Using Geographic Information Systems and Remote Sensing to Improve the Management of Kelp Resources in South Africa

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Declaration

I declare that this thesis is my own work. All work discussed in this thesis was carried out under the supervision of Prof. J. J. Bolton, Department of Botany, University of Cape Town; Dr. R. J. Anderson, of the Seaweed Unit, Marine and Coastal Management; and Mrs. S. Butcher, Department of Environmental and Geographical Science, University of Cape Town.

The material presented here is the original work of the author and has not been submitted in any form to another university. Parts of the work have been presented as follows:

Rand, A. M., Bolton, J.J., Anderson, R. & Butcher, S. 2004. *Introducing a spatial geographic information system (GIS) into kelp management in South Africa.* The 20th Phycological Society of Southern Africa conference (Oral presentation).

Rand, A. M., Bolton, J.J., Anderson, R. & Butcher, S. 2005. *The management of kelp resources in South Africa.* Southern African Marine Science Symposium (SAMSS, 4-7 July 2005). (Oral presentation).

Rand, A, M. 2005. *Mapping South Africa's Kelp Beds.* Phycological Society of Southern Africa Newsletter No. 59 - June/July 2005 pp 10-12.

Where the research of others has been used, acknowledgements have been given at the appropriate points in the text.

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Abstract

In 2002 the Department of Environmental Affairs and Tourism (DEA&T), Marine and Coastal Management (M&CM) and the Seaweed Unit undertook a program to document the localities and quantities of the standing crop of the economically important kelps, *Ecklonia maxima* and *Laminaria pallida*, in the fourteen commercial seaweed Concession Areas that contain commercial quantities of kelps.

The primary objective of this study was to establish a coastal kelp resource database for the South African coastline from Cape Agulhas to the Orange River (the international border with Namibia). The method was designed to integrate past and current analysis of multi-year kelp data from commercial harvesting, biomass and kelp bed extent while allowing for the integration of future surveys within the inventories.

This study is the first in South Africa to create a kelp inventory (with a Geographical Information System, GIS) using new and historical datasets, namely hard copy kelp habitat maps from a Master of Science thesis (Tarr, 1993); M&CM (DEA&T), an aerial kelp survey conducted during 1996 (digitized into vector format); and Landsat 7 ETM+ satellite imagery (Geospace Pty Ltd., 2002). Research conducted during this study includes an aerial digital Colour Infrared (CIR) survey in 2005 of previously uncharted kelp beds along three areas of the coast, and ground truthing and field work done between 2003 and 2005. Furthermore, satellite imagery (Landsat 5, 1991) and hardcopy maps were studied to gain insight into alternative survey methods. Biomass information originated from various surveys and the literature was highly variable (3 – 24 kg/m^2), due to both spatial variability of kelp beds and methods used in this study. Kelp bed area estimates were combined with number of kelps per square metre and mean weight per plant data obtained from field samples to derive a standing crop estimate for kelp beds.

The different estimates and methods of kelp bed area estimation were compared so that the best methods could be identified. Landsat 5/7 is useful in identifying the presence of kelp beds, but not for determining kelp bed area; because of poor resolution and the fact that the images are not all from low tide periods. The CIR survey done in 2005 found nearly all (94% -100%) of the kelp beds identified by Landsat 7 (within a 30m threshold). There is a high level of precision and repeatability within the CIR (2005) method. The two CIR methods (1996 and 2005) compare well and give similar estimates of the kelp beds in certain Concession Areas (14, 15 and the proposed Groen-Spoeg MPA).

The amount of beach cast kelp collected in South African seaweed Concession Areas fluctuated between 500 and 2000 tonnes in the period 1986 -2003. Fresh cut kelp harvested is used primarily as abalone feed and has seen a large increase in the demand and supply. This demand started to increase year on year in the late 1990's and peaked at 6000 tonnes in 2003.

