous and the pan margins usually contain extensive calcrete deposits which may be eroded into low cliffs. In the east of the country, with higher rainfall and greater vegetation cover, calcrete is mostly absent and bedrock outcrops often constitute the margins. The pans are generally vegetated on the margins and sometimes, also the pan floor, depending on the frequency and persistence of standing water. As the pan floor is typically impervious, rainwater will remain standing in a pan, forming an ephemeral surface water body. In areas of shallow ground water the pan can reflect the regional water table.

In plan most pans are subcircular, often with one side indented to give a kidney or clam shape. Elongated and linear pans are common where topographic controls are apparent, particularly in the presence of linear dunes as in Zimbabwe and the southwestern Kalahari (Shaw 1988). Beach ridges, common in the Makgadikadi-Okavango complex of central Botswana and fossil valleys termed *mokgacha* in the Kalahari also strongly influence pan shape. A characteristic of all pans, however is a flat basin floor within the depression. The depression may be up to 30 metres below the surrounding terrain with slope profiles strongly influenced by duricrust development.

Although pans occupy ancient geomorphic surfaces, it is not self-evident that soils, duricrusts and unconsolidated sediments are related to these periods of planation (Scott 1988; Scott and Brink 1992). The accumulation of parent materials, and especially the pedogenic processes operative in the pan environments, appear to be substantially younger than these planation episodes.

Verster *et al* (1992) established broad relationships between pan soils and environmental factors. Soil type is dependent upon the degree of inundation. Gleying is regarded as the predominant process, but decreases from high rainfall (Eastern Transvaal) to arid areas where clay illuviation resulting in diagnostic cutanic subsoils becomes the prevalent process. Furthermore, there is an abnormally high accumulation of organic matter in the topsoil of humid pan soils with a significant decrease in content towards the arid regions. The climate regulates the leaching of ions to such a degree that soils in the higher rainfall areas display less calcareous features than those in arid areas. The increase in the accumulation of salts on the surface, due to efflorescence, is also directly related to the aridity factor. Pan soils contain more salts and extractable cations than their associated valley-bottom equivalents because of the closed-system (endorheic) conditions operating in pan environments. These soils are derived from parent materials accumulated from fluvial, aeolian and colluvial (high rainfall areas) processes. Apart from the wetter regions, the contribution made by weathering of the parent rock is considered to be limited. The variability in textures of the pan soils and unconsolidated sediments indicates a cyclic deposition of pan sediments.

A common land form associated with pans is a crescentic lunette dune feature to the leeward side of pans. These are common in the southern Kalahari, Northern Cape Province and North West Province and are generally absent from the pan fields of Zimbabwe and Zambia (Goudie and Thomas 1985). The dunes may reach up to 60 metres above the pan floor, although relief in the range 10-20 meter is more common. Inner and outer dunes may occur with different sediment characteristics and triple dunes also occur such as at Koes Pan in Namibia (Lancaster 1986). In this type of series the outer pan is composed largely of sand with smaller clay dunes occurring closer to the pan where the adjacent pans have clay and salt beds, suggesting that the pans contribute little sediment to the dunes at present.

Many of the lunettes, particularly those associated with pans on the Ventersdorp Lavas in the North West Province consist of single ridges, contain multiple layers of aeolian sediments interspersed with calcrete layers. In fact, some lunettes such as Delareyville pan and Hartsfontein Pan are composed largely of calcrete. Such *calunettes* appear to be restricted to areas underlain by, or close to outcrops of Ventersdorp lavas. These lavas contain more calcium than do the Ecca sediments for example, and this probably accounts for their preferential development on this rock type (Goudie and Thomas 1985). The orientation of lunettes suggests that they are formed by deflation by prevailing winds during periods of greater aridity as there is little evidence for current deflation (Lancaster

1978).

Pans in low rainfall regions form alkaline environments with a high level of chemical activity represented by a range of conditions from calcic clay soils at one extreme to large-scale salt deposits at the other. The processes involved are evaporation from surface and subsurface waters and the activity of groundwater as a weathering agent on susceptible rock types (Shaw 1988) with duricrusts being a common manifestation of this type of environment.

2.2 Calcretes

Calcrete types encountered in association with pans cover the range from calcic soils to massive hard pan calcretes occurring as both precipitates and alteration products. Marshall (1990) suggests that there are only two basic types of calcretes of major importance in South Africa:

1. **Pedogenic calcrete** - a soil formed by a solution of carbonate from the upper horizons and the deposition in the lower horizons which undergoes all the soil-forming factors of climate, topography, parent material and time.

2. **Non-Pedogenic Calcrete** - can be considered as a geological horizon, formed chiefly by the deposition of carbonate in the saturated zone above a shallow water table. The most important mechanisms of calcrete deposition are evaporation, transpiration and carbon dioxide loss. Pure evaporation as a mechanism for water loss becomes ineffective when the water-table is deeper than 1-2 metres and is even less effective in sands and gravels. This mechanism cannot be responsible for the calcification of thick alluvial deposits. On the other hand, transpiration can remove greater quantities of water from the soil with its influence extending to much greater depths, for example 2-8 metres (Marshall 1990), depending on the nature of the roots responsible for transpiration.

Perhaps the most important mechanism for calcrete formation is the solution and precipitation of calcium carbonate during changes in pore-water pressure (Netterburg

1969). This is as a product of a water-table fluctuation which influences the solubility of calcium carbonate and as a consequence carbonate solution and precipitation can occur at any depth. With the scenario of water-table consisting of river water containing soluble carbonates which descends slowly over a period of time with fluctuating levels during the year, it is possible for this mechanism to calcretize any thickness of alluvium without any assistance from evaporation or transpiration.

Pedogenesis has acted on most calcretes formed by other processes and hence many calcretes are complex, being pedogenic and non-pedogenic in origin and may have also undergone more than one phase of calcrete formation.

Calcretes develop according to a well defined genetic sequence (Netterbug 1969). The mode of evolution in most soils is one of [illegible] alescing to form a honeycomb calcrete, the voids of which eventually fill [illegible] In a sandy or gravelly sequence nodules do not generally form and a ca[illegible] sand or gravel results which proceeds directly to the hardpan stage. The hardpan, [illegible] product of calcrete formation is ultimately sealed by a hard, thin, laminar crust. If they remain covered by soil, calcretes undergo a form of decomposition or dissolution of carbonate resulting in the formation of *makondos*, an advanced state of solutional weathering which may be infilled with later surface material and may or may not be subsequently recalcretised (McCarthy 1983).

Calcretes occur beneath pans often to great depths (Shaw 1988) and because of their relatively impervious nature they act as aquitards, creating perched water tables in many Kalahari pans. On the pan peripheries calcretes may form ridges and terraces which can extend several meters beyond the pan, usually along subsurface drainage alignment. Some of the higher-level pan calcretes of the Aminuis area of the Namibian Kalahari contain algal mats and stromatolites, suggesting an origin as spring tufas at points of high water discharge (Lancaster 1986).

Silcretes are encountered as layers or nodules within the calcrete as a product of direct precipitation or by calcium replacement eg Heuningvlei Pan in the Northern Cape Province and the Makadikgadi area in Botswana (Shaw 1988). Ferricretes, which are indicative of more humid conditions, are less common but may be encountered on slopes above pans as in eastern Botswana and the North West Province .

The major salts found in pans are sodium and calcium sulphates, sodium chloride and sodium carbonate, mostly as efflorescence at the pan surface or as a saline clay layer as in Soutpan north of Bloemfontein, for example. Less common are nitrates such as found in Matsap Pan in Griqualand.

3 PAN INITIATION MECHANISMS

The integrated model of pan formation of Goudie and Thomas (1985) combines the initiation and propagation mechanisms and presents them as a single genetic model without distinction. Marshall and Harmse (1992) favour a modified model distinguishing between pan initiation and pan propagation. They propose that three integrated mechanisms are responsible for the origin of pan fields and the localisation of individual pans within the field:

1. Suitable substratum: sediment, rock type or soil-forming processes.
2. Disrupted drainage: either tectonic or climate induced.
3. Geological structure: dolerite sills, fracture intersections, volcanism.

The above mechanisms are responsible for the initiation of a pan-field or an individual pan, to a greater or lesser extent, aided by the processes of pan propagation.

3.1 Substratum

Given a specific set of circumstances pans are more likely to develop where the substratum is easily weathered and contains a high proportion of dissolved salts. The lithologies that are most susceptible to pan formation are those which contain a high concentration of salts which may be leached and mechanically removed from the pan (De Bruiyn 1971). This explains in part the spatial distribution of pans on the Dwyka tillite and shale of the Karoo Sequence. The more homogenous of the Dwyka and Ecca sequences also appear to be conducive to pan development over the alternating sand and shale sequences of the Beaufort group (De Bruin 1971; Le Roux 19). Susceptible rock formations containing high levels of soluble salts are not restricted to sedimentary sequences as demonstrated by the pan fields evident on the Ventersdorp lava (Shaw 1988; Marshall 1990) and the Karoo dolerite sills (De Bruiyn 1971).

In the southeastern North West Province many small pans occur along interfluves between current drainage not associated with palaeodrainage. These surfaces display varying degrees of laterisation. On a lateritic surface, even one with an inverted topography, iron can be leached downwards from the overlying soil into the laterite horizon during surface lowering (McFarlane 1976). The impermeable hardpan laterite layer allows for the ponding of water and sediment and a pan begins to develop. Differential erosion of surrounding, more easily weatherable material may result in an inverted topography with the pans located on top of positive topographical features.

Pan belts in Botswana and the Northern Cape Province are mainly associated with the Kalahari sand and the Ecca shale and sandstone (Lancaster 1978; 1986). The accepted explanation is that unconsolidated nature of the material and the tendancy for fines to migrate to topographic lows and forming impermeable layers (Shaw 1988; Lancaster 1978). Shaw (1988) further suggests that groundwater seepage occurs in the pre-Kalahari bedrock (mainly Karoo sequences) along subsurface aquiducts and this, in conjunction with lithological considerations leads to the localisation of pans.

Karst landscapes display closed depressions which may or may not contain water. Dolomite and limestone are susceptible to corrosion and subsidence, forming dolines which may in turn form pans as seen in the North Western Province (Lichtenburg area). The surface expression of swallow holes may also be in the form of a pan.

The fact that a suitable substratum is present is not sufficient reason for a pan or pan field to develop. It seems that a complex interplay involving water flow (surface or subsurface) and geological structure is a prerequisite.

3.2 Disrupted Drainage

It has long been recognised that some pans are preferentially orientated along disrupted drainage lines by mechanisms such as sand accumulation and river piracy (Geyser 1950; Wellington 1958). More recent studies have confirmed that the pans of the northern Free State (Grobler et al. 1988; Marshall 1987, 1988) and the southeastern North West Province (Marshall 1990) are a product of tectonic and climatic disruption of tertiary drainage systems. Prior to the formation of pans, the northern Free State was affected by Miocene (Post-African 1) and Pliocene (Post-African 2) tectonic movements along the Griqua-Transvaal Axis (Marshall 1988). Together with climatic changes, lowered rainfall and or temperatures, changes in the hydrodynamic equilibrium of the palaeodrainage system were initiated from degrading to aggrading. The prevailing northwesterly winds removed loose dry sediments producing deflation hollows and a centripetal drainage system would start to form towards these depressions, initially aligned parallel to the stream at each point. Along other parts of the stream calcrete may develop as the result of excessive evaporation over infiltration down the original stream course. This process would continually promote the formation of calcretes which can be used to detect the nature of the palaeodrainge system.

The pan-fields of the Northern Cape Province can also be attributed to the disruption of palaeodrainage lines by climatic and tectonic processes. The Koa, Sak, and Hartebees valleys have been ascribed by Dingle and Hendey (1984) as late Cretaceous-Miocene drainages which have been successively abandoned by the Orange River system through river capture. Pans occurring in these abandoned drainages such as Bosluis pan, Van Wyksvlei and Brandvlei all display evidence of a desiccating climate in the Miocene (Marshall and Harmse 1992). Studies by Brown et al. (1990) and de Wit (1988) indicate that uplift occurred along the west coast at about the same time as the break-up of West Gondwanaland. This uplift was followed by extensive regional denudation of up to 3000 metres in the early Cretaceous. Since the end of the Cretaceous relatively little denudation appears to have occurred inland of the escarpment. This attributed to a significant decrease in the rainfall during the Tertiary (Dingle and Hendey 1984). A scenario is proposed that under such dry climatic conditions standing pools of water in the abandoned reaches of the early Createceous drainage system could develop into pans. At Brandvlei, it is interesting to note that the fluvial deposits are developed on Dwyka rocks - a substratum which is easily weathered and contains high concentrations of salts. This is conducive to groundwater seepage (Marshall and Harmse 1992). The origins of pans in the Lake Chrissie district of the Eastern Transvaal can also be ascribed to the interplay of tectonic disruption and susceptible substratum. The pan floors consist of coarse feldspathic sandstones belonging to the Karoo sequence (Shaw 1988) and occur to the west of the Great Escarpment on what is thought to be the African surface (Lageat and Robb 1984). This area now represents a major watershed between the drainage towards the Komati River to the north and the rivers which drain south towards the Great Usutu River. The westernmost pans of the Lake Chrissie area are recognisably part of a disintegrating drainage system but this relationship becomes less obvious the further to the east ones moves. It has been suggested that the Lake Chrissie pans are the remnants of the drainage on the African surface that has been tectonically disrupted by the flexural bulge of the Great Escarpment. As the bulge retreats the gradients of the headwaters of the southwestwardly flowing rivers are flattened and the streams are finally beheaded. The scenario again is that standing pools of water occur in the easily weathered Ecca lithologies and pan development is initiated. The relatively high rainfall of this region ensures that the pans are usually filled with water for most of the year (Marshall and Harmse 1992).

3.3 Geological Structure

Tectonic disruption of a pre-existing drainage system, suitable substratum together with climatic changes are the major reasons for the initiation of a pan field. Geological structure plays an important role in the localisation of individual pans within any field.

Pans generally occur on lithologies that are easily weathered (De Bruiyn 1971) and this observation can be taken a step further in that pans will preferentially occur where the landsurface is most susceptible to weathering. Such loci are most likely to be at fracture, fault or dyke intersections for the following reasons:

1. The rock is already weakened at this point and susceptible to further weathering.
2. Ground water throughflow is concentrated at these points enhancing decomposition and mechanical erosion.
3. This accelerated weathering leads to the liberation of salts which, in turn, encourages further weathering.

This type of structural control of pan distribution has been shown to be the case in the southeastern North West Province (Marshall 1990). Most of the pans occur within palaeodrainage channels and those that do not are, for the most part, the products of laterisation or plinthic development. The pans within the drainage channels are described as occurring along structural lineaments and preferentially at the intersection of two or more such lineaments. The term, lineament, is a loose one and with a field check can probably be identified as a fault or fracture. Examples are Zoutpan, Spinnekop Pan and Zevenfontein Pan. Five lineaments intersect under Spinnekop Pan which always contains water even during the driest periods. The fractures weaken the already susceptible substratum (Spinnekop Pan occurs on Ecca Shales; Zoutpan and Zevenfontein Pan on Ventersdorp Lava); underground throughflow enhances weathering and the release of salts and thereby promotes pan development at these loci (sodium chloride and sodium sulphate are mined at Zevenfontein Pan).

Other pans which have a structural control are those of the Wesselbron panfield. The maximum extent of this pan-field appears to be developed over a peripheral graben on the northern flank of the Wesselbron dome. This also coincides with the most disrupted portion of the Wesselspruit palaeodrainage system (Marshall 1987).

Pans also develop in the presence of dolerite basin structures (sills/sheets) which, due to the resistance of dolerite to weathering, lead to the development of local centripetal drainage patterns (De Bruiyn 1971). Water accumulates in these basins and dissolved salts are concentrated when the water evaporates. This in turn causes mechanical weathering of the overlying sediments due to crystallisation and thermal expansion, enhancing the erosion processes (Marshall and Harmse 1992). Examples of these pans occur in the western Free State (Petrusburg area) preferentially where dolerite basin structures are overlain by Karoo shales and sandy shales that have high soluble salt concentrations.

To summarise, pans, whether isolated or within pan-fields are initiated by an interplay of three mechanisms:

1. A suitable substratum has to exist - the lithology has to be susceptible to weathering and must preferably contain soluble salts that can aid in the chemical and mechanical weathering and erosion of the rock.
2. A disrupted drainage on a flat surface - tectonic and climatic factors may combine to produce a desiccation of a drainage system and the subsequent ponding of waters to form pans. Deep weathering along subsurface flow paths also contributes to pan initiation.

3. Geological structures such as fractures, faults or dyke intersections promote the weathering of certain portions of the landsurface and are often responsible for local distribution of pans in a pan-field.

4 PROPAGATION OF PANS

Once a series of pans has been created by one or a combination of the initiation mechanisms they may become infilled with sediment over a fairly brief span of time and cease to be active landscape features. On the other hand a pan may continue as an active landscape element for millennia by propagating itself in one or combination of ways. Marshall and Harmse (1992) have concluded that many of the mechanisms of origins of pans as described by different authors are in fact ways in which pans propagate and remain features of the landscape. There does not appear to be consensus on these mechanisms but it is clear that not all pans propagate by the same mechanisms.

4.1 Lithological Model

De Bruiyn (1971) proposed that lithology was the key factor in pan formation (propagation). He felt that a correlation existed between the occurrence of dolerite dykes and sills that have intruded into Karoo shales and sandstones and the occurrence of pans in the western Orange Free State. Although this model may explain the occurrence of pans in this area, it is not applicable to many other geological settings.

4.2 Deflation Model

Several authors - Rogers (1934), Van Eeden (1955), Le Roux (1978) - considered that wind deflation was the major element in pan formation and propagation. Lancaster (1978b) felt that wind deflation is the mechanism by which blowout hollows and eventually pans developed in the Kalahari. The occurrence of lunette dunes on the downwind side of many pan floors tends to substantiate this theory. However, again this probably a mechanism by which pans are propagated rather than a means by which they were initiated.

4.3 Biogenetic Model

Alison (1899), Laloy (1909) and Passarge (1911) thought that the vast herds of game that roamed the African continent not so long ago had a major impact on pans that they visited. These pans provided water as well as a salt lick (le Roux 1978). The idea was that excavation of these pans took place through trampled mud clinging to the hooves and flanks of migrating animal. Le Roux (1978) thought that the trampling of the pan floor by herds of animals prepared the pan surface for wind deflation. Geyser (1950) largely refuted this thinking as he found no pan with a sticky clay base and it seemed impossible that animals could have carried large amounts of mud from pan floors by their hooves. The present line of thinking is that such a mechanism of pan propagation could not been a very active one (Marshall and Harmse 1992). However, it is not an idea that should be totally discarded as one tends to view the landscape and its processes as we see it today and not in the millennia gone by and its wealth of mobile game.

4.4 Multiple Models

To explain the wide variety of pans found combined mechanisms of pan propagation have been proposed. For example Schmitz and Harmse (1990) investigated the pans of the northwest Orange Free State before and after the local floods of 1989. They concluded that during dry spells wind deflation plays an important part in excavating pan floors. However, during exceptionally wet periods the pan systems exhibit all the properties of a lacustrine environment with sediments being moved by a fluvial rather than aeolian mechanisms.

4.5 Ecological Model

The ecological model of Verhagen (1991) is probably the most plausible to date in terms of propagation of pans in southern Africa because it incorporates elements of cyclicity and thus different processes by which to account for many different types of pan.

Verhagen devised his model through his observations of pans in southern Botswana on the Kalahari deposits together with the behaviour and excavating activity of domestic animals around boreholes. This model could be applied to pans elsewhere.

1. He states that where superficial (Tertiary Kalahari) sediments accumulate drainage interruption will form isolated depressions in which water collects through surface runoff. Weathered clay accumulates in the bottom of these depressions and shallow

ground water seepage cause calcretes to form in the margins and the floor, decreasing its permeability. Salinity and alkalinity in the standing water body increase due to evaporation. Perched ground water conditions develop as the thickening calcretes become aquitards. Animals congregate around the bare clay pan for water and surface salt licks and in dry periods dig into the floor or pan edge to obtain water which in turn becomes increasingly saline.

2. Verhagen continues the scenario by stating that with prolonged drought conditions, loose pan material would be deflated by the prevailing wind and deposited as lunette dunes. Calcrete would continue to be deposited by producing an increasingly permanent landform. The increasing salinity of the water would make the pan less attractive as a watering place. During wetter periods the salinity may rise to unacceptable levels when perched saline water rises to the surface. Eventually the saline pan is abandoned as new migration routes are sought.

3. Verhagen proposes as the next phase of the cycle, in the absence of animals churning up the pan and its surrounds, the gradual re-colonisation of vegetation at the pan margins and eventually the pan floor. Soil formation and humus production would then commence on the pan surface. The soil water would become increasingly acid which would leach solution channels into the floor and sides of the pan, allowing perched water to infiltrate to greater depths. Over time the salinity would be reduced, further stimulating plant growth, reducing the deflation of the pan by the wind. the overall morphology of the depression remains unaltered, although the profile will be less pronounced as the pan fills with sediment. Standing water can remain on the argillaceous sections of the pan floor. The pan is no longer frequented by herds, except for casual grazing by individuals or small groups of animals. The main watering place is now some other pan which is under going the same cycle of denudation and salination. Gradually the freshwater pan may be rediscovered and another cycle of denudation and salination initiated. These developments may take the order of many centuries or millennia. It is quite feasible that a pan may disappear altogether if 'rediscovery' fails to take place.

A pan or pan field once initiated has to be propagated through time and may survive through successive erosion cycles to remain a landscape feature. Verhagen's (1991) ecological propagation model presents itself as the most viable one to date to explain the persistence and variation in the appearance of some pans. However, with the loss of the vast migrating game herds, wildlife in general, and a change in landuse over much of the southern African landscape, it is a matter of speculation as to the fate of many of the pans detectable as landscape features at this point in time.

5 WETLANDS

The RAMSAR Convention definition of a wetland is extremely broad and incorporates the following:

'...... areas of marsh, fen, peatland or water whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine waters, the depth of which at low tide does not exceed six metres and may incorporate riparian and coastal zones adjacent to wetlands and may incorporate riparian and coastal zones adjacent to the wetlands and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands.'

Wetlands are subject to considerable temporal and spatial variation. They occur over a variety of sites, from the tops of mountains to mud flats at sea-level, and are subject to differing climatic, hydrologic and topographic influences. They all have one or more of the following features in common (Mitsch and Gosselink 1986):

1. Soil that is at least periodically, saturated with water.
2. Soil within which reducing conditions prevail.
3. Impeded drainage.
4. A characteristic position in the landscape.
5. Distinctive plant communities.
6. Distinctive animal communities.

5.1 Pans as Wetlands

Pans are shallow endorheic basins which display marked fluctuations in water depth and duration of inundation (Goudie and Thomas 1985) and are significant sites of local ecological diversity and particularly, an essential habitat for aquatic avifauna. In arid and semi-arid regions life in temporary waters is characterised by a lack of fish predators and by organisms with life-histories which enable communities to survive extended periods of drought. As temporary water bodies vary considerably in size, period of inundation and water quality, it is to be expected that their animal communities will also vary in composition, diversity and life history. Furthermore, many of the organisms will be specific to the geographical region being studied (Seaman and Kok 1987).

Pans as wetland ecosystems have three limnological characteristics which are major factors in determining their response to the input of water, light, nutrients and pollutants. Rogers *et al* (1989) summarised these factors as follows:

1. As a result of the surface area to volume ratio of pans being large, their capacity to buffer the effects of environmental factors which act over the surface is limited. Pan ecosystems are therefore subject to marked fluctuations in light, temperature and high evaporative water loss. Wind action has a pronounced affect, causing frequent resuspension of sediments creating changes in oxygen, pH and nutrients in the water body.
2. Depending upon the type of pan and length of inundation, the ratio of the littoral zone, to the pelagic zone is high and benthic algal and aquatic plant communities generally dominate, providing potential habitats for aquatic, amphibian and avian fauna.
3. The endorheic nature of pans means that allochthonous inputs into the water body will accumulate rapidly as there is no discharge downstream. Pans are therefore sensitive to eutrophication in particular and pollution in general.

Seaman and Kok (1987) demonstrated the ecological diversity in Free State Pans and came to the following conclusions, summarised as follows:

1. Free State pans are characterised by great diversity in size and mean physical and chemical values.
2. Within each inundation there are large changes in physical and chemical conditions.
3. Although pans are generally different, they often share similar conditions for short periods.
4. Pan communities share many taxa with permanent water bodies.
5. The pans are devoid of fish.
6. Organisms characteristic of pans share either the inability to withstand predation

by fish or the ability to reproduce rapidly and produce dessication-resistant resting stages, or both.