A case study of part of a seaweed Concession Area, centered around Jacobsbaai, on the South African west coast made use of detailed kelp bed and individual bay harvesting and collection records for the period 1996 – 2004; as well as field surveys in conjunction with aerial photography (Colour Infrared taken in 1996). This showed that certain localities are preferred for harvesting, and that beach-cast collections are twice as high in winter (when there are storms) than in summer. Annual yields increased from 100 tonnes fresh weight of beach cast plus harvest in 1997 to 100 tonnes of beach cast plus 500 tonnes of fresh harvest in 2004 reflected a steady increase in the size of the abalone farm that uses the kelp. Overall, there is no evidence of over harvesting: consistent yields are still being obtained from individual beds after eight years, and diving inspection (and biomass measurements in 1997, 2001 and 2005) show that the beds appear to be normal. The seasonal trends in preference for kelp harvested (higher in early summer, October/November/January and winter) and beach cast collected (twice the quantity is collected during winter, when storms loosen and wash up kelp); and the preferred harvesting localities; as well as investigating the preferred scale of management. In 2003, total harvest from this Concession Area approached 99% of the amount that is allocated by the authorities (M&CM). This case study indicates that careful 'micromanagement' of the resource (on a bed by bed basis) by the commercial operator can provide good management data, and the example set by this operator should be encouraged.

The various datasets used in this study are integrated into a ArcGIS database, and hardcopy maps are provided in Appendices. Possible technical refinements in the spectral accuracy of imagery are discussed in relation to the findings of this study, and future imagery of these kelp beds should attempt to estimate kelp density. A goal for future research is to produce a long-term time-series for temporal and spatial analysis using a single method that would negate inter-method errors.

Acknowledgements

Project supervision was provided by Prof J.J. Bolton (Department of Botany, University of Cape Town), Dr R.J. Anderson (Principal Specialist Scientist, Marine and Coastal Management) and Mrs. S. Butcher (Department of Environmental and Geographical Science, University of Cape Town).

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THESIS STRUCTURE

Chapter 1. General introduction

Chapter 2. Data methods and kelp mapping

Chapter 5. General discussion and recommendations

Appendices

Chapter 1 General introduction

Chapter Outline

This chapter starts with a statement of research aims and questions. In order to answer these questions the following need to be established: the study area and species of kelp which are the focus of this resource management investigation. The biology and ecology of the three genera of kelp found along the west coast of South Africa are briefly outlined in the light of their importance to the commercial harvesting industry. Following the description of current harvesting practices in a global and local context, relevant marine legislation is discussed and compared with international practices. The focus of this study includes aspects of marine inventories, resource management, remote sensing (including satellite and aerial surveys), and Geographic Information Systems (GIS) that provided the framework onto which field studies and sampled/collected data were integrated.

1.1. Research background and rationale

1.1.1 Aims of this study

The primary aim of this study was the establishment of a coastal kelp resource mapping database of exploitable kelp resources in South Africa. The GIS database aims to allow for the incorporation of supplementary information that could be useful in understanding, allocating and managing the resource, including information on commercial exploitation, biomass changes, the environment and ecosystem and any other factors that may be relevant in the future. Kelp beds could be used as indicators of climate change in near-shore marine ecosystems. For example, this study could provide a baseline against which change (one cause could be climate variability and shift away from prevailing conditions of water temperature, level and solar radiation) could be measured.

1.1.2 Research Questions

This study also aims to answer the following questions:

- What is the distribution of kelp resources?
- How do different methods of data acquisition/mapping compare?
- What are the trends in commercial kelp harvesting between 1986 and 2003?
- At what scale should management of this resource be done?

1.1.3 Thesis Outline

Chapter 1 is a general introduction to the concepts and fields of knowledge within which this research took place.

Chapter 2 provides details of the methodology of data acquisition, creation and manipulation.

Chapter 3 contains the results of this study, namely the kelp inventory, biomass statistics and harvesting trends.

Chapter 4 is a case study in micromanagement of kelp beds at Jacobsbaai and aims to investigate the appropriate scale of management of the resource.

Chapter 5 is a conclusion and discussion of the findings of this study and views on future research.