7. Pans with 'short' inundation periods share organisms with those having 'long' inundations.
8. Pans with 'long' inundation periods have a greater diversity of species than those having 'short' inundations.
9. Organisms in 'short' inundation pans are more rigoroursly selected for their opportunist and survival abilities.
10. Certain organisms, notably the *Eubranchiopoda*, are characteristic of pans.

Changes in activity in the pan catchment, particularly those which affect water depth, will act through these factors to initiate changes in the biotic and abiotic nature of pan ecosystems. Furthermore ...gers *et al* (1989) suggest that the major determinants of the abundance and wide variety of aquatic birds which utilize pans is a product of the diversity of pans in both space and time and the major threat to avifauna of pans is that of water level stabilization as a result of man's activities in the catchment. The range of habitat conditions will be reduced in both space and time and so too will the range of avifauna that will visit the ecosystem.

6 STUDY AREA (Fig 2 Map pocket, Fig 6 Map Pocket)

The study area is centred on Barberspan in the North West Province, extending some 25 km west towards Geysdorp and northwest into the old Kunana Tswana location. It lies on the andesitic to basaltic lavas of the Ventersdorp Supergroup on a Post-African Phase 1 geomorphic surface and is characterised by a lack of prominent streams and a multitude of large and small pans. The landscape and drainage features of the area are attributed to crustal movement associated with the Griqualand-Transvaal Axis of uplift towards end of the Tertiary Period. The development of this axis along a north-east - south-west Precambrian Lineament which now forms the divide between the Harts and the Skoonspruit Drainage and the Vaal River, produced an oblique crustal tilt causing the disruption of the palaeo-Nossob, the palaeo-Dry Harts and the Palaeo-Harts Rivers (Mayer 1973) (Figure 2, map pocket).

The area northwest of the upper Harts River is characterised by two distinct lines of large pans: one is the Barberspan-Manuni pan-line and the other the Riet Pan-Geysdorp line (Figure 6, map pocket). The gradients along these two lines connecting the pans are practically zero and is manifest in times of flood when the Harts River rises, and there is a reversal of drainage so that the water from the river flows into Barberspan. Mayer (1973) postulates that as the pans along the Barberspan-Manuni Pan line and the Riet Pan-Geysdorp line lie in broad open, but distinct valleys, they were most likely former drainage lines which were eroded by water and the greater width of the Barberspan-Manuni Pan valley suggests that it was eroded by a major stream. The conclusion drawn is that the Barberspan-Manuni Pan Line was once the main river course of a former or palaeo-Harts system and the Riet Pan-Geysdorp line was one of its western tributaries. This would imply that the present main stream of the Harts River between Lichtenburg and Barberspan was an eastern tributary of this former or palaeo-Harts system.

Figure 6 is 7, 4, 2, (RGB) band combination of scene WRS - 172-78D (southeast quadrant) acquired on 03. 12. 86, scale 1: 325 000; see also Figure 2. The scene clearly depicts the present day course of the Harts and Klein Harts Rivers draining from the northeast and southwest in a southerly direction. The Riet Pan-Geysdorp pan-line in the south west corner of the image and the Barberspan-Manuni pan-line extending to the north of Barberspan can be easily picked up. With this band combination, vegetation is depicted as green, water as blue, soils as reddish tones through to white. The darker reddish hues in the northeast and northwest of the scene are most likely to be a rainfall response (see chapter 7 for explanation of Landsat TM band responses). The vegetated drainage courses of the headwaters of the Molopo River can be seen in the northwest corner of the scene indicating a change in direction of drainage to the northwest. This scene also demonstrates the characteristic distribution of the pans in this area. The large pans, many with calunettes on their southeastern fringes (detectable as a paler-hued signature) occur as strings in the palaeodrainage courses of the Harts River. Scattered across the landscape on the interfluves between present and palaeodrainges, visible as circular greenish specs in the cultivated lands, are numberable smaller pans or depressions which appear to show a vegetation response across their entire surface. The general size, morphology and distribution of pans is very different to that of the Free State pan field (Figure 2).

To explain the present-day physiographic character of this area Mayer (1973) suggests that the former main course of the Harts River (Barbers-Manuni Pan line) and its western tributaries (of which the most distinct relict at present is the Riet Pan-Geysdorp line of pans), were beheaded in their upper reaches by tributaries of the Molopo River, which by headward retreat, actively eroded towards the south-east and cut into the general level of the original Harts drainage surface (Figure 2). Furthermore, the larger pans, which are strung in definite lines in the Delareyville district possibly developed from a series of standing pools which marked the low-gradient down-stream sections of the main course of the palaeo-Harts River and its western tributaries, after truncating of its headwaters. During arid periods these pools must have dried up and become prone to wind erosion. This resulted in their gradual enlargement and the accumulation of calcareous material blown from the pans which have in time built up low rounded hills (calunettes) on their southern perimeters.

6.1 Barberspan

Barberspan, 26^0 35' S, 25^0 35' E, lies in an area characterised by the absence of any marked physiographic features, and is generally gently undulating or very flat farming land, characterised by extensive mealie lands with hills seldom rising more than 130m above the surrounding flats. Barberspan is a nature reserve, 3118 ha in extent, of which about 1750 ha is water surface at high water. The pan is connected with the extant Harts River via a channel. The pan itself is about 2.5km at its widest point by 5km in length. The 1:50000 topocadastral map of the area shows the maximum floodline of the pan to be 4km wide and 6km in length. Barberspan lies near the commencement of the fossil course of the Harts River which can be traced northward by a series of pans for a further 45km terminating at Manuni pan. Although at a lower elevation and adjoining the flood plain of the Harts River, Barberspan did not receive water along the fossil course except in peak floods because of a limestone obstruction, and the Harts water went past Schweizer-Renecke to the Vaal (Milstein 1975).

In 1918 General J. C. Smuts was responsible for diverting the Harts River into its fossil course. This was achieved by the construction of a still visible stone wall (4.3m long and 1.2m high) blocking the current course of the river, and the removal of the 50m limestone obstruction in the fossil course. The first subsequent flood by-passed a sluice intended to control it, and commenced enlarging the fossil course into Barberspan. Von Backstrom in 1963 estimated the enlarged channel to exceed $14m^3$/sec. Since this diversion Barberspan has never dried up, the last occasion being in 1913 (Polderman 1945). It now has first call on the upper waters of the Harts River, although during peak floods, when the river flows in places only a few centimetres deep and 5km wide, much water flows past to Schweizer-Renecke.

Barberspan's own catchment area is 39 k^2 with a run-off of only about $77610m^3$ per year (Von Backstrom 1963), while an average flow of over 60 times as much reaches it annually from the Harts River. Local rainfall consequently seems to be of minor importance to the water level in the pan. The system is essentially endorheic, however Barberspan is connected to the next pan in the series, Leeupan, by a shallow channel, into which it overflowed in 1943 and 1967, through a shallow channel. Water has been prevented from pushing past Leeupan this century by a limestone obstruction; thus all water entering these pans is lost by seepage or evaporation. Barberspan is now a perennial, shallow, alkaline body of water. Other pans in the area are non-perennial. It is one of the few permanent natural waterbodies on the western highveld and provides food and shelter during the dry months for large numbers of waterfowl. Migrating aquatic species use the pan as an important stopover. Almost 300 species of birds have been recorded here, about one-fifth being migrants. A research station was established in 1952 but is no longer operational. Approximately 4000 birds of 190 species were ringed annually for study of their distribution and migration. The pan is also a popular angling resort and recreational area in the North West Province..

6.2 Geology and Geomorphology

The prevailing northern winds have played an essential role in carving out Barberspan and Leeupan, blowing pan limestone into hills south of the pans, 24.4m and 23.2m high respectively (du Toit 1954), though trampling by herds of game were possibly contributory. Barberspan is the largest of a series of pans on the fossil bed of the Harts River. The reserve is underlain by amygdaloidal lava of the Ventersdorp System (2100 million years). This is covered by surface limestone (100 million years) and classified as vlei or pan limestone according to origin. The quality varies from pure limestone to calcrete which is hard and massive on the surface but soft and granular beneath the crust.

6.3 Soil Type and Chemistry

Soils are shallow, alkaline and calcareous with sandy patches in certain areas. Mispah forms predominate in the reserve, while Katspruit forms are found near the water (Milstein 1975).

6.4 Water Quality

The water of the pan is reasonably clear with marked increase in clarity in winter. The pH averages 9. 4 over a range of 8.2 to 9.8. Surface temperatures vary from 15.0 ^{0}C to 17.2 ^{0}C in June and from 24.5 ^{0}C to 31.0 ^{0}C in December. The depth varies from 5m to 9.5m flooding an area of 1000ha to 1700ha. The storage capacity varies according to depth from 33000m^3 x 10 to 96000m^3 x 10.

6.5 Climate

Situated in the summer rainfall region, the pan and its catchments receive their rains during the hot summer months and experience cool dry winters. The rainfall over the entire catchment averages 557mm per annum. The annual average temperature range varies between $9^{\circ}C$ (minimum) to $27^{\circ}C$ (maximum). According to the Koppen climate classification, Barberspan's climate can be coded as BSK referring to an arid zone with an average temperature below $18\ ^{\circ}C$.

6.6 Vegetation

The vegetation around Barberspan falls within the Dry Cymbpogon-Themeda veld as classified by Acocks (1975) of which very little remains. Relatively few naturally occurring shrubs and trees are found on the reserve. At present 60% of the reserve is made up of old lands in various stages of succession. Few naturally occurring trees and shrubs are found on the reserve. The most common are:

> *Acacia karroo, Rhus lancea, Rhus pyroides, Diospyros lyciodes.*

Common grasses are:

> *Themeda triandra, Cymbopogon plurinodes, Eragrostis lehmannia, Eragrostis superba, Heteropogon contortus, Lippia scaberima.*

Aquatic vegetation is dominated by :

> *Potomageton pectinatus* with other species including *Ceratophyllum demersum, Lagarosiphon* sp. and *Ludwigia* sp.

The pan supports a rich plankton community.

The pH of the water ranges between 9.2 and 10.4. This hampers the growth of higher vegetation which is usually present in the littoral zone of fresh waters. The vegetation of this zone is predominantly sedges (*Juncus, Eleocharis* and *Cyperus* spp). These grade into small prostrate herbs on the exposed shore and then into open grassland t[illegible]al of Mispah soils. In shallow water areas, thick stands of the grass *Panicum repens* provide cover for birds during times of flood and the limestone outcrops support an abundance of *Cynodon dactylon.*

Numerous shallow pans of varying size occur on the landsurface between fossil and extant drainage channels and these consist mainly of depressions vegetated with grass communities or a mixture of grass and forbs which fill with water to greater or lesser extent. Their presence is more enigmatic and can probably be ascribed to underlying geological structures and soil type. Many of these pans occur in cultivated mealie lands and may or may not be fenced off. They remain as landscape features because in many cases the pan soils are too hard to plough through. Furthermore, depending upon the location, the pans are used for grazing of livestock as some of the newly flushed grasses appear to be palatable, for example, the Kalahari pan grass. The pans are very variable in their ability to retain water but when water-filled, depending on the vegetation they support, they provide sites for avifauna such as the Spurwing Goose.

6.7 The Harts River Floodplain

The Harts River meanders through its floodplain in a west south west direction from its junction with the Klein Harts to its junction with the bed of the palaeo-Harts (the channel to Barberspan). The width of the flood plain is about 2000 metres, narrowing to about 400 metres at road 657. It then fans out to a width of about 4000 metres at road 140. Here the river changes course and flows south. Some 200 metres west of road 657 the main channel swings sharply to the right to flow down the middle of the widening plain to join the palaeo-river bed on the way to Barberspan. A secondary channel a metre or so deep branches off the river at this point to flow along the left bank of the river until high ground diverts it back to the plain where it again joins the main channel. The two channels described are linked by three or more shallow runs with a final link near the fossil bed of the river where it joins the pan. This link channel is also deep enough to draw water from the main channel and Barberspan but it has been sealed off by a stone dike constructed by Nature Conservation. It is at this point that the furrow excavated by J. C. Smuts is to be found. It increased the flow to the pan and reduced the loss through the link. The river bed lies some nine metres above the bottom of the pan and gravity will flow to the pan.

When the flood plain is first submerged after a dry period, the following birds have been observed (Morgan 1989):

Herons, Egrets and Sacred Ibis in large numbers, Spurwing Geese and Knobilled Duck and Glossy Ibis. They follow the advancing waters and stay only a short while. Coot, Moorhen and Gallinule come in undetermined numbers and some stay to breed.

The floodplain drains quickly into the deeper main channel and dries up. Vegetation growth is dense with Quail species nesting. Neither Francolin or Guinea Fowl were reported as being seen. The commonest birds in long grass were Desert Cisticola, Quail Finches and Longclaws. River pools occur some three metres below ground level and the banks are often vertical. Duck, grebes, cormorants and Glossy Ibis appear in small numbers. When and while the flood plain is wet the bird populations are significant. When dry, the grass communities are grazed by cattle.

7 LANDSAT TM AS A REMOTE SENSING PLATFORM

Although astronaut spacecraft programmes have provided photography of the earth's surface, the bulk of remote sensing data has been obtained from earth observation satellites carrying electro-optical sensor systems (Lillesand and Kiefer 1987). Landsat represents the first international satellite programme designed specifically for collecting synoptic and repetitive multispectral image data of the earth's surface that could be used to analyze and monitor the world's resources and environments. It was initiated by NASA with an 'open skies' policy, meaning that images would be acquired on a worldwide basis and users from any country would have access to any of the collected data. To date there have been five satellites in the Landsat series, one of which is still operational. Three types of sensors have been used in various combinations on the five Landsats:

1. Return Beam vidicon (RBV) camera (Landsats 1 and 2 - not used)
2. Multispectral Scanner (MSS)
3. Thematic Mapper (TM)

Landsats 1 to 4 are defunct. The orbit of Landsat 5 is near polar and sun Synchronous with a nominal altitude of 705km, with a ground resolution of 30m for the Thematic Mapper. It accquires data from seven bands within the electromagnetic spectrum: three in the visible part of the spectrum, one in the near infrared (IR), two in the short-wave IR, and the last in the thermal part of the IR. The satellite's sun synchronous orbit has an ascending night-time trajectory with a southern hemisphere over-flight at about 10am local time. Bands 1 to 5, and 7, have a ground cell-size of $28.5m^2$; while band 6 detectors in the ground projection cover some $114m^2$. There are sixteen detectors for each of the bands 1 to 5, while band 6 has four on the primary plane (Avery and Berlin 1992).

7.1 Multispectral Scanner

The MSS is an across-track scanner device carried by all five Landsats. The MSS collects earth-reflected radiation in four contiguous spectral bands between 0.5 and 1.1 μm. Two numbering systems are used to designate the four bands. What are known as MSS bands 4, 5, 6, and 7 for Landsats 1, 2, and 3 are called respectively MSS bands 1, 2, 3, and 4 for Landsats 4 and 5. The former numbering system remains in place for identifying MSS images from the earlier satellites. The MSS was the primary or lead sensor on the first three Landsats (Avery and Berlin 1992).

The MSS incorporates six detectors per band at the focal plane (24 detectors). For each sweep of the collection mirror, six lines are scanned simultaneously in each of the four bands; image data are only recorded during the eastward sweep of the oscillating mirror. The across track swath is 185km wide and perpendicular to the orbital path. The forward motion of the satellite provides the along-track build up of scan lines. For the first three Landsats, the angular field of view (AFOV) for the MSS was 11.58°. However, the AFOV was increased to 14.9° for Landsats 4 and 5 in order to maintain the nominal 185km swath width (altitude changed from 915 to 705km). The instantaneous field of view (IFOV) for the MSS on the earlier satellites was 0.086 mrad; this yielded a ground resolution cell measuring 79m x 79m (determined from pre launch Keplerian geometry). The IFOV of the MSS on Landsats 4 and 5 was changed to 0.116 mrad, which produces an 82m x 82m ground resolution cell (Markam and Barker 1983).

Radiance data are collected by the MSS along a ground track at a fixed width or swath. Once telemetered to the ground stations, The MSS data strips are 'framed' into individual scenes that cover a nominal ground area measuring 185 x 185km. A standard MSS image deviates from a rectangle by the distance the earth rotated beneath the spacecraft during the 25 seconds the data were being collected from the top to the bottom of a MSS scene. As a result, the image incorporates rotational skew and is represented as a slanted parallelogram.

Table 7.1 Characteristics of the Landsat Multispectral Scanner (adapted from Lillesand and Kiefer 1987).

Landsats 1 - 3	Landsats 4 - 5	Wavelength Range (μm)	Spectral Location	Landsats 1 - 3 (resolution)	Landsats 4 - 5
Band 4	Band 1	0.5 - 0.6	Green	79m	82m
Band 5	Band 2	0.6 - 0.7	Red	79m	82m
Band 6	Band 3	0.7 - 0.8	Near IR	79m	82m
Band 7	Band 4	0.8 - 1.1	Near IR	79m	82m

The MSS on Landsat 3 contained a thermal IR band but it was never operational.

A summary of responses of each MSS band to various surface materials are as follows (band designations are for Landsats 1 - 3):

1. Band 4: most useful for studying water features. It has greatest depth penetration in clear water of the four MSS bands and it is sensitive to turbidity (suspended sediments) and pollution patterns. A major drawback is its sensitivity to atmospheric haze, which causes band 4 data to have limited quantization levels.

2. Band 5: spans one of the chlorophyll absorption regions and thus shows good contrast between vegetated and most non vegetated surfaces. Haze penetration is better than for band 4, but water penetration is significantly less. Band 5 provides a good spectral region for differentiating silt-laden and clear water and many natural and cultural features.

3. Band 6 and band 7: Spectral responses in the wavelength regions represented in band 6 and band 7 tend to be similar for most surface features. They are responsive to the amount of vegetation or biomass present in a scene; this can facilitate the identification of different crop and timber types, or discriminating planted and natural vegetation. Band 6 and 7 images accentuate the contrast between land water surfaces because water is a strong absorber of IR radiation an

moist ground registers in darker tones than dry land. Both bands have good haze penetration ability. For visual interpretations, band 7 images are usually preferred over band 6 images because they show greater tonal contrast.

Certain surface materials have similar spectr. responses over the wavelength interval of the four MSS bands, causing them to appear in similar tones in each image, for example clouds and dry snow are rendered in light tones whereas young volcanic features and asphalt register in dark tones.

7.2 Thematic Mapper

The lead sensor carried by Landsats 4 and 5 is the Thematic Mapper (TM). Although relying heavily on the technology of the MSS, the TM incorporates improved resolution, additional spectral bands, higher radiometric sensitivity and improved geometric fidelity over its MSS predecessor. TM is designed to operate simultaneously with the MSS. The thematic mapper (Lillesand and Kiefer 1987) spectral band are summarised as follows:

1. Band 1., wavelength (WL), 0.45-0.52 nanometres., nominal spectral location (NLS) - BLUE
   Designed for water body penetration - useful for coastal water mapping. Also useful for soil/vegetation discrimination, forest type mapping and cultural feature identification.
2. Band 2., WL 0.52-0.60., NSL - GREEN
   Designed to measure green reflectance peak of vegetation for vegetation discrimination and vigour assessment. Also useful for cultural feature identification.
3. Band 3., WL 0.63-0.69., NLS - RED
   Designed to sense in a chlorophyll absorption region, aiding in plant species differentiation. Also useful for cultural feature identification.
4. Band 4., WL 0.76-0.90., NLS - NEAR-INFRARED
   Useful for determining vegetation types, vigour and biomass content, for delineating water bodies, and for soil moisture discrimination.
5. Band 5., WL 1.55-1.75., NLS - MID-INFRARED
   Indicative of vegetation moisture content and soil moisture. Also used to

differentiate snow from clouds.

6. Band 6., WL., 10.4-12.5., NLS - THERMAL INFRARED

   Useful in vegetation stress analysis, soil moisture discrimination, and thermal mapping applications eg thermal pollution in water bodies.

7. Band 7., WL 2.08-2.35., NLS - MID-INFRARED

   Useful for discrimination of mineral and rock types. Also sensitive to vegetation moisture content.

Bands 6 and 7 are out of wavelength sequence because band 7 was added to the TM after the original system design process.

For the six non-thermal bands, 20 different 3 - band colour composite images can be produced. A colour infrared composite is generated by projecting band 2, 3, and 4 positive images through blue, green and red light respectively. Other 3 - band combinations can be colour composited to enhance features of special interest.

The angular field of view (AFOV) for the TM is 14.9^0 which produces a 185km swath width from a Landsat altitude of 705km. The standard full-scene TM image measures 185km across track by 170km along track and is depicted as a slanted parallelogram.

The instaneous field of view (IFOV) for the visible and reflected IR bands (bands 1-5 and 7) is 0.0425 mrad; this produces a ground resolution cell measuring 30m x 30m. The IFOV for the thermal IR band (band 6) is 0.17 mrad; this produces a ground resolution cell of 120m x 120m. The larger cell size for band 6 translate to a longer dwell time, ensuring that a signal of adequate strength can be collected to maintain its temperature resolution of 0.6^0. The TM scans in both directions normal to the ground track ie bidirectional scanning. A 16 element detector array is used for each of the 30 metre resolution bands and 4 detectors are used for the thermal IR band. Therefore, 16 scan lines are generated for bands 1 - 5 and 7 and 4 are generated for band 6 during each sweep of the mirror

7.3 SPOT

In the late 1970s, the French government initiated the Systeme Pour l'observation de la Terre (SPOT) programme. SPOT was designed to be a fully operational and commercial remote sensing programme, as opposed to a government-sponsored research and development programme. Analogous to Landsat, the data were to be collected on a global basis but unlike the Landsat programme, the satellites were to be equipped with high-resolution along-track scanners with across track pointable optics that would provide both nadir and off-nadir viewing. In the multispectral mode the high resolution visible (HRV) scanner operates in three narrow spectral regions (Rees 1990):

1.	Band 1	0.50 - 0.59μm	Green
2.	Band 2	0.61 - 0.68μm	Red
3.	Band 3	0.79 - 0.89μm	Near IR

These band sensitivities were selected to optimise the capability of discriminating different plant species (Jaakola 1989;). For each band, a 3 000 element array is used; this sampling mesh corresponds to a ground element that measures 20m x 20m. Black and white images are normally used to make colour infrared composites.

The spatial structure of an image will determine the type and amount of information in it. Increasing spatial resolution (viewing smaller ground units) will expand both the amount of information in the image and the problems of scene heterogeneity of variance of the data in it since more unique ground classes will be identified in it The number of parcels containing more than one land cover type was a function of both complexity of the scene and the sensor spatial resolution (Haak et al 1987). Interclass separability is a function of both sensor parameters and site conditions. Generally with the advent of higher resolution sensors such as Landsat TM and SPOT, classification and geometric accuracies have shown a marked improvement over the former Landsat MSS results.

Thompson (1994) summarises the availability of remote sensing data in South Africa as follows:

Table 7.3 Remote Sensing Data Types Available in South Africa (adapted from Thompson 1994)

Data Types	Data Format
Landsat multispectral scanner (MSS)	False colour infrared
Landsat thematic mapper (TM)	False colour infrared (including moisture information)
SPOT multispectral scanner	False colour infrared
SPOT panchromatic (PAN)	Black/white
Aerial photography	Black/white or true colour
Airborne video (developing, not yet operational (except by individuals)	Black/white or true colour, possibly infrared
Research rather than operational tools: AVIRIS and RADAR	

Table 7.3.1 Data Types and Frequency of Image Acquisition (adapted from Thompson 1994)

Data Type	Period Available	Frequency
Landsat MSS	Archival: pre-1989	@ 16 days
Landsat TM	1989 - current	@ 16 days
SPOT X	1990/1 - current	@ 22 days
SPOT PAN	1990/1 - current	@ 22 days
Aerial photos	Historical/current	No restrictions
Airborne video	Not yet operati[illegible] in SA	No restrictions

8 DIGITAL IMAGE PROCESSING

Many types of remote sensing are recorded in digital form. This is accomplished by imaging systems that collect and measure radiance intensities at *n* points in a rectilinear pattern. The sampled intensities are first translated into proportional electronic signals and then encoded into numerical equivalents as integers (analogue to digital conversion) from which the digital image can be constructed. Digital remote sensors include most electro-optical systems, imaging radars, passive microwave radiometers and imaging sonars. Digital image processing encompasses four major areas of computer operation (Moik 1980):

1. Image Restoration or Preprocessing: Computer routines correct a degraded digital image to its intended form, usually a precursor to the following steps.
2. Image Enhancement: computer routines improve the detectability of objects or patterns in a digital image for visual interpretation. These techniques can be broadly classified as: contrast manipulation - grey-level thresholding, level slicing and contrast stretching; spatial feature manipulation - spatial filtering, edge enhancement and Fourier analysis; multi-image manipulation.
3. Image Classification: Quantitative decision rules classify or identify objects or patterns on the basis of their multispectral radiance values (as such, the normal output is analogous to an image map requiring little or no visual interpretation).
4. Data-Set Merging: Computer routines integrate multiple sets of data from the same location such that congruent measurements can be made (representative types of information include geographical, geological, geophysical, geochemical and multispectral radiance data.