1.2. The distribution of kelps in South Africa

The climatological and oceanographic processes of the west coast of southern Africa are described in Tyson (1986). Sink *et al.* (2004) and Lombard *et al.* (2004) provide more recent descriptions of the current understanding of the marine components of the West Coast of South Africa. The west coast is subject to coastal upwelling (the process whereby cold water is brought to the surface near the coast as a result of longshore southerly winds). The areas along the west coast of southern Africa where the southerly winds are consistently strongest are also the areas where upwelling is most pronounced.

Coastal upwelling in the Benguela is not uniform in time or in space and is a function of seasonal variation in climate and land-ocean-atmosphere processes. In the northern Benguela peak upwelling and insolation are out of phase, and sea surface temperatures over the shelf follow a distinct seasonal cycle. Maximum insolation and the upwelling season coincide in the waters off the Cape Peninsula, and average sea temperatures inshore vary seasonally by little more than 1°C (Shannon & O'Toole, 1999).

The West Coast is influenced by the cool Benguela Current. Nutrient-rich upwelled waters nourish microscopic floating phytoplankton. Both phytoplankton and seaweeds are far more productive on the West Coast than on the South and East Coasts, and fuel more productive food-chains, culminating in the commercial fisheries that are concentrated in this region (Stegenga *et al.* 1997). Because productivity is high on the West Coast, there are far fewer seaweed species than along the East Coast. The West Coast is characterised by prolific kelp forests (Bolton & Stegenga, 2002). The genera are *Ecklonia, Laminaria* and smaller beds of *Macrocystis*. Bolton & Anderson (1997), Sink *et al.* 2004 and Lombard *et al.* (2004)

provide further information and description of the west coast flora and fauna. Figure 1.1 provides a location map for this study.

The four species of kelps that are found in South Africa have somewhat different geographical and vertical distributions. *Ecklonia maxima*, *Laminaria pallida,* and *Macrocystis angustifolia* (see Figure 1.2 for illustrations) are restricted to the cool temperate west coast and to the south coast/west coast overlap zone between Cape Point and Cape Agulhas (Bolton & Anderson 1997), while *Ecklonia radiata* occurs on the warm temperate south coast.

Ecklonia maxima forms extensive beds from just west of Cape Agulhas to north of Cape Columbine, but decreases in abundance up the northern parts of the west coast, although it remains a significant component of the kelp beds and may be locally abundant in places just to the north of Lüderitz in Namibia. In central and northern Namibia, *Ecklonia* is absent (Stegenga *et al.* 1997).

Laminaria pallida occurs from at least as far as eastward of Danger Point, up into northern Namibia (Stegenga *et al.* 1997). However, it is almost completely subtidal between Danger Point and Cape Columbine, although it may form an extensive sub-canopy (under the surface *Ecklonia maxima* canopy) down to at least 20m depth. North of Columbine, *Laminaria pallida* develops a hollow stipe, and begins to replace *Ecklonia maxima* in shallower water. Thus, in the central and northern parts of the South African west coast (and in Namibia), most of the kelp beds that are visible at low tide comprise *Laminaria pallida.*

Macrocystis angustifolia is very restricted in abundance, and is only found in small patches at a few localities between the west coast of the Cape Peninsula (such as Kommetjie and Oudekraal) and Jacobsbaai (near Cape Columbine), although there is a large bed on the west coast of Robben Island. This species is of no commercial significance in South Africa (R. J. Anderson, *pers. comm.).* The extensive beds of *Ecklonia maxima* in the south, and *Laminaria pallida* in the north, form the basis of the South African kelp industry.