8.1 Image Classification

Automated digital analysis or image classification is an information extraction process that involves the application of pattern recognition theory to multispectral images. Its function is to improve detectability of objects or patterns in a digital image for visual interpretation. Simply stated, image classification analyses spectral properties of various surface features, for example, crops in a multiband image and sorts spectral data into spectrally similar categories by the use of predefined numerical decision rules. It follows five basic steps:

1. **Training Class Selection:** The initial step involves defining image properties ie pixel digital number (DN) values, that represent a group of information or training classes.
2. **Generation of Statistical Parameters:** Statistical algorithms are used to define the unique spectral characteristics (spectral signatures) of the training classes. Typical statistical parameters include class means, standard deviations, covariance matrices,and correlation matrices. The statistical descriptions are used to 'train' the classification algorithm.
3. **Data Classification:** The 'trained' classification algorithm assigns each pixel composing the data set of interest to one of the training class categories.
4. **Evaluation and Refinement:** An assessment is made of the classification accuracy. Returning to step 1 and repeating the process is required if the classification results are judged to be unacceptable. A common reason for classification refinement is the excessive spectral overlap between categories.
5. **Documentation:** Once a final classification is acceptable, the results are documented in the form of maps and tabular summaries.

Two primary approaches can be used for defining training classes : unsupervised and supervised.

1. **Unsupervised classification** uses an automatic clustering algorithm that analyzes the 'unknown' pixels in the data base and divides them into a number of spectrally distinct classes based on their natural groupings ie clusters in *n*-spectral dimensions. The analyst specifies the number of spectral classes into which the data are to be grouped. The spectral classes defined by the clustering algorithm are then used to classify the entire data set. After the classification is completed, the analyst must identify the cover type represented by each spectral class by ground truthing and using various types of reference information eg colour infrared images, photographs, published data, field reconnaissance data etc. Only then are cover-

type labels assigned to spectral classes. Generally, as the number of spectral classes increases, the ability to identify each class becomes more difficult.

2. **Supervised classifications** use areas of known cover type in the image which are specified as training areas. Statistical measures are generated for the training areas and input to the classifier which then determines other areas in the image that have similar spectral characteristics. Supervised classification usually requires less computer time to execute than unsupervised classification because it relies on explicit analyst guidelines and does not require a clustering step.

8.2 Advantages of using Satellite Remotely Sensed Data

Satellite remotely sensed data have a number of advantages over traditional methods for wetland inventorisation purposes:

1. The wide area coverage and repetitive nature provides the opportunity for seasonal and often timely monitoring of large complex areas as well as distant and inaccessible regions such as the Okavango Delta (Hutton and Dincer 1977). Obtaining the wide area coverage sacrifices the detailed resolution available from aircraft.
2. Satellites can provide synoptic, quantifiable, objective and repetitive information of features on the earth's surface (Carter et al 1977).
3. The digital nature of the data enables objective, rapid and automated interpretation of imagery to be undertaken as well as efficient transmission, storage and updating of data.
4. The discriminative ability of different wavebands of the electromagnetic spectrum provides additional information of spectral responses of land cover not previously available.
5. The different resolutions of data ranging from 80m to 10m and less, particularly with the increasing availability of Russian satellite data, can now provide managers and researchers with accuracies that can meet most needs. Previously Landsat data was considered to be useful for mapping broad categories of vegetation and obtaining real estimates at Level 1 mapping (Gammon et al 1979; Jensen et al

1986). Now level 2 mapping is considered feasible with TM and SPOT data.

6. Using satellite data in terms of manpower, time and money if employed properly is potentially highly cost effective. Surface reference data investigations carried out by a few people, in a short time, over relatively limited areas can serve as a basis for classification and be expanded to larger areas (Gervin and Shih 1979).
7. Satellite data and resulting classifications can be stored on a computer and interfaced directly with other geographic information thereby providing up to date information on a particular area.
8. The ability of satellite imagery for dynamic hydrologic conditions, both spatially and temporally, has significant ramifications and may provide guidelines for wetland management.

8.3 Disadvantages of Using Satellite Remotely Sensed Data

The down side of using satellite data involves the following factors:

1. Cloud cover obstructs data acquisition. The time of year and the seasons play a significant role in obtaining suitable imagery.
2. Landsat fixed orbit means that there is a delay period of 16 days between overpasses. The opportunity, therefore to capture optimum conditions may not be available.
3. The amount of light a feature or object reflects in various wavelengths forms the basis of discrimination by remote sensors using multispectral techniques (Avery and Berlin 1992). Often the spectral characteristics of different types of vegetation are to ..ly related and digital separation is often very difficult. Variation in vegetation densities, mixtures of species or different stages of growth will affect spectral signatures and identifying land cover types be obtained. Remote sensing techniques can significantly reduce the amount of field data required but do not eliminate the need for data collection. Furthermore surface reference data are needed that can be tailored for use with remotely sensed data, for example, land cover classes should include stage of growth and canopy cover.
4. Despite the application of sophisticated hardware, software and advanced numerical processing techniques, the end result does not always meet with expectations. (Vlok

and Zietsman 1992/1993). Research reports often cite limitations in the digital data, such as low resolution, the lack of multitemporal datasets, inadequacies in the ground truth data or the complexity of the target area as the cause for poor results. It is implicitly assumed that the analyst is capable and completely objective, rational and without limitations. Rarely, if ever, are low classification accuracies attributed to errors of judgement or lack of knowledge or insight.

9 METHODS AND RESULTS (Fig 9 Overlay - Map Pocket)

The methods employed to extract and interpret information on pans in the study area from the available Landsat TM data are stand-alone techniques. Thus, for ease of reading methods and results are combined in this chapter.

The choice of Landsat TM data is warranted as a time saving device as it would be virtually impossible in the time frame available for this study to visit every pan in the field area and map it. The satellites of the Landsat series are specifically designed to assist in the survey and management of the earth's natural resources by providing repetitive global multispectral coverage.

Two scenes of the field area in digital data form were available: WRS - 172-78D (southwest quadrant), acquired on 03. 12. 86., and WRS - 172-78D, acquired on 26. 06. 92. The scenes were georeferenced across all seven bands using 1:50 000 topocadastral maps, (SA topographic sheet numbers 2625AD, 2625BC, 2625CB and 2625DA) with an error maximum of 20 meters. These data were georeferenced to a Universal Transverse Mercator projection, zone 35, (Clarke 1880, spheroid). The georeferenced scenes were then warped using a second order polynomial transformation and the area of interest extracted to an accuracy of within one pixel. In other words, the area of interest extracted from both datasets correspond with each other to within one pixel.

A groundtruthing field trip was undertaken in mid-December 1994. The rainfall for the season to mid December had been extremely low and the only pan which contained water was Barberspan with a consequent concentration of waterfowl on its waters. The pans in the Harts palaeo-channels such as Leeupan which normally have some standing surface water at this time of year were all dry. All the vegetated pans were dry, though they could be identified as shallow depressions in the landscape with a denser and in many cases different grass and forb vegetation cover to the surrounding lands. It was therefore difficult to relate in terms of vegetation what was on the ground at that point in time to the 03. December 1986 scene since the rainfall for the season to that date had been some 230mm. Hence, the vegetation cover would have been significantly different. Furthermore land-use and crop cover in some areas have changed in the intervening years as have

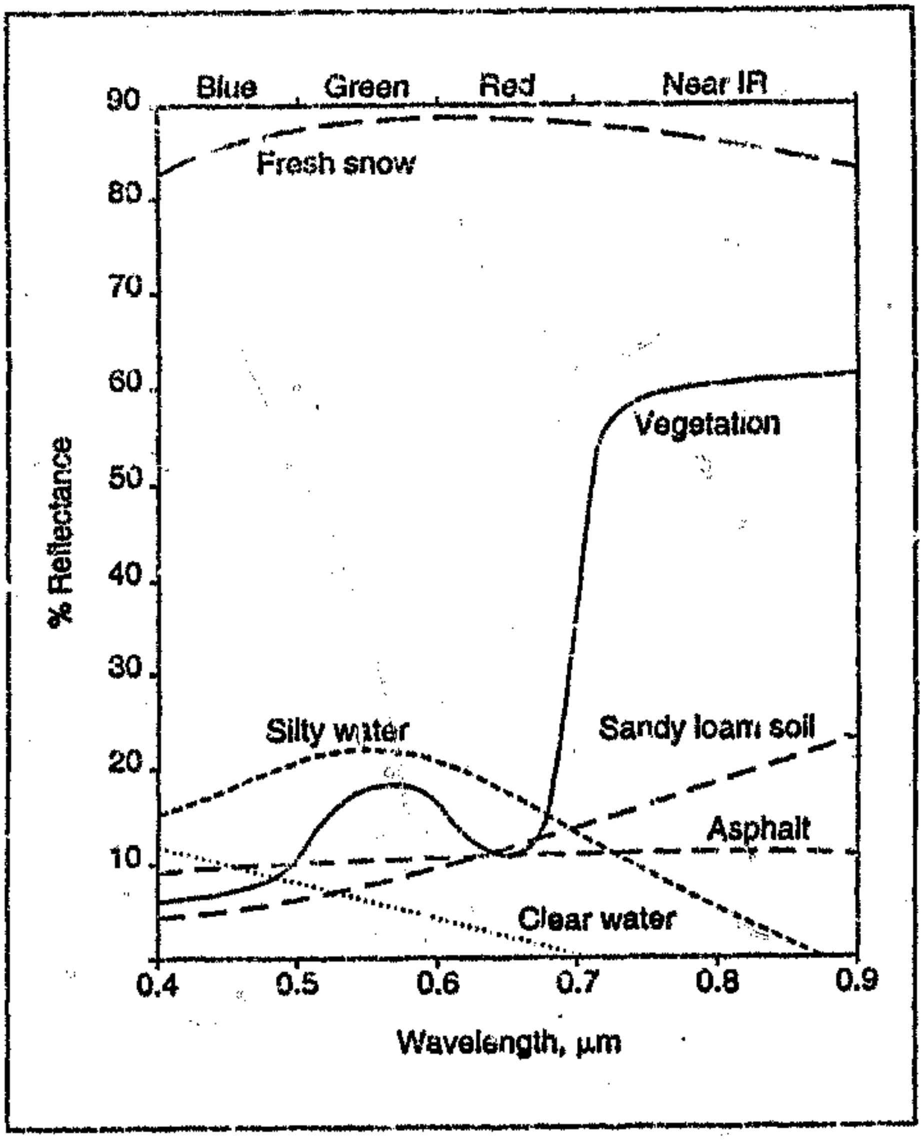

Figure 9.1 **Average spectral response curves for six materials (adapted from Avery and Berlin 1992)**

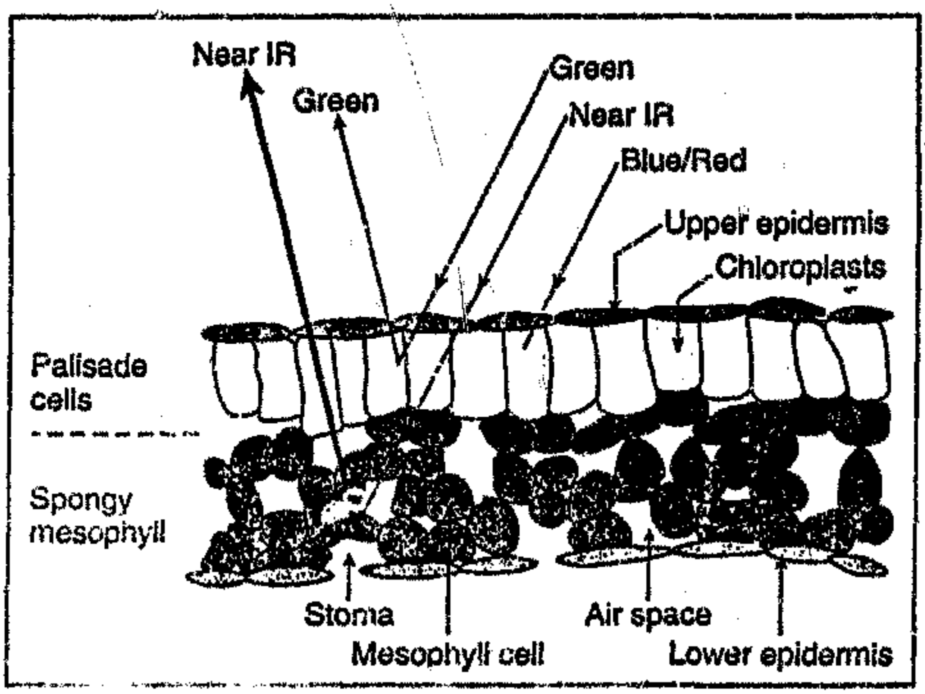

Figure 9.2 Generalised diagram of a leaf's structure and its reflectance characteristics at visible and near IR wavelengths (Adapted from Avery and Berlin 1992)

management practices and burning regimes in the Barberspan Nature Reserve. It is ideal to have access to current Landsat TM data to relate spectral response of vegetation in particular, to what is on the ground at that specific point in time. However, with use of vintage Landsat TM data it is possible to locate pans of varying size and morphology in the landscape. Please refer to Fig 9, overlay - map pocket for site location.

9.1 Spectral Reflectance (Fig 9.1)

Spectral reflectance is the portion of incident energy that is reflected. The fraction of energy reflected at a particular wavelength varies with different earth features which in turn varies at different wavelengths (Fig.9.1.). Thus two features that are indistinguishable in one spectral band may be very different at another wavelength (Colwell 1983b). The vegetation response works in the following way:

9.2 Vegetation (Fig 9.2, Fig 9.2.1, Fig 9.2.2)

Maximum reflectance from vegetation occurs in the near infra-red (IR) region of the elctromagnetic spectrum. The spectral character of light reflected by a normal plant leaf is controlled largely by two groups of cells (Fig 9.2).

1. Palisade cells - long narrow cells below the upper epidermis which contain many chloroplasts with chlorophyll pigments (a and b) that absorb most blue and red light for photosynthesis and efficiently reflect green light. Up to 20% of incident green light is reflected by the chloroplasts in the normal functioning of a plant, causing the green colour of leaves as perceived in the human visual system (Rees 1990). Other plant pigments such as carotenoids, xanthophylls and anthocyanins will also have an effect if present.

2. Mesophyll cells - below the palisade layer are the spongy mesophyll cells, where oxygen and carbon dioxide exchange takes place. This layer consists of mesophyll cells and numerous air spaces. Near IR radiation is unaffected by the chloroplasts, but is strongly reflected by the spongy mesophyll. Most of the reflection takes place at the cell-wall/air-space interfaces. It is not uncommon for more than 50%

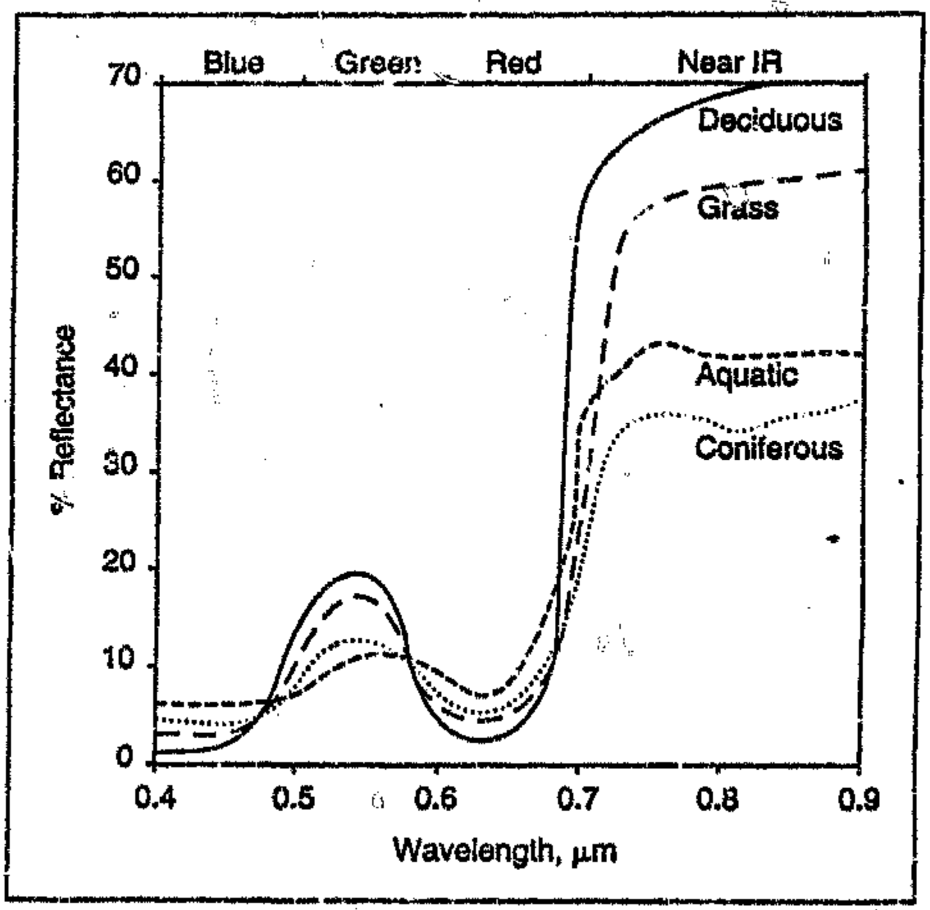

Figure 9.2.1 Average spectral-response curves for four types of vegetation (adapted from Avery and Berlin 1992)

of incident near IR radiation to be reflected upward through the leaf, with most of the remainder being transmitted through the bottom of the leaf.

IR reflectance from various types of healthy vegetation differs because of leaf mesophyll arrangements. For example, a maize leaf has a relatively compact mesophyll, which is responsible for relatively low infrared reflectance and high transmittance. A leaf with a more porous mesophyll, in other words, many wall-air interfaces will have a higher infrared reflectance and lower transmittance. Consequently, different species (or morphological/phenological groups) are spectrally separable (Fig. 9.2.1).

Leaf age is also a cause of variation in infrared reflectance, for example immature citrus leaves have compact its mesophyll with few air spaces (lower IR reflectance), whereas the mature leaf is spongy, with many air cavities in its mesophyll (higher IR reflectance) (Gausman 1974) and are therefore spectrally different. Air spaces do not start to form in a cotton leaf until it attains one-fourth to one-third its full size. Other conditions that can influence the level of IR reflectance from vegetation include the water content of the leaves, density of growth, canopy structure, season of growth and topographic location.

When a healthy plant becomes strained by some type of stress in its environment, changes occur in its spectral response (Fig. 9.2.2). Changes in the typical reflectance property of a plant leaf as it progresses from a healthy state through different stages of damage are as follows (Murtha 1978) :

1. The leaf is healthy; peak visual reflectance is in the green region (about 20%), with lower reflectance in the blue and the red regions (about 10% each). There is considerably higher reflectance in the near IR region (about 70%).

2. The leaf has incipient damage which is accompanied by a drop only in near IR reflectance (about 10%). This diminution is caused by the collapse of some of the air cavities in the mesophyll.

3. The leaf has chronic damage and its colour changes from green to yellow, caused by chloroplast deterioration which increases red reflectance. At near IR

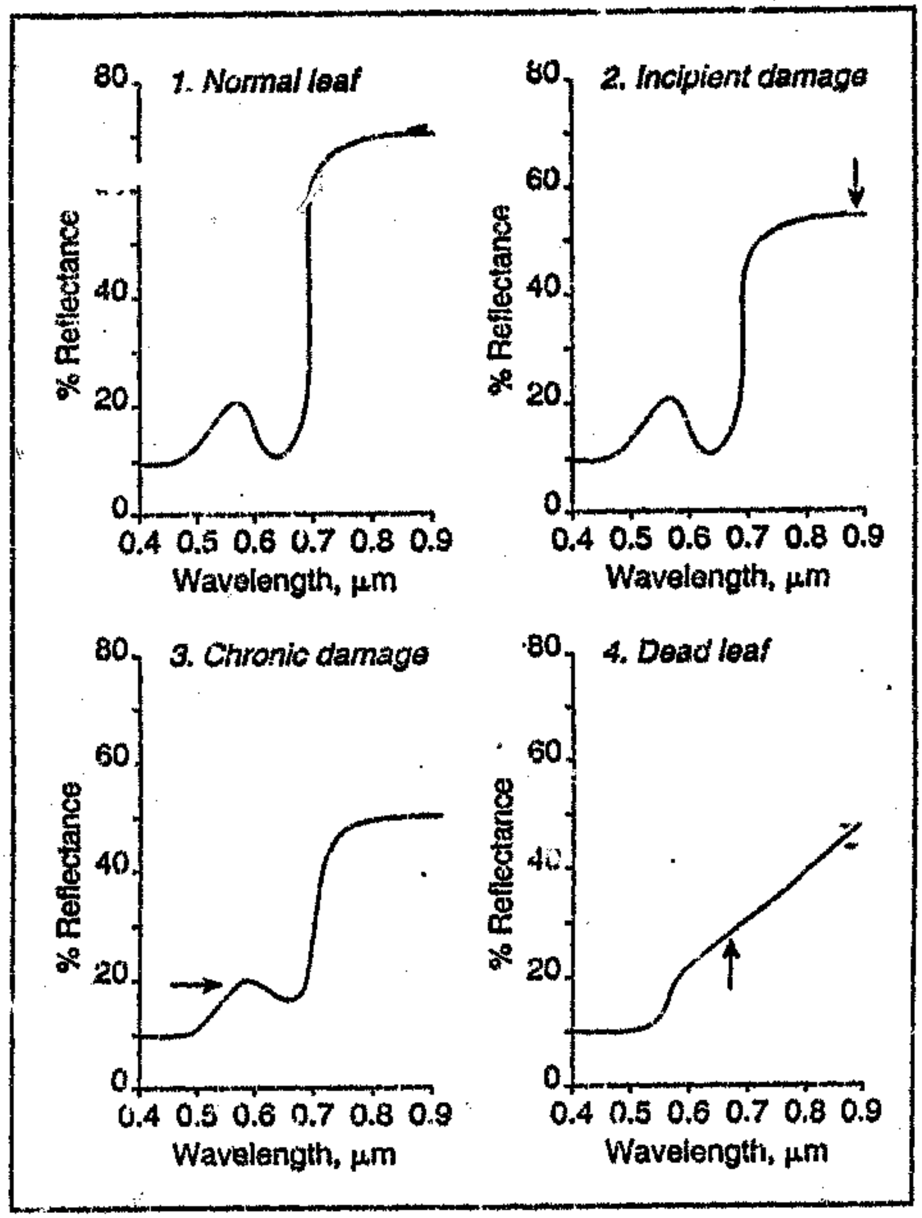

Figure 9.2.2 Average spectral response curves for a plant leaf as it progresses from a healthy state through different stages of damage (Adapted from Murtha 1978)

wavelengths, the yellow leaf has about 5% less reflectance than it had in stage 2.

4. The leaf is dead and its colour becomes red-brown. The major spectra changes are the loss of the green peak, an increase of red reflectance and the loss of the high shoulder of near IR reflectance beyond 0.7μm. At this stage, the leaf's cell structure has collapsed and the leaf becomes dry and brittle.

The spectral reflectance and transmittance of a plant canopy of a given depth and random leaf orientation are functions of total leaf area, an absorption coefficient, a scattering coefficient and the background reflectivity. The coefficients are related to the geometry of the canopy and the optical properties of individual leaves. These differences form the basis of plant community discrimination. In agricultural crops there are also cultural impacts such as planting in rows, planting dates and densities which may be manifested in the overall patterns. On the other hand natural plant communities exhibit different heterogenous mixtures and associations.

9.3 Soil Reflectance

The factors that influence soil reflectance act over less specific spectral bands than with vegetation (Rees 1990). Some of the factors affecting soil reflectance are moisture content, soil texture (proportion of sand silt and clay), surface roughness, presence of iron oxide and organic content. These factors are complex, variable and interrelated. For example the presence of moisture in the soil will decrease the reflectance over a wide bandwidth. As with vegetation, this effect is greatest in the water absorption bands at about 1.4, 1.9 and 2.7μm. Clay soils also have hydroxyl absorption bands at about 1.4 and 2.2μm. Soil moisture content is related to the soil texture - coarse sandy soils are usually well drained, resulting in low moisture content and relatively high reflectance; poorly drained fine textured soils will generally have lower reflectance. In the absence of water, soil will exhibit the reverse tendancies: coarse textured soils will appear darker than fine textured soils. Therefore the reflectance properties of a soil are consistent only within particular ranges of conditions. Two other factors that reduce soil reflectance are surface roughness and organic matter content. The presence of iron oxide in a soil will significantly decrease reflectance, particularly in the visible wave lengths.