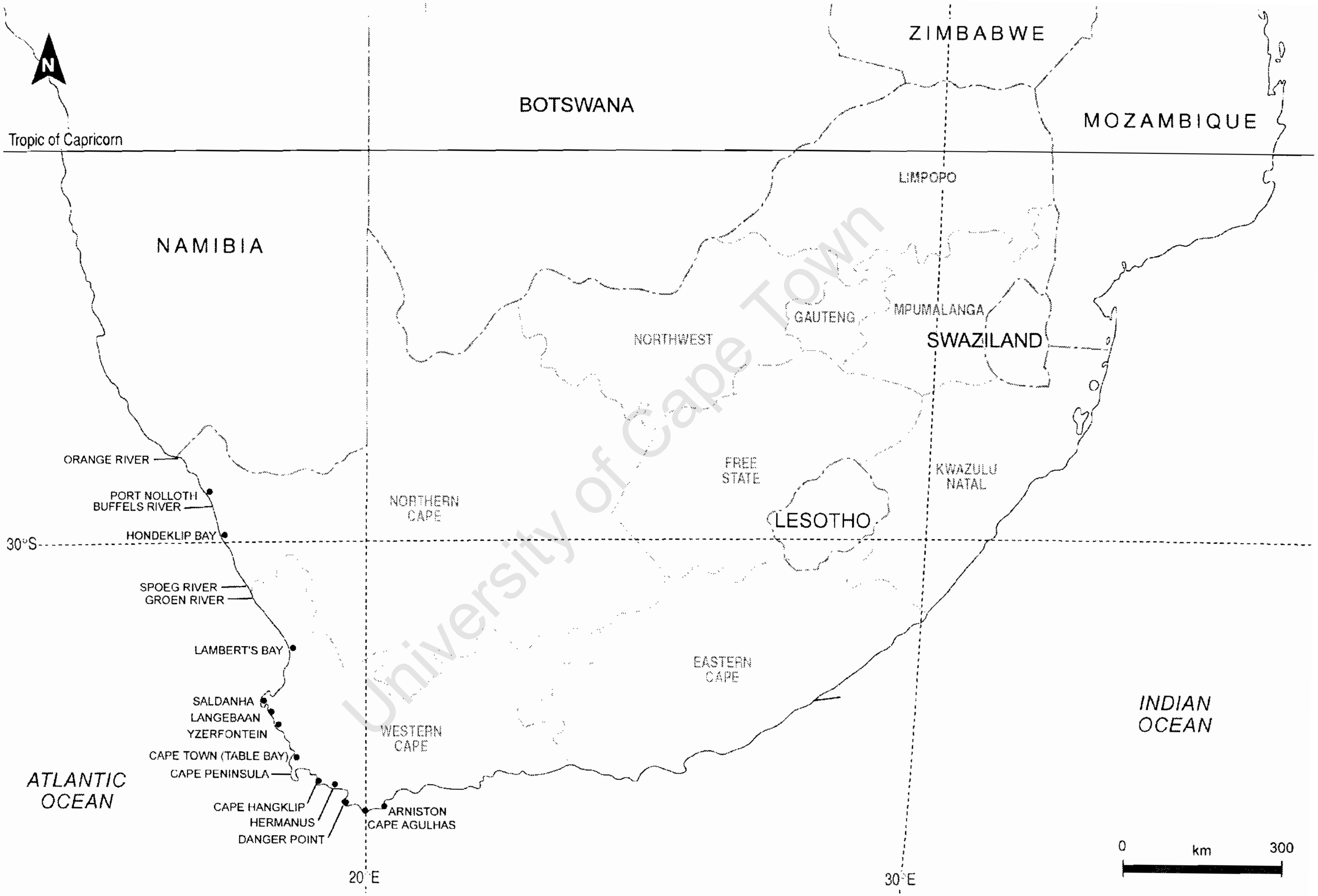


Figure 1.1. Map of South Africa with locations along west coast that are referred to in this study (adapted from Tronchin, 2003, unpublished PhD thesis).