9.4 Water

The most distinctive characteristic of the spectral reflectance of water is the energy absorption at near-infrared wavelengths (Avery and Berlin 1992). Water absorbs energy in these wavelengths whether they are water bodies or water contained in vegetation or soil. Locating and delineating water bodies with remote sensing data are done most readily in near-infrared wavelengths because of this absorption property. However, water conditions manifest themselves mainly in the visible wavelengths and the energy-matter interactions are complex, depending upon a number of interrelated factors. For example, the reflectance from a water body can be a product of specular reflection with suspended material or with the bottom of the water body depending on the depth.

Clear water absorbs relatively little energy having wavelengths less than 6μm. These wavelengths typify high transmittance, with a maximum in the blue green portion of the spectrum. However, transmittance changes with turbidity and therefore reflectance will change. For example, waters containing large quantities of suspended sediments resulting from soil erosion usually have much higher visible reflectance than clear waters in the same geographic area. Similarly, the reflectance of water changes with chlorophyll content of algae contained within the water body. Increases in chlorophyll concentration tend to decrease water reflectance in blue wavelengths and increase it in green wavelengths. These spectral reflectance changes have been used to monitor the presence and estimate the changes in the concentration of algae in water bodies using remote sensing data. Reflectance data have been used to detect the presence of pollutants such as oil and certain types of industrial waste.

Temporal and spatial effects influence virtually all remote sensing data acquisition. These effects are an additional complication in the issue of analysing reflectance properties. However, the process of change detection is premised on the ability to measure temporal effects. Temporal effects are any factors that change the spectral characteristics of a feature over time. For example, the spectral characteristics of vegetation are in a nearly continual state of change throughout the growing season. These changes influence the data collection for a particular application. Spatial effects refer to factors that cause the same type of features, for example crops, at a given point in time to have different characteristics at different geographic locations. Furthermore, it should be borne in mind that in addition to being influenced by temporal and spatial effects, spectral patterns are influenced by atmospheric effects between sensor and ground.

9.5 Multiband Imaging

With Landsat TM imagery a number of different combinations of spectral bands can be chosen which will influence the level of information that can be extracted from the image. As mentioned in chapter 7.2, Landsat TM data comprises seven spectral bands, each of which is a measurement of reflective energy within discrete ranges of the electromagnetic spectrum, over the same ground area. Thus seven images are available, from which can be extracted different types of information. For example, from the visible light band-passes; bands one, two and three it is possible to show internal detail within water bodies, such as depth, turbidity and deposition features. On the other hand, infrared wavelengths are strongly absorbed by water (Avery and Berlin 1992). Therefore any image including spectral bands 4 (near-infrared), 5 (middle-infrared) or 7 (far-infrared) will give an indication of water extent but not detail. For the six non-thermal TM bands $6^3/2$ different three band-pass (red, green, blue: RGB) colour composite images can be produced. A 'natural' colour composite can be created by projecting band-pass 1, 2, and 3, positive images through blue, green and red light, respectively. A colour infrared composite can be generated by projecting band-pass 4, 3, and 2 positive images through red, green and blue light, respectively. Other three band-pass combinations can be colour-composited to enhance features of special interest. For example a useful one for rock discriminations is a false colour composite of bands 1 (blue), 4 (green) and 5 represented in red.

9.6 Band Combination 4, 3, 2, 03 December 1986 (Fig 9.6, Fig 9.6.1 Map Pocket, Fig 9.6.2 Overlay-Map Pocket)

Band combination 4 (red), 3 (green) and 2 (blue) gives an indication of general land-cover and use. To reiterate, band 4 (wavelength range 0.76-0.90 μm, near infrared) operates in the best spectral region to distinguish vegetation varieties and conditions. Furthermore, since water is a strong absorber of near infra-red it is also useful for locating and

Figure 9.6 Band Combination 4, 3, 2, (RGB) 03 December 1986

Scale: 155 000

delineating water bodies, distinguishing between dry and moist soils and providing information about generally wet areas.

Band 3 (wavelength 0.63-0.69 μm, spectral location - red) senses in a strong chlorophyll absorption region and a strong reflectance for most soils. It is therefore a useful band-pass for discriminating vegetation and soil and for delineating urban and rural areas

Band 2 (wavelength 0.52-0.69μm, spectral location - green) covers the green reflectance peak from leavers and can be useful for discriminating broad classes of vegetation. It is also sensitive to water turbidity.

In this early December 1986 4, 3, 2, band combination (Fig.9.6), a strong vegetation response (red, band 4) is seen in the Harts floodplain and in the palaeo-channel of the Harts River around Barberspan, Leeupan and the string of pans Klippan and Witpan in the northeast corner of the scene and around Boskop pan in the south west corner. The rainfall for September, October and November for 1986 was approximately 230mm. The response on the Harts floodplain is the growth of grass and sedge and low forb communities which are displayed as tonal differences (in the spectral locations of green and red) and textures. Around the pans in the palaeo-channel of the Harts river, and Boskop Pan which lies in another palaeo-channel arm of the river, the land is uncultivated. The vegetation response is to grassland and shrub communities (See Fig 9.6.1 for site locations)

In response to the reasonable rainfall, the farm lands in this scene would be newly cultivated and crops in the process being sown (mainly mealies) and the greenish hue is primarily a soil response rather than vegetation cover. The deep red colour and more even textures evident in the fields around Damascus Pan and other locations in the scene are a response to cultivated grass cover. Belts of *eucalyptus* species (blue-gums) associated with farmhouses and along roadsides can be detected. The area around Kopela pan comprises communal land in the former Kunana location and consists of varied communities of grasses and acacia shrubland and the response is one of soil and vegetation cover. Kopela pan occurs on a calcrete outcrop and the soil shows up as being very pale and the vegetation cover as sparse in some areas, probably as result of grazing

Figure 9.7 Band Combination 4, 3, 2, (RGB) 26 June 1992

Scale 1:155 000

impacts.

In the northwest corner of the scene can be seen the beginnings of the headwaters of the Sepane river, a tributary of the Molopo River, indicating a change in direction of drainage towards the northwest. This area is uncultivated and the colour response is to a change in soil type - in this case an encroachment of Kalahari sand, overlaying the Ventersdorp lavas. There is a red vegetation response along the channels of the tributary.

The pans which clearly show up as containing water are those which lie in the palaeo-channels of the Harts river, and a few outside such as Kopela Pan. There is some uneveness in the colouration of water in Barberspan, indicating perhaps differences in depth or turbidity. Barberspan, in this scene, is only partially filled with the shallow northern end of the pan exposed. The bottom of the pan does not have the characteristic flat surface of a pan that regularly dries out and is, or has been subject, to deflation in recent times.

Perhaps the most important feature of this scene in terms of pans is the location of smaller vegetated pans. These vegetated pans appear as reddish circular-shaped entities in the landscape, many of them isolated in the cultivated lands. Some of them have been fenced-off and show up as square-shaped with a change of hue towards the centre. Some of these vegetated pans indicate that they are vegetated over their whole surface, others are distinguished by a ring of vegetation and a moisture response towards the centre. These pans exist as vegetation islands in the cultivated lands and this probably where their true value lies. Their ability to retain water is variable and so too are the plant communities in and around them.

Within the cultivated lands are circular shaped entities showing up as a soil response. They appear to be non-vegetated depressions, the soils of which are ploughable and can sustain crop growth.

9.7 Band Combination 4, 3, 2, 26 June 1992 (Fig 9.7, Fig 9.7.1 Map Pocket)

In this midwinter scene, the vegetation response in the near IR has been lost except in the

Figure 9.8 Band Combination 7, 5, 4, (RGB) 03 December 1986
Scale 1:155 000

belts of blue-gum trees. The whole landscape is drier and the response in the cultivated lands is a product of soil moisture loss and crop remnant. The vegetated pans are still distinguishable but not as clearly in the summer scene. The smaller pans in the Harts Palaeo-channel have less water in them than in the summer scene. However, what is very clear is that Barberspan contains more water than in December 1986 and the surface area of water is greater.

9.8 Band Combination 7, 5, 4, 03 December 1986 (Fig 9.8, Fig 9.8.1 Map Pocket)

Band 7 (red), 5 (green) and 4 (blue) pick up information in the infra-red portion of the electromagnetic spectrum. Band 7 (wavelength range 2.0[illegible]-2.35μm, mid IR) coincides with an important absorption band caused by hydrous minerals such as clays, micas and some oxides and sulphates. This band-pass is therefore valuable in lithologic mapping and for detecting clay alteration zones (dark image intensities) associated with mineral deposits such as copper. It is also sensitive to moisture content in both vegetation and soils. Band 5 (wavelength 1.55-1.75 μm mid IR) is analogous to band 7 in that it is responsive to changes in leaf-tissue water content (reflectance decreases as water content increases) which can be related to plant vigour or different species. This band is sensitive to the presence or absence of iron in rocks (reflectance increases as the ferric iron content increases).

The vegetation response in band 4 shows up as bluish hues and the soil response as a product of moisture and organic matter and mineral content as brownish-yellow hues. The encroachment of uncultivated Kalahari sands in the northwest corner of the scene is again clearly depicted as is the communal land around Kopela Pan. The pans containing water or with a high moisture content of the pan soils within, manifest themselves as being very dark.

9.9 Band Combination 7, 5, 4, 26 June 1992 (Fig 9.9, Fig 9.9.1 Map Pocket)

The overall greenish hues in this dry winter scene indicate a strong response in band 5, probably as a product of the mineral content of the soils. The bluish tinge is a product of crop remnants. The pans in the palaeo-channel to the north of Barberspan show a distinct

Figure 9.9 Band Combination 7, 5, 4, (RGB) 26 June 1992
Scale 1:155 000

Figure 9.10 Band Combination 7, 4, 2, (RGB) 03 December 1986
Scale 1:155 000

brownish signature, as does Damascus Pan, which is probably a consequence of moisture and characteristic pan soils. Boskop Pan in the south west corner of the scene shows up as white, indicating a different in moisture and soil type in the pan. The characteristic calunettes to the south of these pans show up as being slightly lighter entities than their immediate surrounds. Barberspan shows up distinctly as a water body, with its surface area extent clearly delineated..

9.10 Band Combination 7, 4, 2, 03 December 1986 (Figure 9.10)

This band 7 (red), 4 (gr...) and 2 (blue) combination is useful visually since the strong vegetation response shows up as green, cultivated lands as red-brown (no crop cover) and standing water as blue. The areas of vegetation, including vegetated pans are readily distinguished and the calcrete calunettes associated with the pans in the palaeo-channel of the Harts river can be distinguished as higher albedo entities beneath a vegetation mantle.

9.11 Class Discrimination (Fig 9.11, Table 9.11 Map Pocket)

The spectral reflection characteristics of vegetation, soil and water are normally spectrally separable and result in spectral response patterns rather than spectral signatures (see fig 9.1). The degree of separation between types is function of where one looks spectrally. The term signature tends to imply a pattern that is absolute and unique which is not the case with spectral patterns observed in the natural world. Spectral response patterns measured by remote sensors may be quantitative but not necessarily unique.

Six classes were selected in the study area to determine spectral differences.

1. Beach - outer surface area of a range of pans.
2. Crops - standing biomass in cultivated lands.
3. Water - standing water in pans.
4. Riparian vegetation - vegetation on the Harts River floodplain.
5. Barberspan vegetation - around the perimeter of the pan.
6. Geology - geological outcrops.

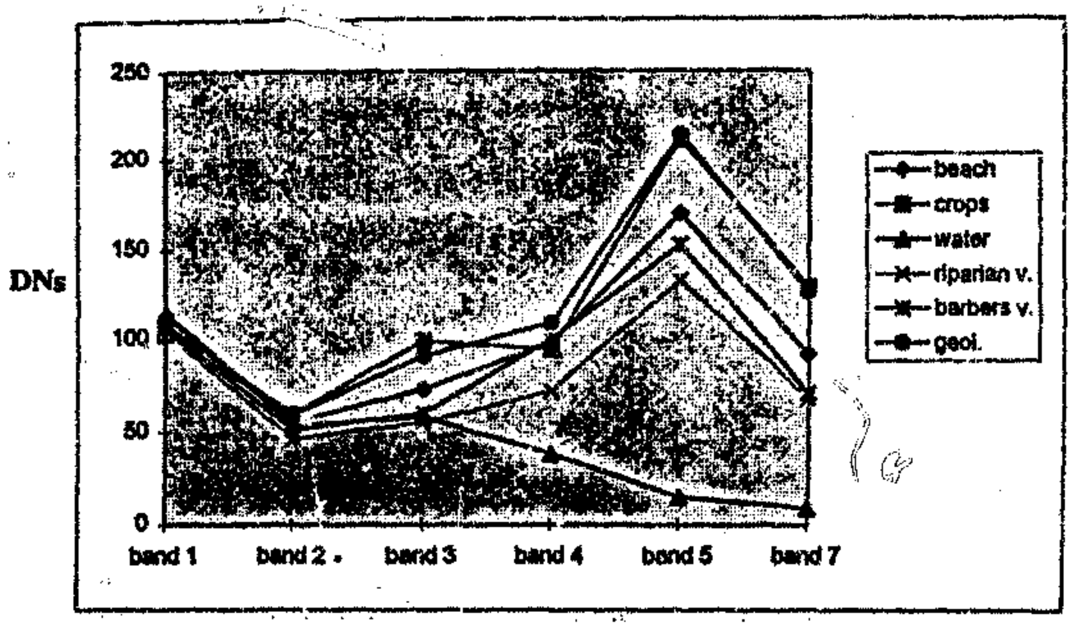

Figure 9.11 Spectral response curves for six classes

The mean of the histograms across band-passes 1-5 and 7 were extracted from a number of sample sites in each class and the mean, median, variance and standard deviation calculated for the samples (Table 9.11). The spectral reflectance curves for each class were plotted digital numbers (DNs) against bands for each class. From Figure 9.11 it can be seen that there is no recognisable discrimination in bands 1 and 2 between classes. In band three, riparian vegetation and water are spectrally very similar and the most probable reason is the silt content and or depth of water. From band 3 to band 7 there is spectral separation between the classes which becomes more distinct with water displaying characteristic energy absorption in the IR wavelengths.

9.12 Transformed Vegetation Index (TVI)

Linear data transformations have been developed for vegetation monitoring with differing sensors and vegetation conditions dictating different transformations. For example, Kauth and Thomas (1976), derived a linear transformation of the four MSS bands that established four new axes in the spectral data that can be interpreted as vegetation components useful for agricultural crop monitoring. This 'tasselled cap' transformation rotates the MSS data such that the majority of information is contained in two components or features which are directly related to physical scene characteristics:

1. **Brightness** is a weighted sum of all bands and is defined in the direction of the principle variation in soil reflectance.
2. **Greenness** is approximately orthogonal to brightness and is a contrast between the near-infrared and visible bands. Greenness is strongly related to the amount of green vegetation present in the scene.

Brightness and greenness together typically express 95% or more of the total variability in MSS data and have the characteristic of being readily interpretable features generally applicable from scene to scene (once illumination and atmospheric effects are normalised).

Crist and Cicone (1984) extended the tasselled cap concept to Landsat TM data and found that the six bands of reflected data effectively occupy three dimensions, defining planes of soils, vegetation, and a transition zone between them. The third feature, wetness,

Figure 9.13 TVI (Greyscale) 03 December 1986

Scale 1:155 000

Figure 9.14 TVI (Greyscale) 26 June 1992
Scale 1:155 000

relates to canopy and soil moisture.

Another vegetation index - the transformed vegetation index (TVI) is a measure of vegetation vitality. Vegetation is strongly reflected in the short-wave infra-red portion of the electromagnetic spectrum and absorbed in the red portion of the spectrum. The TVI is a linear combination of radiance in these portions of the spectrum electromagnetic spectrum (EM) and is expressed as follows:

$$TVI=\left(\frac{DN4-DN3}{DN4+DN3}+0.5\right)^{0.5}x100$$

where DN3 and DN4 correspond to the Digital Numbers in bands 3 (records radiance in the visible-red part of the EM spectrum) and 4 (records radiance in the short-wave infra-red portion of the spectrum), respectively.

Ground reference data have shown the TVI to be proportional to the amount of green biomass present within each pixel. TVIs can be calibrated by relating ground-based biomass measurements from sites within a particular Landsat TM scene to the corresponding TVI values. Separate calibration relationships must be established for each cover type and these become the quantitative basis upon which to depict the biomass present in similar sites throughout the scene. The TVI is useful for reconnaissance mapping as it provides a broad discrimination between different plant communities. However, as it employs only a small portion of the EM spectrum, its ability to resolve detail is hampered.

9.13 Transformed Vegetation Index (Greyscale) 03 December 1986 (Fig 9.13)

In this greyscale TVI image areas of low biomass are depicted as being dark and areas with high biomass as being light. This TVI is useful in terms locating vegetated and non-vegetated areas in the scene. It is evident that most of the farmland areas are still bare of crop growth. In those lands that do have a vegetation cover it is possible to distinguish cultivated cropcover by the intensity and evenness of tone such as in the lands around Damascus Pan. The smaller fields of the old Kunana Location are also easily distinguished in the northeast and northwest corners of the scene. The Harts Floodplain has a light-toned uneven signature indicating a high vegetation biomass but that it is variable across its area. The areas around the pans, Barberspan, Leeupan, Klippan and Witpan in the Palaeo-channel of the Harts River have a light uneven toned signature indicating that the area is uncultivated with a mixed vegetation biomass. In contrast, the lands to the west of Barberspan with a crop cover (probably grass cover) have an more even, lighter response. The communal lands around Kopela Pan, have an uneven dark grey signature indicating a mixed ground cover with a fairly low biomass. The Sepane river (tributary of the Molopo River) area indicates a fairly low biomass except in the river courses.

The vegetated pans in the non-vegetated lands are easily distinguishable though detail is lost where the lands have a crop cover. The vegetated pans can be distinguished in some cases by a lighter signature and a roughly circular shape. It is also evident that the large palaeo-channel pans and Damascus Pan and Kopela Pan are entirely different in nature with vegetation confined to their edges and not continuous across their surfaces.

9.14 TVI (Greyscale) 26 June 1992 (Fig 9.14)

In this winter scene the signatures are a lot more even with consequent loss of detail. However the dark tones of the Harts Floodplain indicate a loss of biomass as the vegetation has died back. There seems to be loss of biomass around Kopela Pan (communal lands) and around Witpan. There is still a fairly strong biomass response in the Sepane water course. The light greyish to white tones in the cultivated lands indicate a vegetation cover to a greater or lesser extent and is probably a crop remnant.

There is loss of detail in locating the vegetated pans though some can be distinguished by being darker than their surrounds (loss of vegetation) or being lighter in which case they are carrying more vegetation biomass. Straight line belts of blue-gum trees can be distinguished by their very light signatures.

9.15 TVI (False Colour Composite) 03 Dec 1986 (Fig 9.15, Fig 9.15.1 Map Pocket)

Digital images are generally displayed as additive colour composites using the three primary colours: red, green, blue (RGB) (Colwell 1983a). In an RGB colour cube which

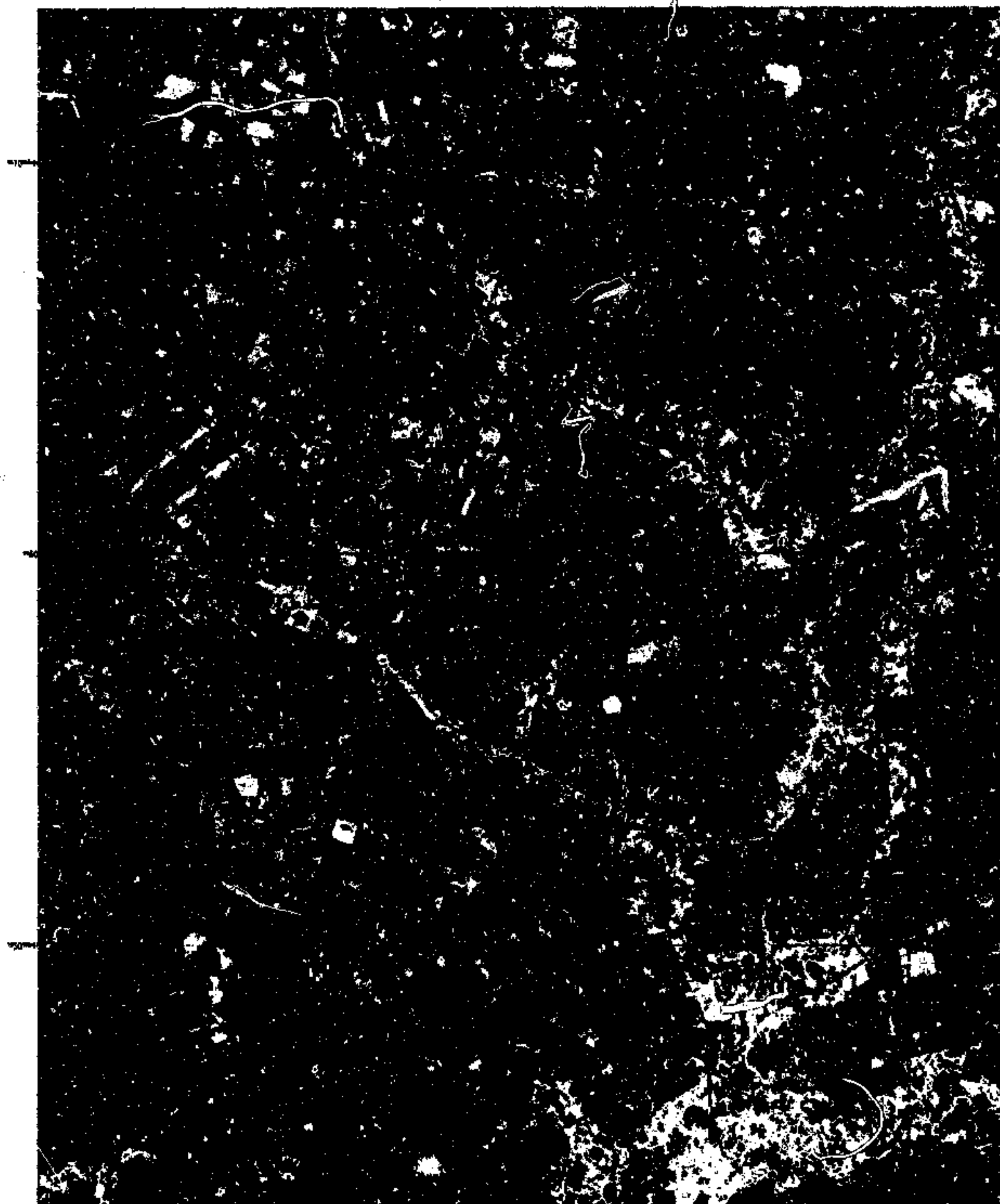

Figure 9.15 TVI (False Colour Composite) 03 December 1986
Scale 1:155 000

is defined by the brightness levels of each of the primary colours, for a display with 8 bit per pixel data encoding, the range of possible digital numbers (DNS) for each colour component is 0 to 255. Hence there are 256^3 possible combinations of red, green and blue DNs that can be displayed. Every pixel in a composite display may be represented by a 3-dimensional coordinate position somewhere within the colour cube. The line from the origin of the cube to the opposite corner of the cube is known as the grey line since DNs that lie on this line have equal components of red, green and blue.

Another way of describing colours is to use the intensity-hue-saturation (IHS) system (Colwell 1983a). Intensity relates to the total brightness of the colour; hue refers to the dominant average wavelength of light contributing to the colour; saturation specifies the purity of colour relative to grey. One approach is called the hexcone model and it involves the projection of the RGB colour cube onto a plane that is perpendicular to the grey line and tangent to the cube at the corner farthest from the origin. the resulting projection is a hexagon. If the plane is moved from white to black along the grey line, successively smaller subcubes are projected and a series of hexagons of decreasing size results. The hexagon at white is the largest and the hexagon at black degenerates to a point.

In the hexcone model intensity is defined by the distance along the grey line from black to any given hexagonal projection. Hue and saturation are defined at a given intensity, within the appropriate hexagon. Hue is expressed by the angle around the hexagon and saturation by the distance from the grey point at the centre of the hexagon. The farther a point lies away from the grey point, the more saturated the colour.

In this December 1986 TVI, the greyscale has been converted via the intensity-hue-saturation model and stretched and assigned RGB colour components so that blue is assigned to 0, ranging through green, yellow, orange, and red at 255. In this colour composite it is easier to visualise the biomass response. The strongest response is evident in certain of the cultivated lands and some of the vegetated pans. The vegetated pans stand out clearly in the cultivated lands, as does the uncultivated land around the palaeo-channel pans. It is clear that the land around Damascus pan is cultivated and from groundtruthing consists of cultivated grassland. The area around Boskop Pan consists of grassland and bush.

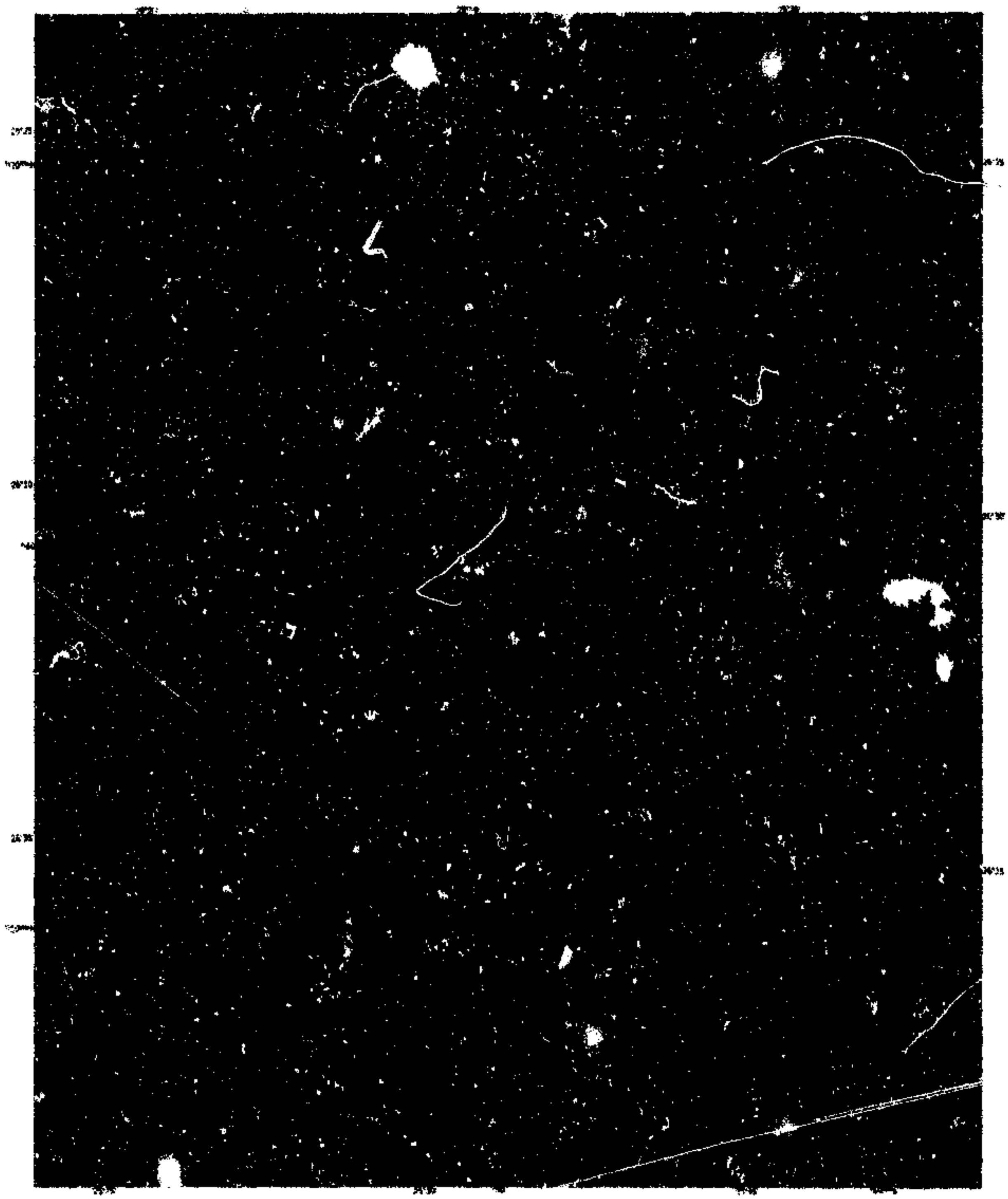

Figure 9.16 TVI (False Colour Composite) 26 June 1992

9.16 TVI (False Colour Composite) 26 June 1992 (Fig 9.16, Fig 9.16.1)

The loss of biomass in this winter scene is reflected in the blue-green colour tones throughout the image and the loss of pan detail, particularly in the vegetated pans. The red high biomass response is given by belts of blue-gum trees.

9.17 Principal Components (Fig 9.17; Figures 9.17.1, 9.17.2, 9.17. 3 Map Pocket)

Extensive interband correlation is a problem frequently encountered in the analysis of multispectral image data (Jensen and Waltz 1979). That is, images generated by digital data from various wavelengths often appear similar and convey essentially the same information. Principal component transformation is a technique designed to remove or reduce such redundancy in multispectral data. This transformation may be applied as an enhancement operation prior to visual interpretation of the data or as a preprocessing procedure prior to automated classification of the data. In the latter context, the transformation generally increases the computational efficiency of the classification process because of a reduction in the dimensionality of the original data. In other words, the purpose of this technique is to compress all the data information contained in original n-channel set into fewer than n 'new channels' or components. The components are then used *in lieu* of the original data. For channels of multispectral data, the first principal component (PCI) includes the largest percentage of the total scene variance and succeeding components (PC2, PC3,........PCn) each contain a decreasing percentage of scene variance. Furthermore, because successive components are chosen to be orthogonal to all previous ones, the data they contain are uncorrelated.

Consider a two-channel data set. Superimposed on the band A/band B axis system are two new axes that are rotated with respect to the original measurement axes and that have their origin at the mean of the data distribution. The form of the relationship necessary to transform a data value in the original band A/band B coordinate system into its value in the new axis 1 (defines the direction of PCI)/axis 2 system (defines the direction of PC2) is:

$$DN_I = {}_{a11} DNA_A + {}_{a12} DN_B$$
$$DN_{II} = {}_{a21} DNA_A + {}_{a22} DN_B$$

where DN_I , DN_{II} = digital numbers in the new (principle component) coordinate system.

DN_A , DN_B = digital numbers in the old coordinate system.

a11, a12, a21, a22 = coefficients (constants) for the transformation.

In short, the principal component data values are simply linear combinations of the original data values (eigenvector loadings) selected in such a way that each successively extracted linear combination or principal component has a smaller variance.

Principal component enhancements are generated by displaying contrast stretched images of the transformed pixel values. As in the case of ratio images, principal component images can be analysed as separate black and white images, or any three component images may be combined to form a colour composite. If used in an image classification process, principal component data are generally treated in the classification algorithm simply as if they were original data. However, the number of components used is normally reduced to the intrinsic dimensionality of the data, thus making the image classification process much more efficient by reducing the amount of computation required. Principal component enhancement techniques are particularly appropriate where little prior information concerning a scene is available.

Reducing the number of image bands input for principal component analysis (PCA) ensures that certain materials will not be mapped and increases the likelihood that others will be unequivocally mapped into only one of the principal component images. During an applications development project (Loughlin 1991) at the UK National Remote Sensing Centre (NRSC), a new and simple methodology was developed for alteration mapping using ATM and TM imagery of the Great Basin Region of the western United States. The technique is fast, robust and reliable, and requires no atmospheric or radiometric correction. Furthermore it can be carried out with standard Principle Component Analysis software. The technique requires only a rudimentary understanding of the spectral properties of minerals and vegetation and it relies on the ability of the principal component to map increasing subtleties of data variance into successive components. No detailed knowledge of specific targets is required.

Figure 9.17 Principal Component Combination PC4 03 Dec 1986; PC2, PC3 26 June 1992 (RGB)

Scale 1:155 000

The statistical variance in multispectral images is related to the spectral response of various surface materials such as rocks, soils and vegetation, and it is also influenced by the statistical dimensionality of the image data. When multispectral image channels are treated as variables and subject to transformation, it follows that the ordering of principal components is influenced both by the spatial abundance of various surficial materials and by the image statistics. The influence of scene statistics which can be both measured and adjusted, in order to 'force' the transformation and provide information on the spatial distribution of particular surficial materials. In other words, using PCA as an image interrogation technique.

For the purposes of this study, a modification [illegible] the Loughlin (1991) technique was applied, using a combination of principal component 4 (PC4) from 03 December 1986, principal components 2 (PC2) and 3 [illegible] 26 June 1986 (PC4-red, PC2-green, PC5-blue) were found to extract maxim[illegible] data of the study area in terms of pan location (see figs. 9.17.2, 9.17.[illegible]

This principal component combination picks up the pan sites of the shallow, vegetated pans with a reddish peripheral signature, a 'beach' effect, possibly a moisture response associated with calcretisation of the pan soils. The same signature is found in the channels draining into Barberspan and Leeupan and around the palaeo-channel pans. What are known to be calcrete burrow-pits have a very strong reddish response. The blue signature indicates the pans with standing water, However, detail of vegetation in the pans has been lost. Paler-hued signatures in the cultivated lands are probably picking up the non-vegetated 'depressions'. This is a flexible technique in that principal component combinations from Landsat TM scenes of different dates over a season will extract new levels of information.

9.18 Fuzzy c-Means Clustering Algorithm (Fig 9.18, Fig 9.18.1 MapPocket)

The fuzzy c-means (FCM) is a segmentation procedure that utilises a clustering algorithm based upon fuzzy set theory (Cannon *et al* 1986). The procedure operates in a nonparametric unsupervised mode and uses the fuzzy c-means algorithm in two stages. The large number of clusters resulting from this segmentation process are then merged by

Figure 9.18 Fuzzy c-Means (Greyscale) 03 December 1986
Scale 1:155 000

use of a similarity measure on the cluster centres. This two-stage procedure leads to the separation of classes that would be otherwise overwhelmed in any practical one-stage clustering.

The analytical procedure used for the location of clusters in multispectral data is a variation of the maximum likelihood method such as CLASSY (Lennington and Rassbach 1979). It operates by interleaving maximum likelihood iterative estimation with adaptive procedure for splitting, combining and eliminating the resultant components of the mixture density. For the extraction of desired information from one-time data (from a single Landsat acquisition) it is customary to work with a supervised version of the classification procedure. The need for supervision can be relaxed if several well-spaced acquisitions of the same scene of interest are available and providing that they can be corrected for any atmospheric and viewing geometry effects.

Cannon *et al* (1986) describe a two-stage approach to the segmentation of Landsat TM image data by fuzzy c-means clustering. In the first stage an image is segmented into 'coarse' hard clusters and at the second each coarse cluster is segmented into 'fine' hard clusters. The many clusters that result can be merged back together to form larger clusters by a technique such as construction of the minimum spanning tree, which is shown to be sometimes as effective in performance for the major clusters as is labelling based upon *a priori* information. The fuzzy c-means provides a viable alternative to the maximum likelihood method and is completely unsupervised. Furthermore, FCM equations require fewer arithmetic operations than the maximum likelihood ones and it has shown that the FCM requires a smaller number of iterations than does the maximum likelihood method.

A modified Fuzzy c-Means Clustering algorithm was set up with 20 different classes which in terms of space are optimally as far apart as possible. An automatic classification was run using bands 3, 4, 5 and 7, 03 December 1986, since bands 1 and 2 are essentially redundant in terms of spectral discrimination between selected classes. Fig 9.10 is a grey-scale raster product of the Fuzzy c-Means clustering algorithm.

This classification is not particularly useful for detecting pan sites, however, calcretes in the palaeo-channel, around Damascus and Kopela pans and on the Harts River Flood plain

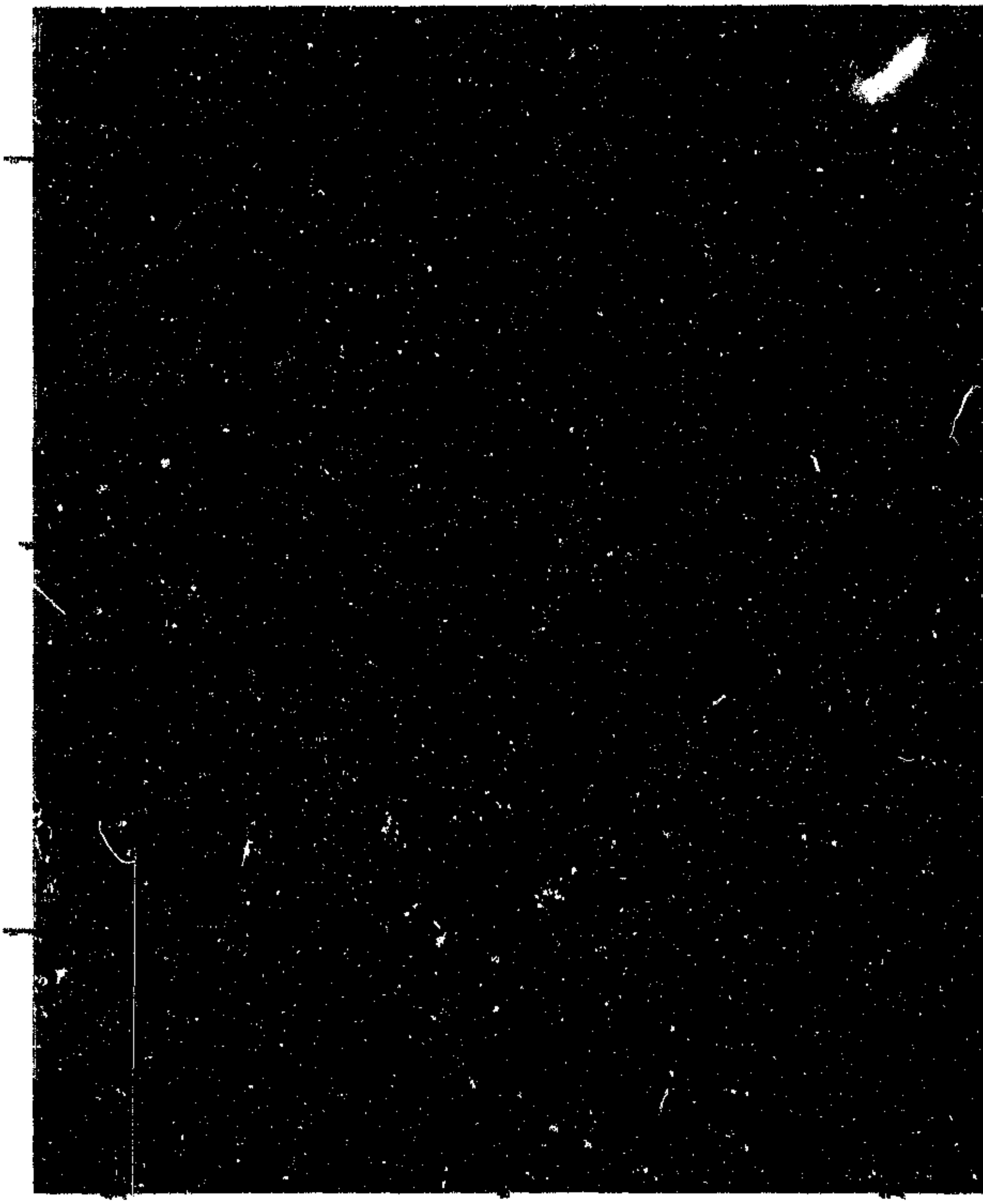

Figure 9.20 Geology Map of Study Area

Scale 1:155 000

Al - alluvium; P - pan; Ra - basaltic amygdaloidal lava, agglomerate tuff;

Rr - amygdaloidal lava, tuff; T-Qc - calcrete

can be distinguished as medium grey signatures. The uncultivated lands around Kopela Pan and the Sepane Drainage have characteristic signatures. The variable hues across the cultivated lands are probably a response to soil and moisture changes. This technique is again flexible in that different numbers of classes can be run to maximise the amount of information that can be extracted from each scene and related to features on the ground.

9.19 Pan Locations in Relation to Geology, Soils and Topography.

Pan locations were determined in relation to soils and geology and topography using the following methods:

9.20 Geology (Fig 9.20, Fig 9.20.1 Fig 9.20.2 Overlay-Map Pocket)

A scanned extract of the Vryburg 1:250 000 geology map (sheet number 2624; gravity edition) of the study area was converted to vector data (a set of vectors joined end to end make an arc or irregular line with a uniform set of properties). A map of the geology of the study area was created from the vector data which was then converted to a raster (a single, related, two dimensionally grouped set of numbers of a single data type). Each grey level represents the value of some parameter. Its position in a group represents its relative position to other values. These data were georeferenced to a Universal Transverse Mercator projection (Clarke 1880 spheroid), and warped to fit the projection using a second order polynomial transformation. The study area was subsequently extracted by copying across the area of interest from previously georeferenced and warped raster data and the map units assigned colours. The map units Al refer to alluvium; P to pans; T-Qc to calcrete; Ra to Basaltic amygdaloidal lava and agglomerate tuff, Rr to amygdaloidal lava, tuff; Qw to aeolian sands.

A map of pan distribution (Fig. 9.20.1, overlay-map pocket) was created using band combination 7, 4, 2. 03 December 1986. The map was converted to a raster and georeferenced, warped, and the study area extracted. P-P refers to the large pans with their associated calunette (palaeopans);. G-P to shallow vegetated pans (mainly grasses); W-P to water filled pans other than the palaeopans; D to unvegetated 'depressions' visible in the cultivated lands. Mayer's (1973) map of certain physical features of the upper

Figure 9.20.1 Extract of Map of Certain Physical Features of the Upper Reaches of the Harts and Molopo Rivers (Mayer 1973)

A - thin soil/rock outcrop; D - watercourse/vlei

P - pan; S - sandy soils

reaches of the Harts and Molopo Rivers was scanned in and the study area georeferenced, warped, converted to a raster and extracted in the prescribed manner and used as a reference for pan distribution. S refers to what Mayer terms sandy soils; A to thin soil/rock outcrop, D to a watercourse/vlei and P to pans.

The basic geology of the study area consists of Ventersdorp lavas with calcrete, alluvium and aeolian Kalahari sand lying on top of it. The large pans in the Harts palaeo-channel are associated with calcrete outcrops and calunettes. The floors of these pans consist of Ventersdorp lavas which break through in places, covered with a layer of greyish pan soils, with a calunette on their southeastern flanks. Damscus pan is an oddity in terms of size and morphology which is characteristic of the pans associated with the palaeo-channel of the Harts River in that it is not associated with an obvious drainage channel. Its position may well be associated with underlying geological structures such as faults and fractures. Kopela pan is associated with a calcrete outcrop which is possibly a product of a fluctuating water table in the palaeo-Harts drainage system. The shallow vegetated pans have a scattered distribution on the Ventersdorp lavas. However, they appear to be too shallow for their floors to be in contact with the lavas but probably owe their existence to slight fluctuations in topography and susceptibility of the local soils to pan formation.

9.21 Soils (Fig 9.21)

A soils map was drawn using the same method applied to Vryburg 1:250 000 Land Type Series map (sheet number 2624). Three main soil types occur in the study area (Macvicar1984). Most of the surface area is covered by the Bd series which falls into the category of plinthic catena where upland duplex and margalitic soils are rare (occupy less than 10% of the area). Unit Bd indicates land in which red/yellow apedal soils (Hutton, Bainsvlei, Avalon, Glencoe and Pinedene forms) that are dystrophic and/or mesotrophic predominate over red and/or yellow soils that are eutrophic, and in which red soils (Hutton and Bainsvlei) are not widespread.

The map unit Ea, found in the present and palaeo-channels of the Harts River are described as vertic, melanic red structured diagnostic horizons. It indicates land with a high base status, dark coloured and/or red soils, usually clayey, associated with basic

Figure 9.21 Soils Map of Study Area

Scale 1:155 000

Ae Soil Series - red-yellow freely drained soils

Bd Soil Series - plinthic catena (upland duplex and margalitic soils rare)

Ea Soil Series - one or more of vertic, melanic, red structured diagnostic horizons

parent materials.

Map unit Ae refers to a red-yellow freely drained soil, without a water table and belonging in one or more of the following soil forms: Inanda, Kranskop, Magwa, Hutton, Griffin, Clovelly. The map unit refers to land that does not qualify as plinthic catena and in which one or more of the above soil forms occupy at least 40% of the area. The Ae series is a red soil with a high base status more than 300mm deep with no dunes.

The large palaeo-pans are associated with the Ea series of soils but probably predate their formation, since the floors of the pans consist of Ventersdorp lavas overlain by a layer of greyish pan soils. Damascus pan again stands out in that it occurs in the Bd series of soils, floor consisting of Ventersdorp lavas and grey pan soils with a well formed calunette on its southern fringe. The shallow, vegetated pans occur on this soil series which is possibly conducive to the formation of non-permeable horizons in the form of calcretes and ferricretes. There are no pans in the study area associated with the Ae soil series.

9.22 Elevation (Fig 9.22, Fig 9.22.1 Map Pocket - courtesy of A. Bloem)

A greyscale elevation map of southern Africa compiled from the world digital data base, scale 1:1000 000, (Fig 9.22.1) gives the location of the study area. Light tones indicate high elevations and dark tones indicate low elevations. An extract of Figure 9.22.1 indicates that the study area straddles three elevation zones (Fig 9.22) with the greater part of the study area lying between 1360 and 1380 metres above sea level. A change of elevation is indicated in the northwest corner of the study area which coincides which the change in direction of drainage (Sepane and Molopo Rivers) towards the northwest. The southeast corner of the study area cuts into another elevation zone which coincides with the northwesterly direction of drainage of the Klein Harts into the Harts River.

10 DISCUSSION

Drawing on trends that have occurred in the USA the key to the problem of wetland management in South Africa is to develop a system involving both local and national control which requires good coordination and good publicity (Walmsley *et al* 1988). It involves the development and modification of policy, legislation and guidelines to be employed by the national or local agency managing a particular area and can only be done if correct information is available. Inventory is a stock-taking exercise, a standard business practice which if not followed can lead to inefficient administration of resources. The purpose of a National Wetland Inventory is to generate information on:

1. the location of southern African wetlands;
2. the characteristics of southern African wetlands;
3. the conservation status of southern African wetlands.

Two different kinds of information are needed:

1. detailed maps which delineate areas that meet the accepted definition of wetlands;
2. status and trend reports.

The problems of wetland management are summarised by a quote from Josephine Cooper of the United States Environmental Protection Agency (1985):

'....because wetlands come in all sizes, occur in all locations and each has differing and unique contribution to local ecology, no one agency has a monopoly on truth, techniques or understanding....'

It is a matter of detail which is affected by the level of decision-making in question - the detail required to make national policy, legislation and guidelines would not be as refined as that required by the local management decision maker. At an 'Inventory and Classification Workshop of Wetlands in South Africa' workshop held in 1988, several mapping options were put forward, including that of the National Wetlands Inventory system, but no consensus was reached.

The standard 1:50,000 topographical maps of South Africa differentiate between perennial non perennial and dry pans but not the type of pan. The operational definitions of these criteria are not clear and possibly is a highly subjective one based on the darker tones of water-filled or vegetation-filled pans on panchromatic aerial photographs used in the compilation of maps. Even though these jobs mostly are flown between May and August because of atmospheric moisture conditions, it would depend upon the month and rainfall for the season as to what is being recorded in the pans. In all probability one is seeing a continuum of pan features from relatively dry through to wet pans and this is reflected also in the plant communities associated with the pans. Another environmental gradient would be one related to salinity of water and substrate. The possibility exists that the features depicted as pans on maps are, in reality, rather different types of wetland that should be separated from one another. In the study area on the Ventersdorp Lavas, there appear to be two characteristic types of pans which occur in this pan-field: the large pans occurring in strings in the palaeo-channel of the Harts River, with their floors sitting on the lavas and having characteristic calunettes. These are well established features of the landscape. Secondly, the generally smaller, shallower, vegetated pans which owe their existence to slight changes in topography, susceptible soils and possible underlying geological structures. These pans display a continuum of size, depth, vegetation cover and ability to retain water and as landscape features are probably younger than the palaeo-channel pans. This pan-field is different in nature and extent to that found in the western Free State, for example.

Satellite data can offer substantial advantages over conventional aerial photographs because of its digital character and if properly handled, the cost-effective utilisation when studying large areas. The digital nature of the imagery allows for the enhancement of landscape features with computer processing techniques. The nature of remotely sensed data constrains investigators to specific working scales. Woodcock and Strahler (1987) determined that it was a combination of the spatial structure of the image and the viewed environment that determine the appropriate scales of observation. The spatial mapping accuracy of South African maps is standardised at plus/minus 0.75 mm. Therefore an area of 1x1 mm on a 1:250 000 scale map represents approximately 6.25 ha; and 2 x 2 mm represents 25 ha. Landsat TM, with 30 x 30 m spatial resolution and an accuracy of plus/minus 1 pixel geo-registration could be used for mapping at the 1:50 000 scale, since

30 m = 0.60 mm at 1: 50 000. The equivalent minimum scales for Landsat MSS and SPOT are:

1. Landsat MSS 80 m = 0.72 mm at 1:110 000
2. SPOT XS 20 m = 0.66 mm at 1: 30 000
3. SPOT PAN 10 m = 0.66 mm at 1: 15 000

This compares with the recommendations for use of remotely sensed data in Indonesia (Kucera 1986) that detailed surveys between 1: 25 000 and 1:50 000 should be possible with high resolution SPOT and Landsat TM imagery.