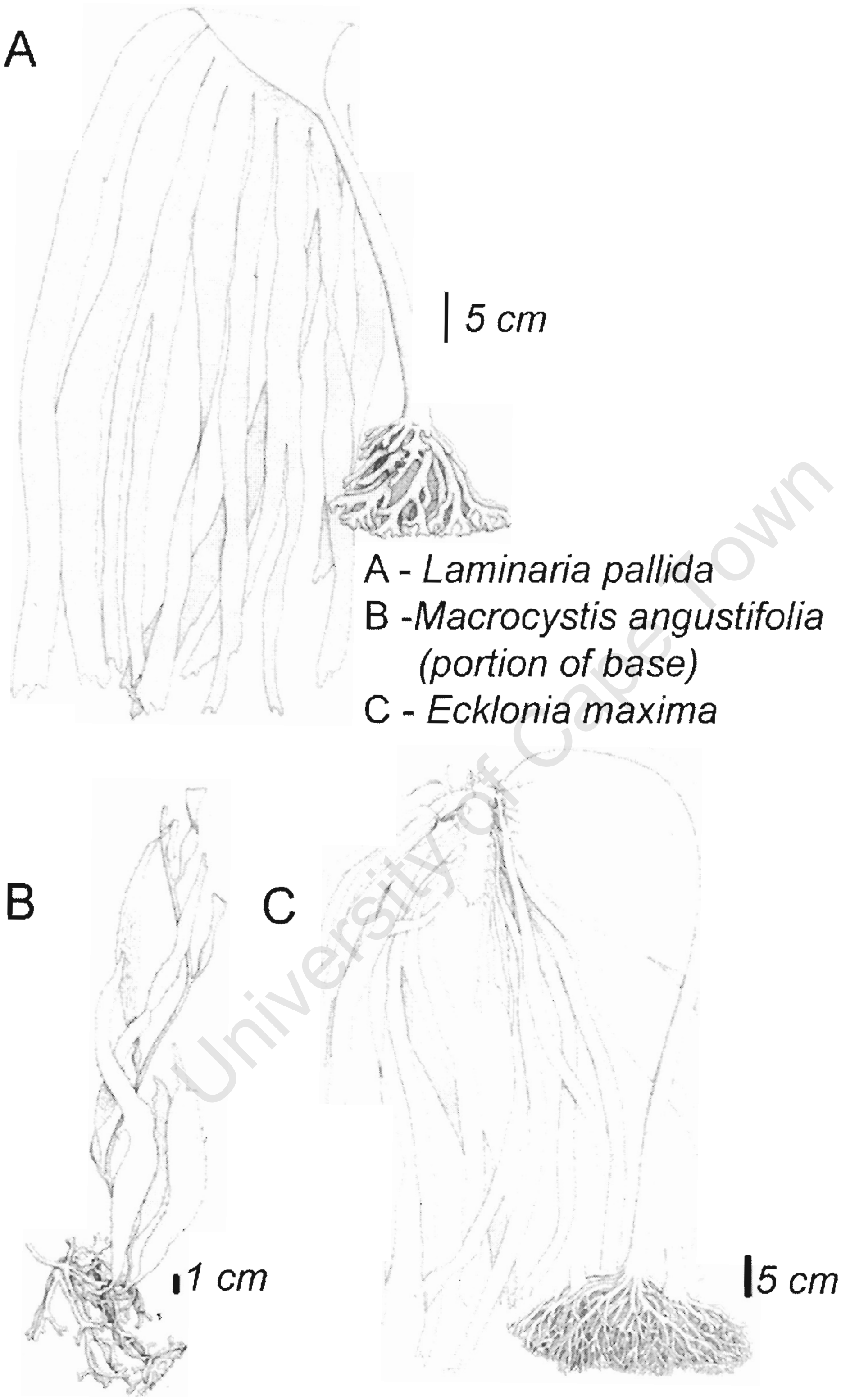


Figure 1.2. Three species of kelp found of the west coast of South Africa (from Stegenga *et al.* 1997, p188-189).

1.2.1 Kelp bed structure and ecology

Within their geographic range, South African kelp beds are of course restricted to the photic zone, which is generally down to 20m depth, to the lower intertidal zone, and wherever there are hard substrata.