Thematic mapping, the usual technique for spatial data, overcomes the problems of delineating boundaries for what may be in reality heterogenous classes and provides a clearer continuum or gradation of information classes in terms of spatial heterogeneity and homogeneity (Robinove 1981). Accordingly, if a Landsat MSS pixel is to contain at least one complete pixel, this will compare to a mappable unit of approximately 2 ha (140m x 140m). Similarly for Landsat TM data, with a pixel size equivalent to 0.09 ha, the minimum mappable area will be approximately 0.5 ha. SPOT MSS at 0.04 ha per pixel will be 0.16 ha.

These area estimates do not appear to be constant throughout the literature. For forestry, Kucera (1986) assumed minimum mappable areas for TM and SPOT to be in the range 0.06 - 0.04 ha. Van der Zel (1988) found MSS accurate to 5 ha, areas of < 25 ha for exotic and < 50 ha for indigenous forest were not mapped. Likewise, Edwards et al (1983) concluded (for visual interpretation of visual veld burns off Landsat MSS) the smallest mappable burnt area was 30 ha. By comparison, Landsat TM data has been used to map fires of less than 10 ha in mediterranean-style vegetation with the limit being 5 ha. These area estimates differ because of the range of ground resolution cell sizes associated with the different remote sensors. Furthermore, the topography being scanned and the ability to discriminate spectral signatures will also influence influence the size of the mappable units.

The flat landscape of the North West Province lends itself to Landsat TM data acquisition. With an instantaneous field of view (IFOV) of 30x30m, Landsat TM is a useful tool for locating pans of varying size, morphology and vegetation structure over a large area. The spatial extent of the pans and the land use around them can be determined and mapped. The smallest vegetated (grass) pan that could be reliably identified from a 4, 3, 2, band combination 03 December 1986 Landsat TM extract of the study area, measured with a measuring wheel, was some 100 metres across. With current Landsat TM data, it may well be possible to identify smaller pans. Furthermore Landsat TM can provide synoptic, quantifiable and repetitive information on these pans.

From this study it was not possible to assess the level of resolution that specific vegetation communities could be mapped within or around the pans (ie zonations) using Landsat TM, firstly because of the vintage of the Landsat TM data and secondly, because of the unusually dry early summer conditions. As a rule species-level mapping is generally not feasible with satellite imagery unless the species involved is totally dominant and shows a significant structural difference to the surrounding vegetation cover. Communities are more easily determined, but again this depends on the structure and cover relative to the surrounding vegetation. In general, specifics are difficult to map, but major differences are not, such as mangrove or saltmarsh extent. Likewise areas within large wetlands that have been lost to agriculture (ie cropped or drained for pasture) will also be identifiable. In some cases, certain vegetation covers will not be able to be separated on satellite imagery. An example of this is the inability to separate exotic wattle stands amongst indigenous riparian vegetation since both have the same spectral characteristics due to similar structural appearances. However, in this particular flat, semi-arid, agricultural landscape this sort of discrimination should not be a problem.

With the Landsat TM data used in the study, it was possible using a 4, 3, 2, band combination and a Transformed Vegetation Index, to discriminate between crop and natural vegetation and biomass. Current Landsat TM data and groundtruthing would be required to assess what vegetation communities can be identified by their spectral signatures, growing around the edges of the large pans which occur in the palaeo-channels of the Harts River. Likewise the smaller, vegetated pans scattered across the landscape. These pans manifest themselves as vegetation islands in the cultivated lands of the December 1986 scene, since these lands are not yet crop-covered. It would be interesting to determine whether they can still be identified in sequential Landsat TM scenes as the crop cover emerges. Judicious use of band combinations and the Transformed Vegetation Index can provide additional information with synoptic data. Furthermore it should be possible to relate the spectral signatures of the vegetation zones around Barberspan as the water level in the pan rises and falls.

In general terms the type and area of wetland that can be effectively identified using Landsat TM are based upon the fact that detail or features that are identifiable on a satellite image are dependent on two basic factors. Firstly, the size of the feature in relation to the minimum area that can be identified, and secondly, the difference in 'spectral signature' between specific features and its surroundings. If the wetland 'type' is sufficiently different in either form or structure to its surroundings then it should be visible for example, open water bodies such as farm dams, impoundments, lagoons or lakes) are clearly discernible. Wetlands which do not contain areas of open water, in other words, closed vegetation communities, may be more difficult to discriminate unless they differ significantly from the surrounding vegetation types. For example, large vlei areas such as Nylsvlei are only inundated on an infrequent basis and unless the imagery is obtained when water extent is at a maximum, the area could feasibly be classified as a combination of grassland and woodland/savanna, and as such may not be clearly identifiable. Similarly riparian forest (in terms of satellite imagery) is only riparian in the sense of its location, and may appear (visually and spectrally) to be similar to other areas of closed-canopy indigenous forest communities. Other 'types' such as dry, non vegetated will easily be identifiable, due to the different image colours associated with the dry sand/clay deposits compared to the surrounding vegetated lands.)

The question of whether it is possible to recognise the functional limit of pans of different types in the study area, in terms of water fill and retention is difficult to assess with the two scenes available for this study. The only perennial water body in the study area is Barberspan and that through a diversion of the Harts River. The water level in the pan is very much dependent on the flow of water in the river. Furthermore, it is difficult to assess how much the water level in the pans is affected by subsurface flow and secondary sources of information such as rainfall data, soil structures and analysis of geological structures such as faults, fractures and other lineaments would have to be correlated to provide an insight into the water retention of the pans. It would be possible to correlate the construction of structures such as dams and roads with synoptic Landsat TM data and water fill of pans in their vicinity.

The wetland condition of the pans can be, to a certain extent, inferred from Landsat TM data. Whether or not the pans contain water and the surface area of water can be determined and whether or not they contain vegetation and to what extent. The 4, 3, 2, band combination 03 December 1986 scene of Barberspan shows tonal differences which are either a product of changes in depth and/and turbidity. In the 26 June 4, 3, 2 band combination the level of water is higher and the colour tone very much more even in response to the greater depth of water. Information on the distribution of water in both the palaeo-channel pans and the smaller vegetated pans plus their vegetation cover would be useful in determining the dispersal of water birds. This would be of particular use if the pans favoured by particular birds is known and the water level and vegetation cover they require.

It is interesting to speculate on what the impact of the cultivation practices around these vegetated pans are having on them and where in Verhagen's (1991) ecological model of pan propagation, the pans in this semi-arid, human-altered landscape are headed. The smaller, vegetated pans may well be into a cycle of in-filling with soil drift from ploughed lands exceeding any windblown deflation and the exclusion animal of animal excavation. The picture with the shallow grass pans in the old Kunana location which still retains natural bushveld and communal grazing systems may be different. Some of the pans which occur in the area are subject to grazing and trampling by livestock and persist as distinct depressions. Use of synoptic Landsat TM data and groundtruthing could shed some light on the condition of these pans.

There are enigmatic signatures in the cultivated pre-crop covered lands in the December 1986 Landsat TM scenes of the study area. They are visible in the principal component combination image as well as 4, 3, 2; 7, 5, 4, and 7, 4, 2 band combinations, which suggests that it is both a soil and moisture response. Detail is lost in these band combinations in the winter scene. It was not possible to come to any conclusion about these features in the cultivated lands because conditions were so dry and also gaining sufficient access to enough fields to have a good look at them However, I would speculate that these 'depressions' have ploughable soils unlike the other vegetated pans in the lands which owe their existence largely to the fact that their soils and pan margins are too hard to plough. It is probably worth investigating these vegetation islands to determine whether there are any vegetation communities, remnant or otherwise, worth recording and preserving. Sequential Landsat TM could be used to monitor activity in the fields around the pans in terms of cropcover and water content and vegetation cover in the pans.

There many different types of pans found in the pan-fields across southern Africa. Allan (1987) suggests that they could be grouped according to their vegetation types, recognising five main types of pan:

1. Grass pans - covered with a variety of grasses and sedges.
2. Salt pans - have an extremely saline substrate and are fringed with the sedge, *Schoenoplectus triqueter.*
3. Reed pans - with a central *Phragmites* reed bed surrounded by a ring of open water within which submerged aquatic plants like, *Potamogeton* species occur. (eg Lake Chrissie area pans).
4. Sedge pans - with locally dense stands of sedges like *Schoenoplectus corymbosus* and *Eleocharis palustris.*
5. Open pans - largely devoid of plant cover except around their shorelines where a common grass is *Cynodon dactylon* and sedges, of the genera *Scirpus, Cyperus* and *Juncus.*

This classification was put forward as a tentative scheme, but clearly reflects the variation in major plant communities between pans. To date, no effort has been made to link geomorphology of pans with vegetation type and it would probably prove to be a near impossible task since pans are subject to such diverse environmental influences and variable histories as landscape features. The vegetation that grows in and around pans at a particular point in time is influenced by substrate and climate (Verhagen 1991). The classification system should define the limits of the pans as wetland ecosystems according to ecological characteristics (Breen 1987) and its primary purpose to describe ecological units having certain homogenous natural attributes (Cowardin et al 1979).

In this study it has been shown that it is possible to distinguish the type of pan, firstly by its location in the landscape (whether or not it is associated with the fossil Harts River drainage system. Damascus pan is an obvious exception - which possibly has a geological structural explanation). Secondly, whether it is vegetated across its surface or around its perimeter. A classification of pans for this area could be set up based on site, morphology and associated vegetation. However it would require a lot of foot-work, hopefully with current Landsat TM data in hand to pick out spectral signatures of note and relate them to the ground. There is no literature on the use of satellite data in determining pans as landscape features or their associated vegetation so the data and techniques employed would have to be adapted to the season of the year and rainfall to pick up detail in the pans. However, once the system has been developed it can serve other purposes:

1. to arrange the ecological units in a system that will aid decisions about resource management;
2. to furnish units for inventory and mapping;
3. to provide uniformity in wetland concepts and terminology.

In the USA Landsat TM is used by Ducks Unlimited (international conservation organisation currently undertaking an inventory on the primary waterfowl production area for north America), to monitor 'wet' wetlands. Ducks Unlimited uses a standard image processing procedure; for each scene a file with 230 spectral classes is used, each group of spectral classes forms an informational class such as shallow or deep marsh (Thompson 1994), whereas 20 spectral classes were used in the Fuzzy-c Means Clustering Algorithm to pick up detail in the pans. The grouping is unique for each scene and varied according to the image interpreter, time of year, precipitation etc. They use Band 5 of TM because of its capacity to discriminate levels of vegetation and soil moisture (and is best used with bands 3 and 4 for wetland discrimination). Band 3 is useful for determining water quality, band 1 for separating open water from open water with submerged vegetation.

In searching for cost effective and repetitive ways to monitor estuaries, Australian researchers (Lavery et al. 1993) arrived at statistically significant, empirically based algorithms which were successfully developed for: pigment concentration, SDD and salinity. They can thus effectively determine surface water characteristics and provide a synoptic view of processes through the use of time series. They found that the problems involved in using this method of monitoring estuaries include cloud cover, time delay in data acquisition and processing and finding the requisite computer facilities when needed. They found that the taxonomic nature of algal blooms could not be determined.

Landsat TM was used to monitor wetland land-use of the lower basin of the Mekong River (Thompson 1994), though aerial photographs were used as well for their greater resolution when mapping at the 1:50,000 scale.

On the mapping of wetland, Howman (1987) suggested Landsat or SPOT imagery be used for a broad-brush inventory. Howman and Kempster (1986; 1987) investigated the use of algal content (chlorophyll a) and turbidity measurements from Roodeplaat Dam combined with Landsat reflectance data to develop a model which could be used to interpret data from other South African wetlands. The end product was CALMCAT (Canonical Analysis Landsat Model of Chlorophyll a and Turbidity). Quibell (1987; 1992) found that CALMCAT only worked successfully if recalibrated for each overpass and each impoundment, and speculated that chlorophyll is not an adequate measure of reflectance in water quality studies.

McCarthy *et al* (1993) used multispectral SPOT 2 imagery to survey the Okavango Delta, where a transformed vegetation index (TVI) was found to be semi-quantitatively related to standing crop and thus to resource availability and water movement in the delta. The TVI image proved useful in exposing what appear to be tectonic lineaments. Of interest were areas of abnormally prolific growth which were highlighted in the multispectral images by the artificial colours used, which might well have been missed had another system been used.

These applications of satellite data to the problem of monitoring and mapping wetlands demonstrate the flexibility of using digital data. Satellite imagery and the algorithms derived to deal with it are improving rapidly as is the computer modelling of the data which also incorporates data from other disciplines, so any system chosen for wetland monitoring must take cognisance of the fact. The image processing techniques applied in this study with two sets of vintage Landsat TM have shown that it is possible to locate pans over a wide surface area and to determine size, type and extent of vegetation and whether they were water filled. The techniques can be adapted and changed to extract maximum information and detail according to the season and date of acquisition of the data.

11. CONCLUSION

Landsat TM data, properly handled, could play a significant role in the inventory of pans into the National Wetland inventory in terms of their identification, mapping and monitoring. However, what has also emerged from this study is that remote sensing is a specialist field which requires years of training to acquire all the skills needed to attain any level of competence. It is possible in a relatively short period of time to become familiar with the necessary image processing techniques with to extract information from a particular scene, but to learn the art and the science of a really good image processor takes [illegible] and practice. It would seem that educators in the field of global and environmental monitoring face four major challenges in terms of educating environmental managers:

1. Inclusion of the indispensable tools of both remote sensing and geographical information systems (GIS) as standard components in curricula of courses in environmental management or environmental science.
2. Encouragement of interdisciplinary training both within the natural sciences and between these and social economic sciences.
3. Stimulation of a new approach with more direct measurement of dynamic environmental characteristics and on a range of extreme spatial and temporal scales.
4. The development of skills and attributes to influence decision makers. The horizons of scientists are usually confined to the knowledge and technology of their particular discipline. They see their role as presenting information, on which others, the planners, policy and decision makers will act in the naive belief that the evidence and logic of their analyses and arguments will yield a desirable outcome.

Remote sensing not only extends our spatial and temporal observation capabilities; it also increases the variety of sensor (visible, infrared, radar, ther[illegible] etc) with which to observe and monitor. This multitude of sensors for data collection has generated a data overload in the bio- and geosciences thus requiring much filtering, decoding, preprocessing and compression of raw data to obtain useable information. Probably the most important consideration in the mapping and monitoring of pans or other wetlands is that it should be geographical information system (GIS) based as it allows for statistical and graphical manipulation and output. Different aspects of the pans can be monitored continuously, or at intervals whether it is water quantity, quality, or vegetation in and around the pan. Trends can be identified and monitored and impacts determined. The major problem is to get over the moment of inertia in organising and delegating the means and methods of setting up a wetlands inventory for southern Africa. Pans by their very nature are located in flat landscapes which are ideally suited to satellite data acquisition. The use of Landsat TM could be employed in delineating pan-fields, locating pans within the field and assessing their size, and saying something about their morphological form and vegetation. In terms of building up a database on the pans, Landsat TM could be invaluable in providing synoptic, quantifiable and repetitive information.

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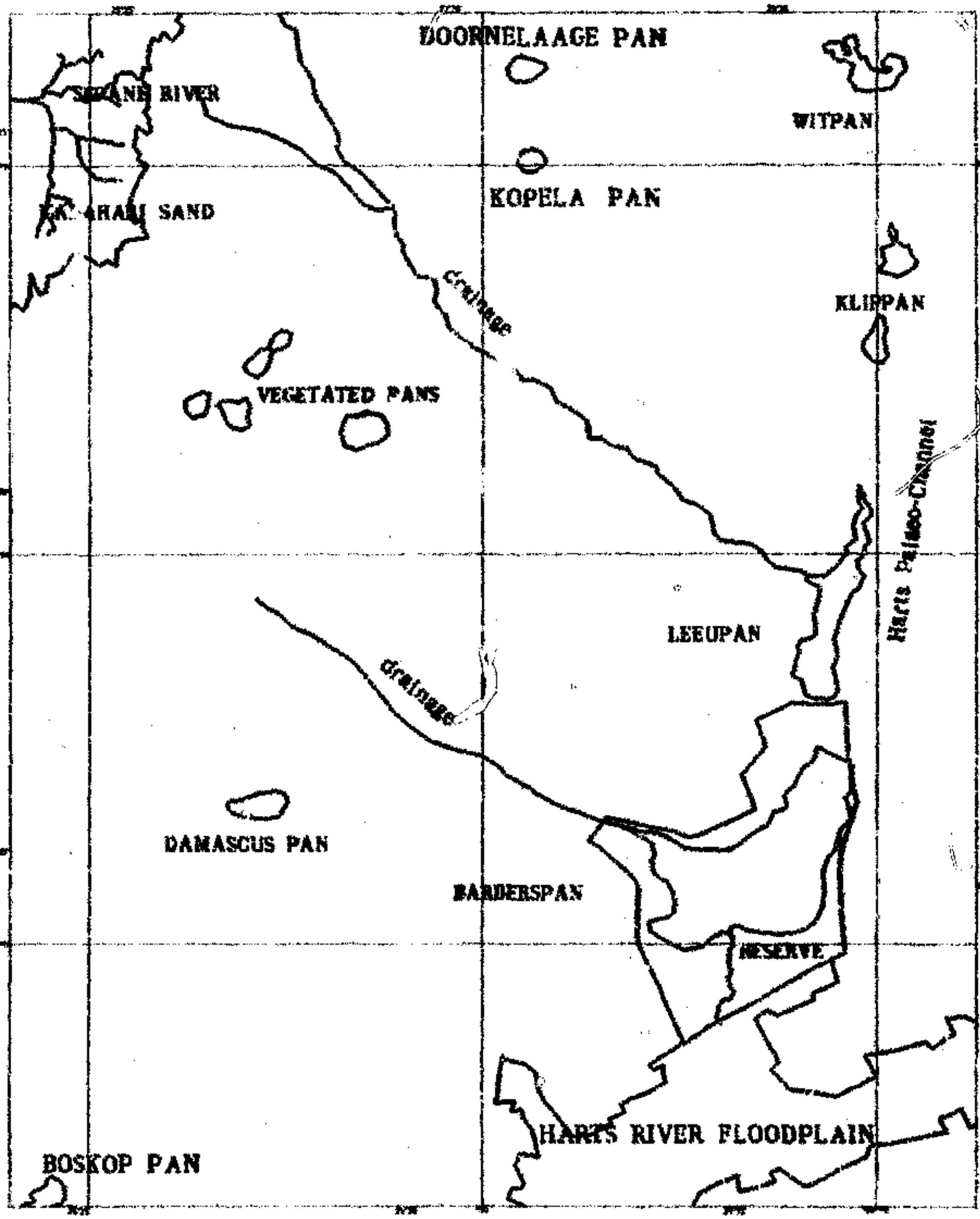


Figure 9.6.2 Map of Site Locations in the Study Area

Scale 1:155 000

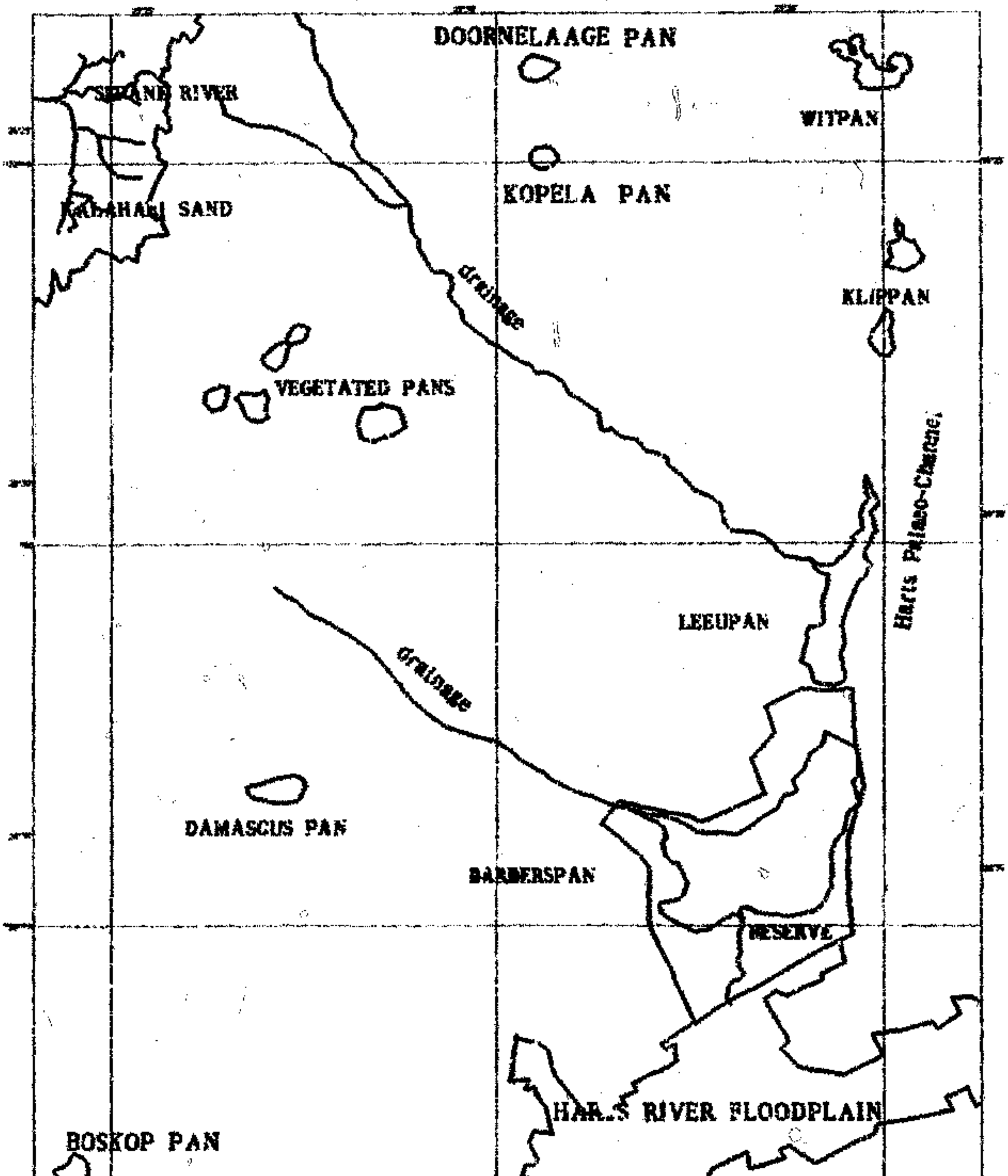


Figure 9.6.2 Map of Site Locations in the Study Area
Scale 1:155 000

Table 9.11 Summary of Spectral Reflectance Data in six Classes

Beach:										mean	median	var.	std.
band 1	98	93	116	115	102	113	98	220	136	*122.1111*	*113*	*1668.359*	*40.84556*
band 2	48	42	61	58	48	55	47	121	71	*61.22222*	*55*	*566.5*	*23.80126*
band 3	59	47	87	79	58	73	64	173	96	*80.96667*	*73*	*1428.188*	*37.79137*
band 4	100	87	96	100	98	98	93	142	111	*103.3333*	*98*	*239.4844*	*15.47526*
band 5	142	118	184	170	146	176	138	248	195	*168.5556*	*170*	*1402.938*	*37.4558[illegible]*
band 7	67	54	102	32	70	95	51	148	100	*89.44444*	*92*	*779.8594*	*27.92596*

Crops:					mean	median	var.	std.
band 1	102	91	106	103	*100.5*	*102.5*	*32.25*	*5.678908*
band 2	57	48	62	62	*57.25*	*59.5*	*32.6875*	*5.717298*
band 3	94	81	104	114	*98.25*	*99*	*149.1875*	*12.21423*
band 4	93	78	96	106	*93.25*	*94.5*	*100.6875*	*10.03432*
band 5	205	187	218	234	*211*	*211.5*	*297.5*	*17.24819*
band 7	126	117	134	146	*130.75*	*130*	*113.6875*	*10.66243*

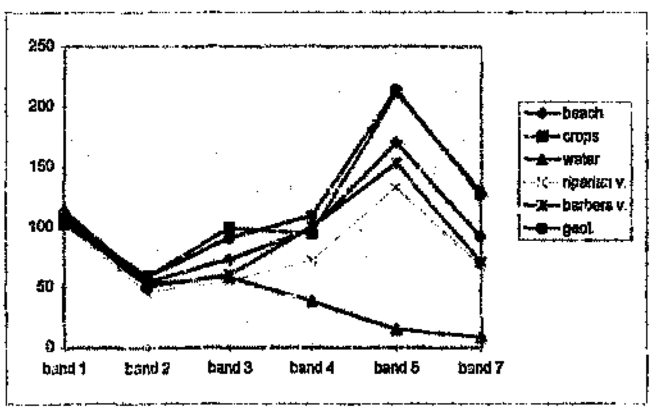
Water:							mean	median	var.	std.
band 1	118	111	111	127	101	134	*117*	*114.5*	*119.6667*	*10.93923*
band 2	55	52	51	68	42	76	*57*	*53.5*	*122*	*11.04536*
band 3	60	56	55	92	51	111	*70.83333*	*58*	*507.1389*	*22.51974*
band 4	31	26	25	45	46	79	*42*	*38*	*343.3333*	*18.5[illegible]*
band 5	15	14	13	14	44	18	*19.66667*	*14.5*	*120.8889*	*10.99[illegible]*
band 7	9	7	8	7	14	9	*9*	*8.5*	*5.666667*	*2.38047[illegible]*

Riparian:						mean	median	var.	std.
band 1	103	110	101	104	101	*103.8*	*103*	*10.96*	*3.310589*
band 2	40	50	43	44	46	*46.2*	*46*	*6.56*	*2.56125*
band 3	55	66	56	55	54	*57*	*55*	*20.4*	*4.516636*
band 4	86	72	68	57	93	*79.2*	*72*	*159.76*	*12.63962*
band 5	131	152	131	133	137	*136.8*	*133*	*62.56*	*7.909488*
band 7	60	62	68	69	63	*68.4*	*68*	*57.04*	*7.552483*

Barbers:												mean	median	var.	std.
band 1	89	90	96	165	190	132	105	90	152	209	92	*128.2727*	*106*	*1779.835*	*42.18809*
band 2	41	38	48	87	102	67	51	40	77	110	45	*64.18182*	*51*	*621.2397*	*24.92468*
band 3	45	45	60	120	143	92	60	44	105	158	54	*84.18182*	*60*	*1586.512*	*39.83105*
band 4	82	53	107	95	119	100	93	73	102	131	116	*98.27273*	*100*	*424.9256*	*20.61372*
band 5	118	115	153	192	221	176	137	108	178	243	138	*161.3636*	*153*	*1797.504*	*42.39698*
band 7	50	54	71	132	146	104	59	43	114	159	57	*89.9090[illegible]*	*71*	*1631.719*	*40.39454*

Geol:						mean	median	var.	std.
band 1	138	100	97	128	109	113.8	108	248.16	15.75309
band 2	83	63	53	76	59	94.8	59	153.76	12.4
band 3	144	91	89	128	87	107.4	91	541.84	23.27745
band 4	140	92	99	130	109	114	109	333.2	18.25377
band 5	256	214	186	248	196	220	214	738.8	27.18056
band 7	161	127	110	140	109	128.8	127	407.76	20.19307

	beach	crops	water	riparian v.	barbero v.	geol.
band 1	113	102.5	114.6	103	106	108
band 2	55	59.5	53.5	46	51	59
band 3	73	99	58	56	60	91
band 4	96	94.5	38	72	100	109
band 5	170	211.5	14.5	138	153	214
band 7	92	130	8.5	68	71	127



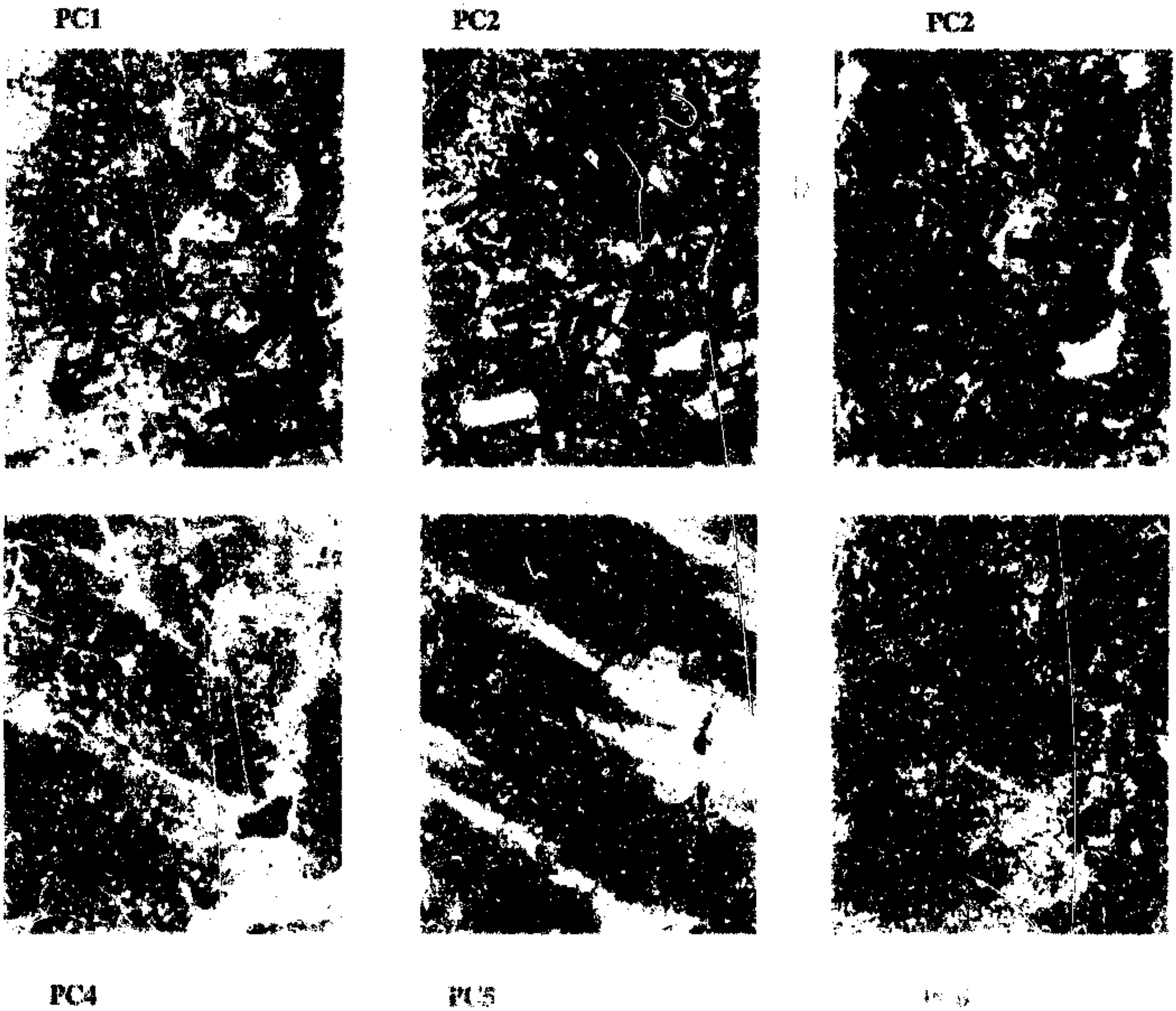
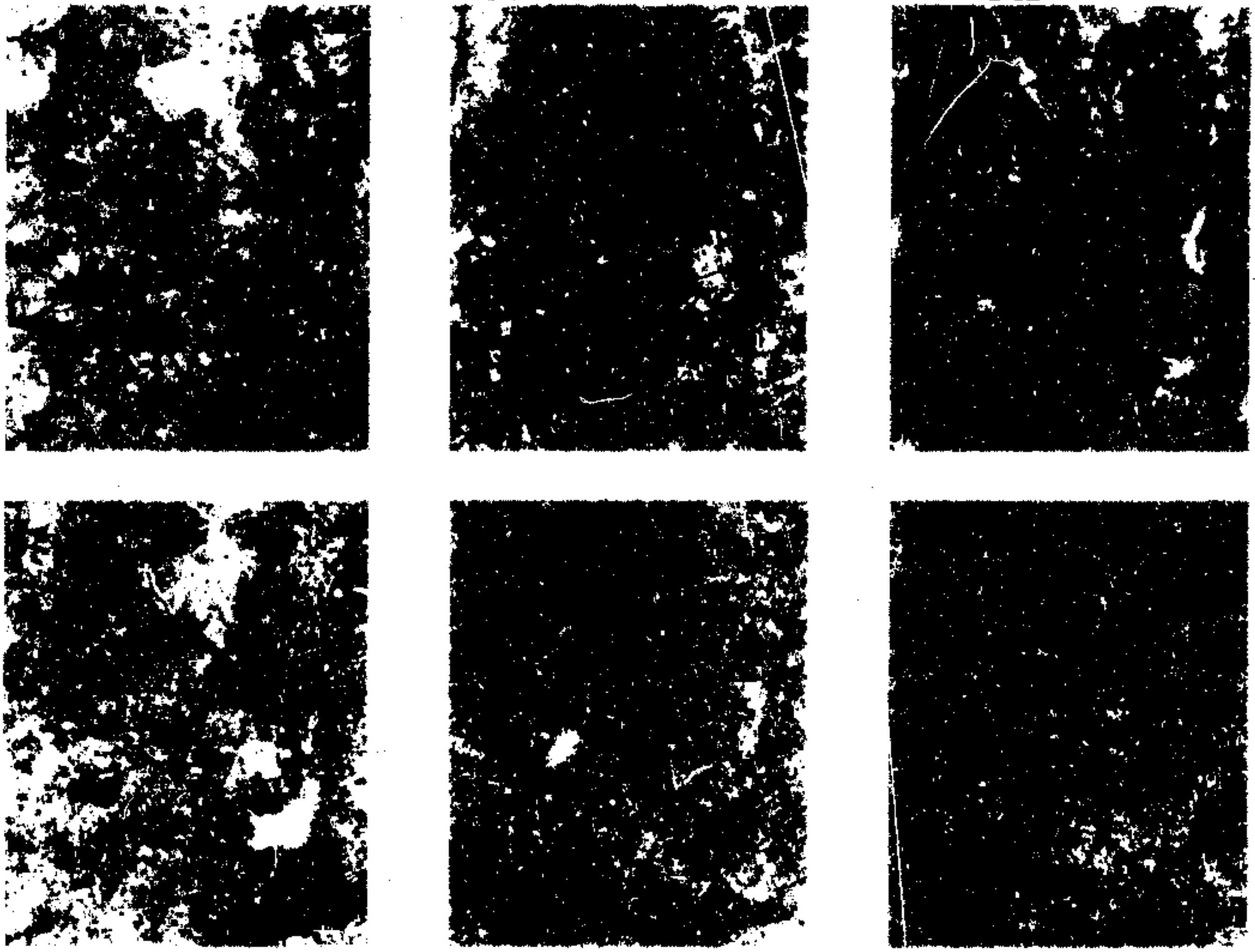


Figure 9.17.2 Principal Components 03 December 1986

PC1 PC2 PC2



PC4 PC5 PC6

Figure 9.17.2 Principal Components 26 June 1992

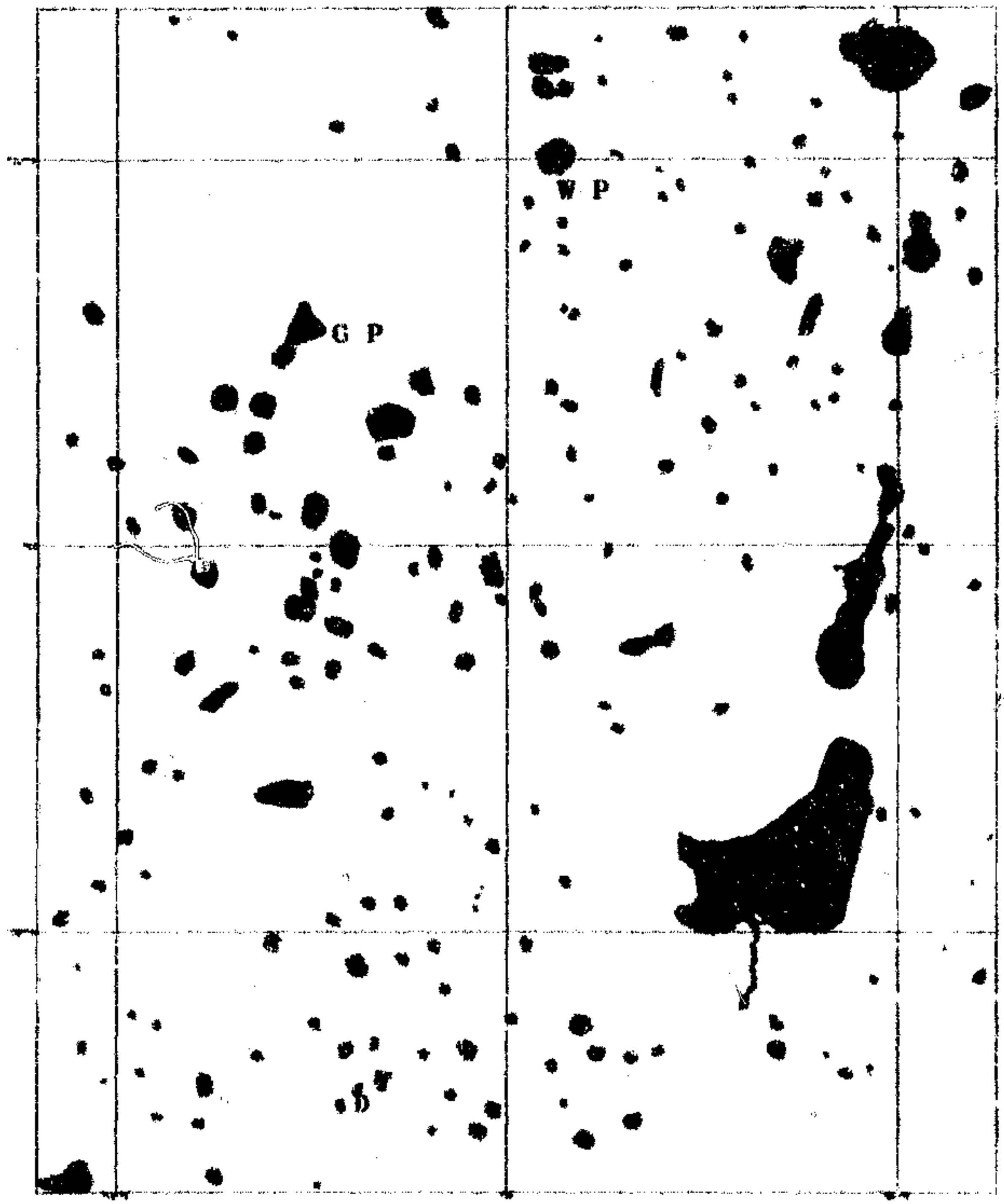


Figure 9.20.2 Map of Pan Distribution in Study Area (Overlay - Map Pocket)

Scale 1:155 000

D - depressions; G-P - grass pans;

P-P - palaeochannel pans; W-P - water-filled pans

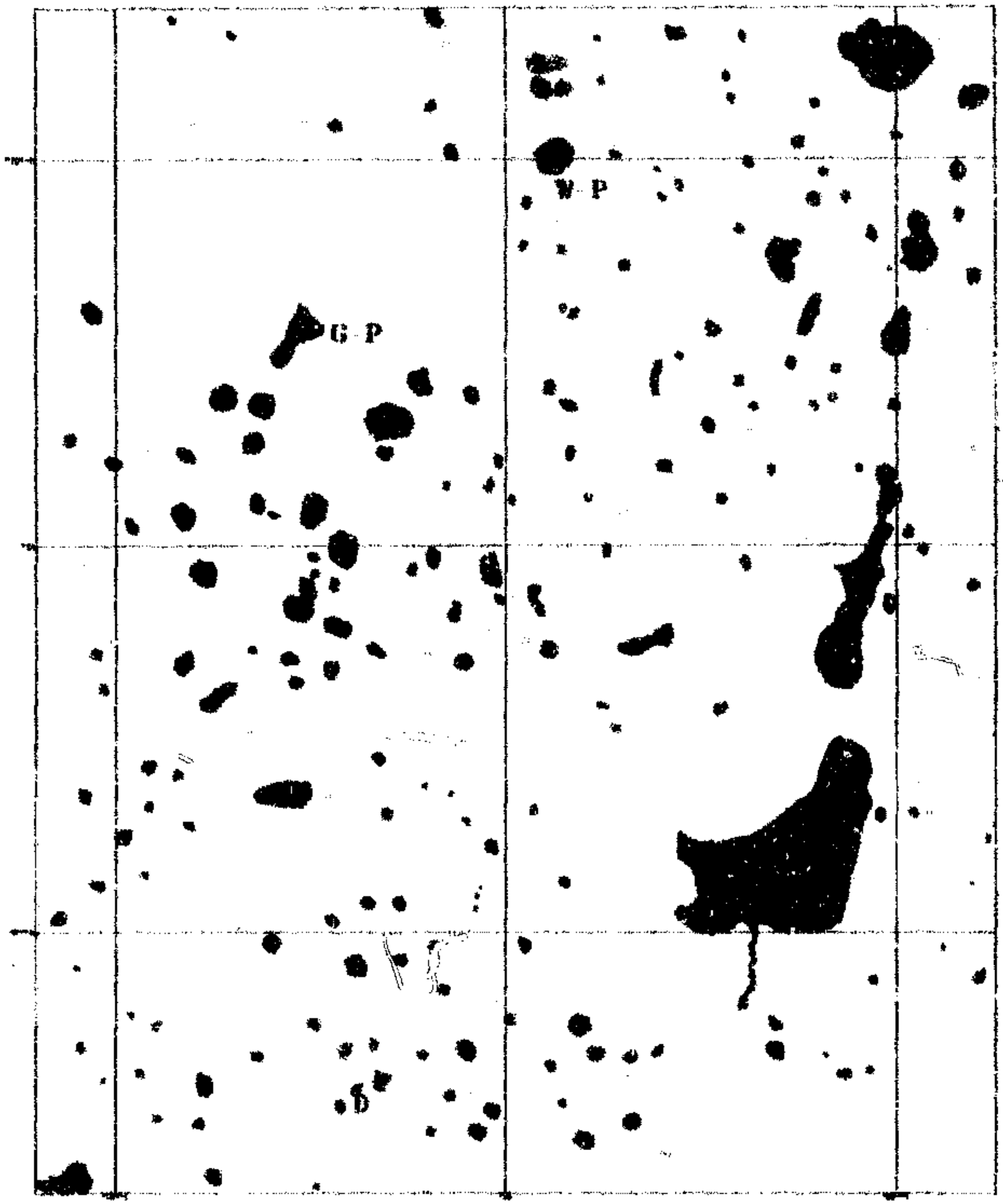


Figure 9.20.2 Map of Pan Distribution in Study Area (Overlay - Map Pocket)
Scale 1:155 000
D - depressions; G-P - grass pans;
P-P - palaeochannel pans; W-P - water-filled pans

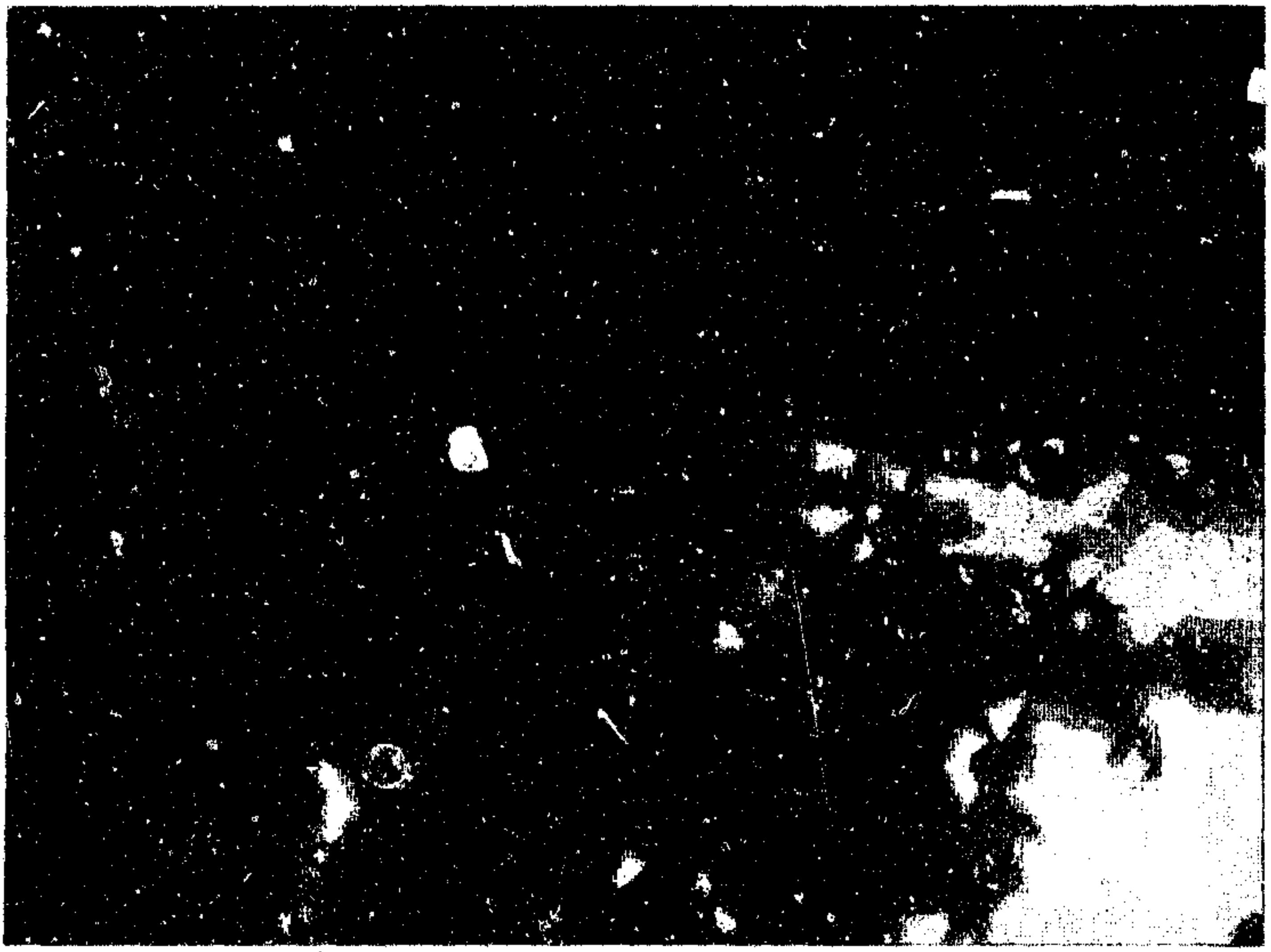
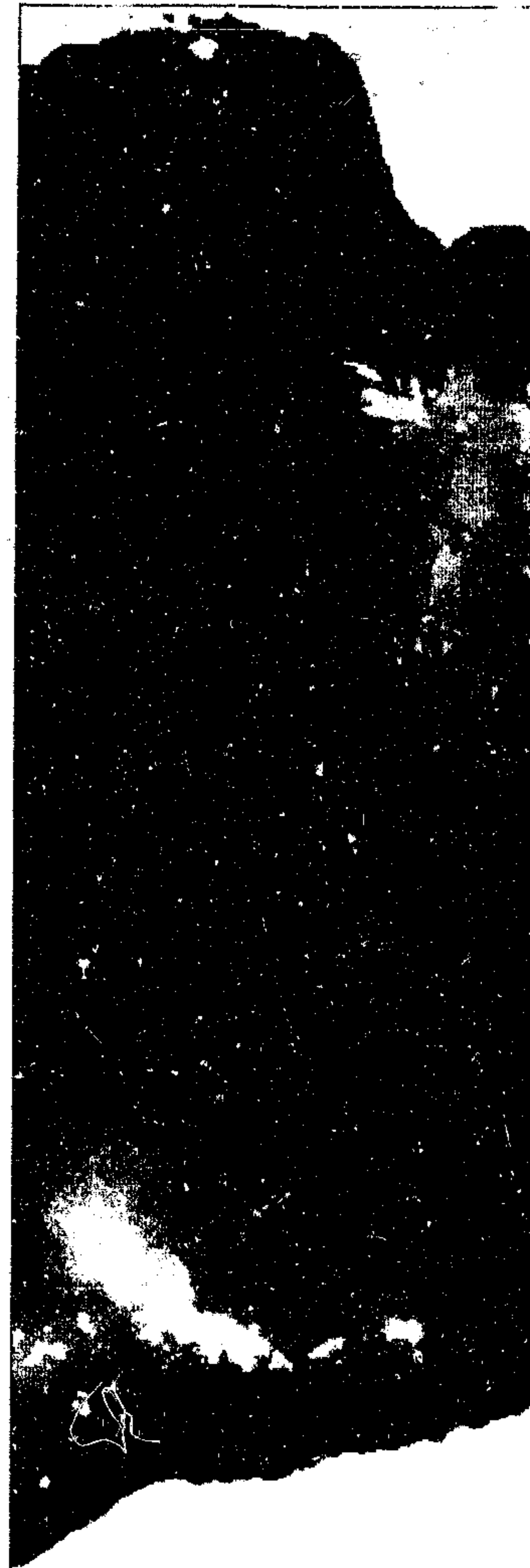