Ecklonia maxima is seldom found below about 10 -12 m and mature sporophytes mainly reach the surface at low spring tides. The gas-filled bulbs at the top of the stipe suspend the fronds near the sea surface, so that a typical *Ecklonia maxima* bed has a fairly dense canopy. Under this canopy, the shorter sporophytes of *Laminaria pallida* typically form a sub-canopy about 1-2m above the substratum, extending out beyond the *Ecklonia maxima* depth limit (10-12m) to the photic limit.

The ecology of South African kelp beds is reviewed by Stegenga *et al.* (1997) and Bolton & Anderson (1994, 1997). General descriptions of the marine vegetation and the boundaries of marine provinces are provided by Sink *et al.* (2004) and Lombard *et al.* (2004). As mentioned previously, north of Cape Columbine, *Ecklonia maxima* is to a large extent replaced by hollow-stiped *Laminaria pallida*, but the later plants seldom exceed 3 m depth. The result is that these northern beds are often denser. They are only wide and extensive at the surface where there are large expanses of relatively shallow (maximum depth of 2-3 m at low tide) substrata. In this study, no attempt was made to map completely subtidal kelp beds, i.e. those which do not reach the surface at low spring tide. These are probably far more extensive than beds which do reach the surface, but to quantify them would require a prohibitive amount of underwater sampling, whether using divers or sidescan sonar.

The structure of *Ecklonia maxima* beds has been studied at Danger Point by Levitt *et al.* (2002) and at Bordjiesrif by Rothman (2006) and Rothman *et al.* (2006). These studies found that the populations of *Ecklonia maxima* sporophytes comprise a range of plant sizes, with relatively high densities of juveniles, a range of plant sizes in the sub-canopy and a canopy of mature individuals. The density and biomass of *Ecklonia maxima* beds can vary significantly over time, because large storms can remove many plants, and recruitment appears to be stochastic and unpredictable (Levitt *et al.* 2002; Rothman *et al.* 2006). This is probably true for *Laminaria pallida* as well, although it has not been studied.

1.2.2 Factors affecting the distribution of kelps

The role of temperature, light and nutrient uptake in the determination of speciation events, growth, recruitment and the current distribution of *Ecklonia maxima* and *Laminaria pallida* kelp beds has been documented by Bolton & Anderson (1994). The earliest study of the growth of South African kelp was that of Dieckmann (1978, 1980), who showed that *Laminaria pallida* fronds grew fastest in spring and early summer. Rothman (2006) and Rothman *et al.* (2006) showed that harvesting of canopy plants of *Ecklonia maxima* did not affect stipe elongation rates of juvenile and sub-canopy sporophytes. Furthermore it was shown that most of the *Ecklonia* bed biomass is contained in mature plants that reach the surface, indicating the importance of quantifying the surface canopy, from a resource management perspective.

Energy-flow with South African kelp beds (mainly off the Cape Peninsula) was studied by Field *et al.* (1977), Velimirov *et al.* (1979) and Field *et al.* (1980). The bulk of organic material produced by the kelps enters the food web as particulate matter which is ingested by filter feeders. Algal biomass and production is highest in shallowest water, and animal biomass highest below about 10m depth. *Ecklonia maxima* is estimated to lose about 10% of its annual production in sporophytes torn loose during storms and cast ashore (Simons & Jarman, 1981). This material forms the basis of a commercial industry (see later).

Stegenga *et al.* (1997) provide detailed descriptions of kelp bed ecology, including physical factors (wave action, sand substratum, desiccation and light) and biotic interactions (grazing, competition, epiphytism and parasitism). Oceanographic (upwelling and sediment transport) and solar radiation processes have major effects on the distribution and ecology of kelp beds. The following two sections outline the basic principles involved in these environmental processes as well as factors which influence remote sensing techniques employed in this study.