Figure 9.22.1 Extract of the Southern African Elevation Map Showing Study Area
Scale 1: 116 000

Figure 6 Band Combination 7, 4, 2, WRS - 1742-78D (Southeast Quadrant)

Acquisition Date: 03 December 1986

Scale 1:325 000



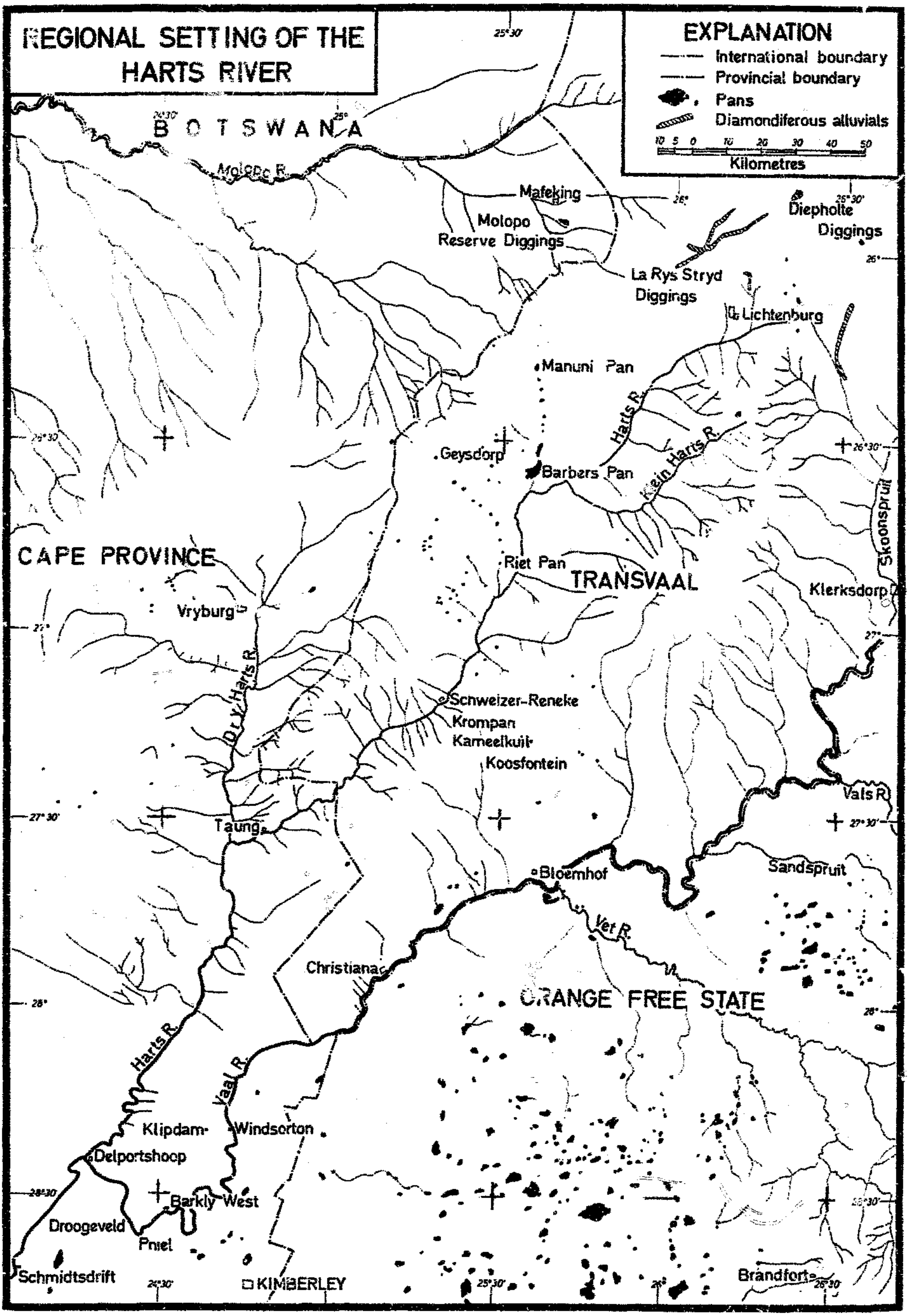


Figure 2 Map of the Regional Setting of the Harts River (Mayer 1973)

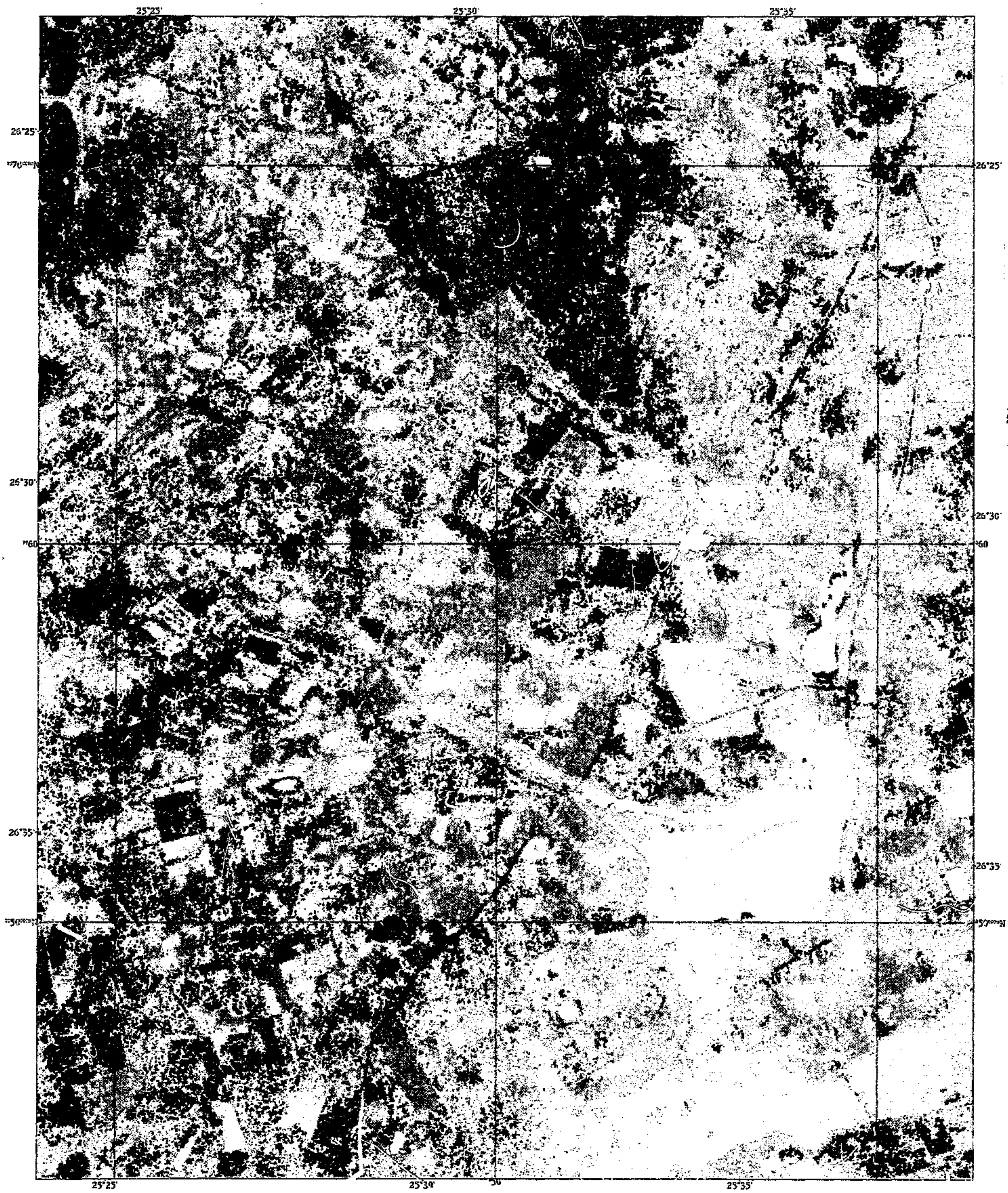


Figure 9.18.1 Fuzzy c-Means (Greyscale) 03 December 1986

Scale 1:100 000

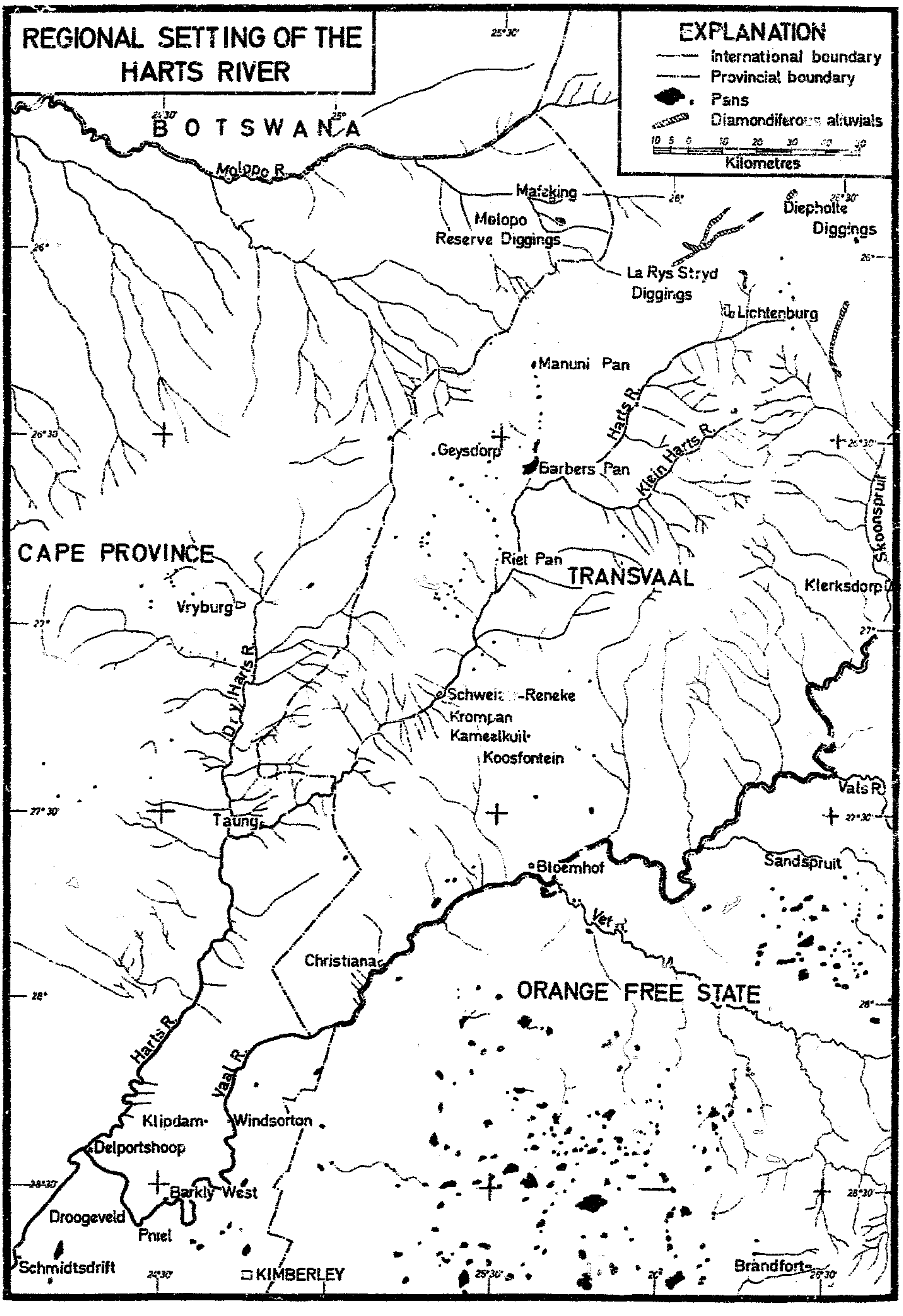


Figure 2 Map of the Regional Setting of the Harts River (Mayer 1973)

Figure 9.17.1 Principal Components Combination PC4 03 December 1986;
PC2, PC3 26 June 1992 (RGB)

Scale 1:100 000

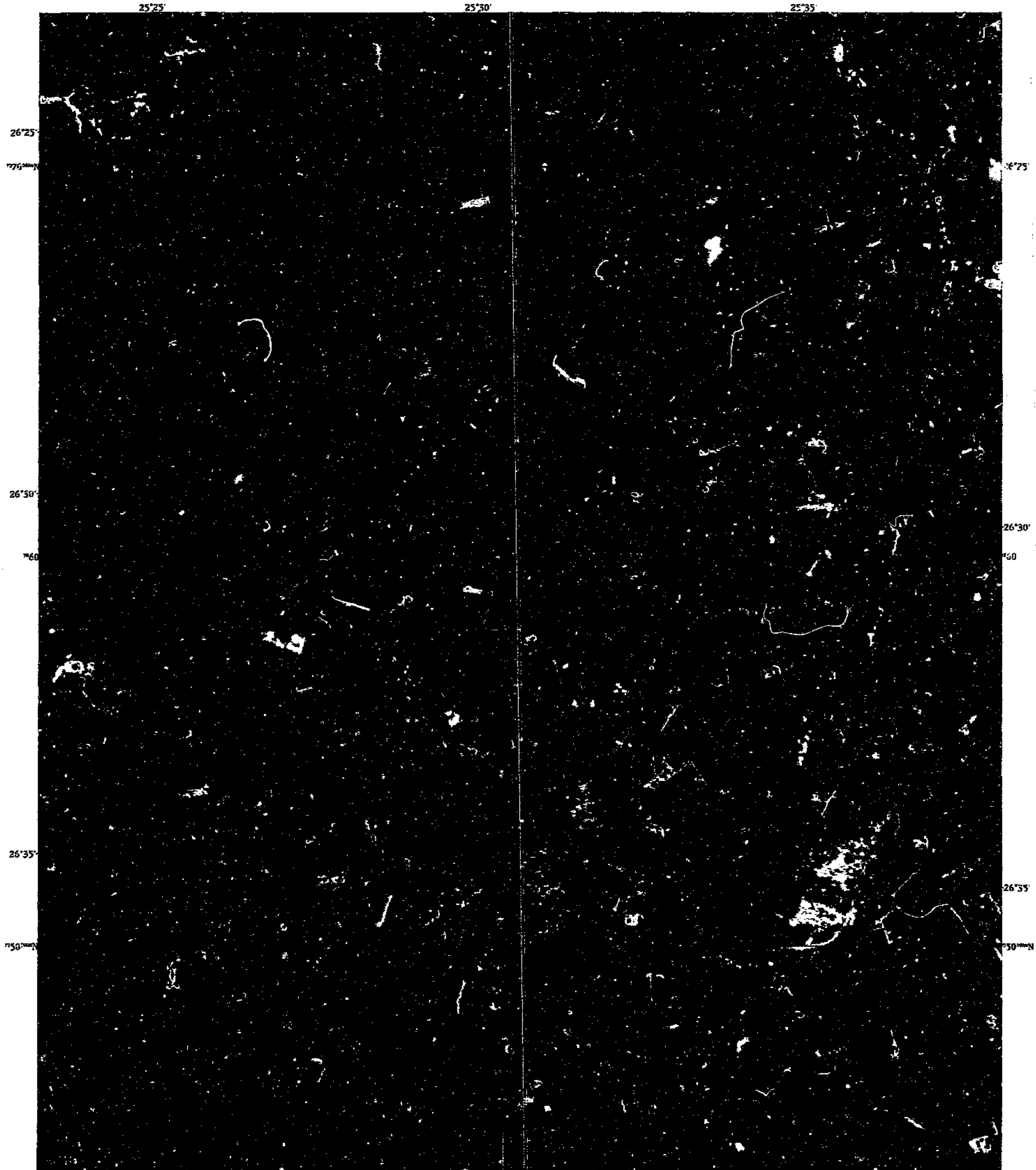


Figure 9.16.1 TVI (False Colour Composite) 26 June 1992
Scale 1:100 000

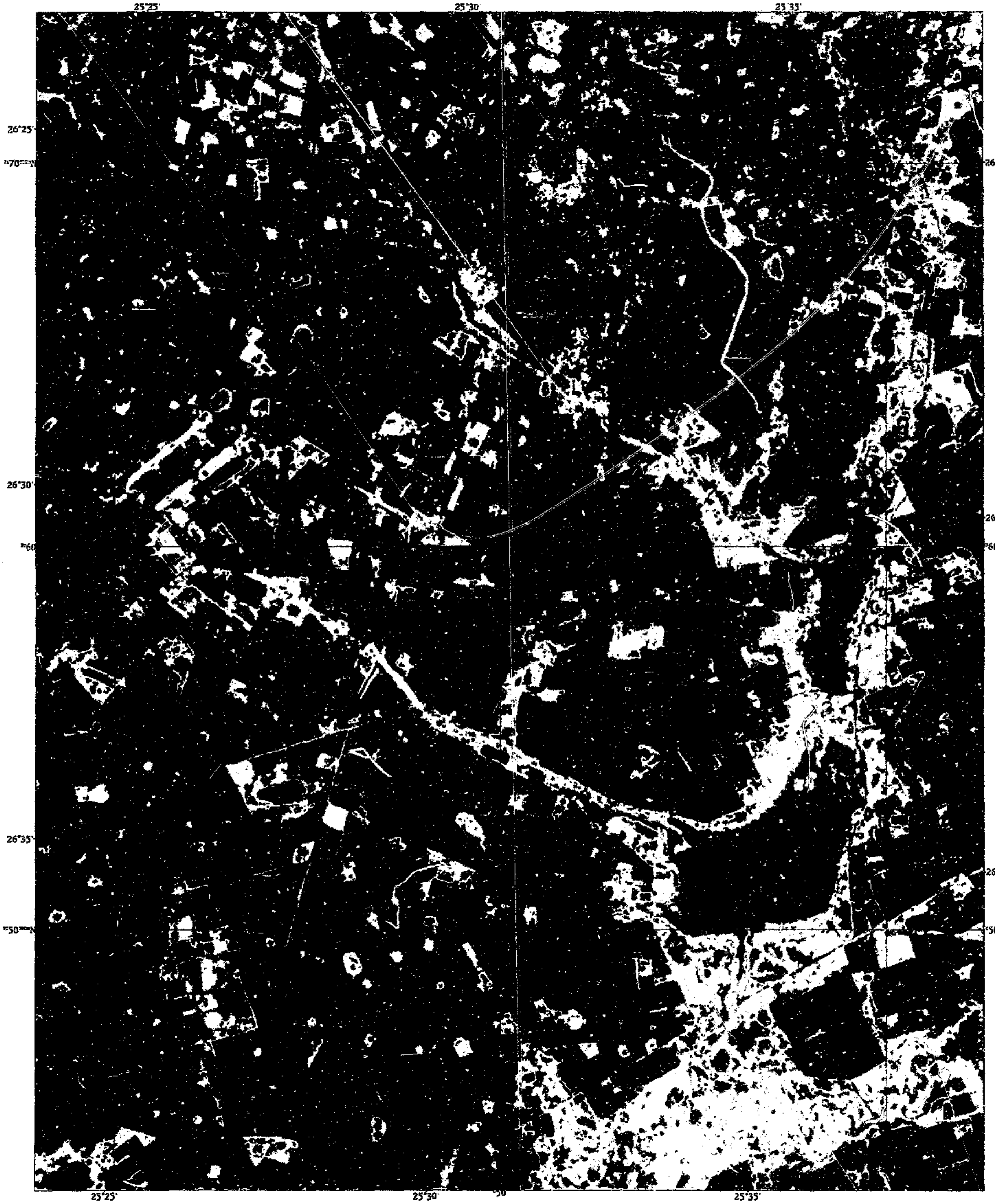


Figure 9.15.1 TVI (False Colour Composite) 03 December 1986
Scale 1:100 000

Figure 9.9.1 Band Combination 7, 5, 4, (RGB) 26 June 1986

Scale 1:100 000

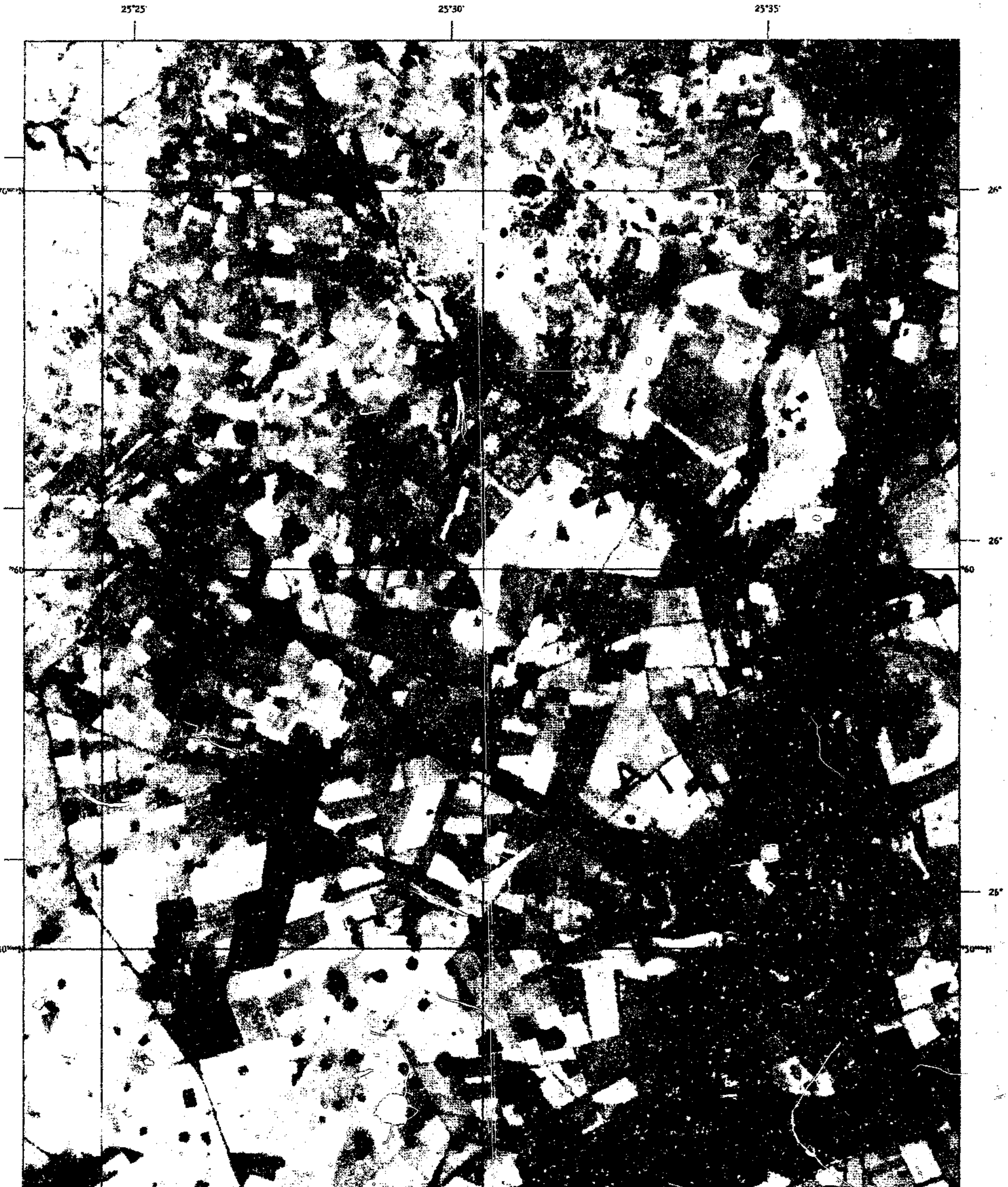


Figure 9.8.1 Band Combination 7, 5, 4, (RGB) 03 December 1986
Scale 1:100 000

Figure 9.7.1 Band Combination 4, 3, 2, (RGB) 26 June 1992
Scale 1:100 000

Figure 9.6.1 Band Combination 4, 3, 2, (RGB) 03 December 1986
Scale 1:100 000