1.2.2.1 Large-Scale Oceanographic influences of the Benguela System

The Benguela system comprises a northward flowing current from which cold, nutrient-rich water upwells to the surface along the west coast of South Africa and Namibia. This is responsible for the high nutrient levels and productivity along the shallow waters of the coastline. The warmer Agulhas current flows down the east coast of South Africa. Thermoclines at the meeting point of the Agulhas and Benguela currents can cause warmer water to 'retroflect' offshore into the Benguela system,. This dynamic state drives the difference in inshore temperature between the east and west coasts (Chapman & Shannon, 1985). Sediment transport and sand inundation of bays caused by natural and human mining processes along the west coast can cover rocky substrate and potentially prevent kelp recruitment.

1.2.2.2 Incoming solar radiation

Photosynthetically Active Radiation (PAR) includes parts of the electromagnetic spectrum (primarily visible light, ultraviolet and near-infrared) that are used by photosynthetic organisms for a variety of biochemical processes. Ultraviolet (UV-R, 290 to 400 nm), specifically ultraviolet-B (UV-B, 290 to 320 nm) radiation is known to be harmful to many photoautotrophic marine organisms. The effects of ultraviolet radiation on *Laminaria saccharina* in relation to depth and tidal height have been studied in the Gulf of Maine by Apprill & Lesser (2003). Zhang *et al.* (2004) offer methods for the calculation of radiative fluxes at the top of the atmosphere. The results may then be combined with an atmospheric modeling system, such as 6S (as described in Vermote *et al.* 1997) to provide more accurate predications of the current and future atmospheric conditions.

Light, exposure to the atmosphere and nutrient availability are moderated by wave/current states, turbidity and near-surface radiative fluxes. Changes to these variables will effect kelp individuals and in turn species growth and abundance. Changes in climate are likely to have an effect on the boundaries of populations and ecosystems. In the case of kelp beds – areas of species overlap and marginal populations could be the first to experience an effect of climate change. A comprehensive review of climate change research on marine macrophytes, up to the mid 1990's, has been given by Franklin & Forster (1997). Specifically their study deals with the consequences for marine macrophyte physiology and primary productivity of the oceans. Due to its strong attenuation effect, the water column provides substantial ultraviolet radiation (UVR) protection to attached subtidal benthic macrophytes in coastal waters. Unattached macroalgae such as *Sargassum natans* and *Ascophyllum nodosum* var. *mackaii*, or the floating, canopy-forming parts of such algae as *Macrocystis pyrifera* do not have this protection and may be exposed for long periods to high irradiances of UVR and Photosynthetically Active Radiation (PAR). The possible effects, causing dynamic and chronic photoinhibition, due to impaired protective and repair mechanisms in the alga has been shown by Franklin & Forster (1997, p223) and Hoffman (2003, p135)

Kelps are adaptable and show seasonal responses in growth and reproduction to environmental stimulus (Levitt *et al.* 2002). Bischof *et al.* (2002) describe how photosynthetic activity of kelps collected from under the ice of an Arctic fjord was strongly inhibited by UV, but the degree of inhibition decreased during spring and summer. *Palmaria palmate* (a red seaweed) exhibited a relatively flexible response. Photosynthesis in specimens collected under the ice in June or in turbid water in July/August was relatively strongly inhibited; specimens collected during sunny periods and in clear water in spring showed a much lower degree of photoinhibition after UV exposure because of decreased chlorophyll a content in the brown algae (*Laminaria saccharina, Saccorhiza dermatodea, Desmarestia aculeate*).

Solar radiation varies depending on geographical location, time of day and the earth-sun cycle. Direct observation of the incoming shortwave radiation and outgoing long wave radiation is preferable. This is done by a number of orbiting satellites, such as Landsat. These values were used in radiometrically correcting the Landsat imagery used in this thesis.

Monthly average insolation values are recorded at base stations. In South Africa, these are spread too far apart for studies below a regional scale, and thus could not be correlated with kelp bed distribution on a sub-regional level in this study. Data for five sites (see Figure 1.3) spread across the western region of South Africa has been collected and graphed in Figure 1.4. From these data, a pattern of increasing solar insolation (both short and net radiation budgets) increases northwards up the west coast. There is a seasonal trend in insolation of less variation at the equator.

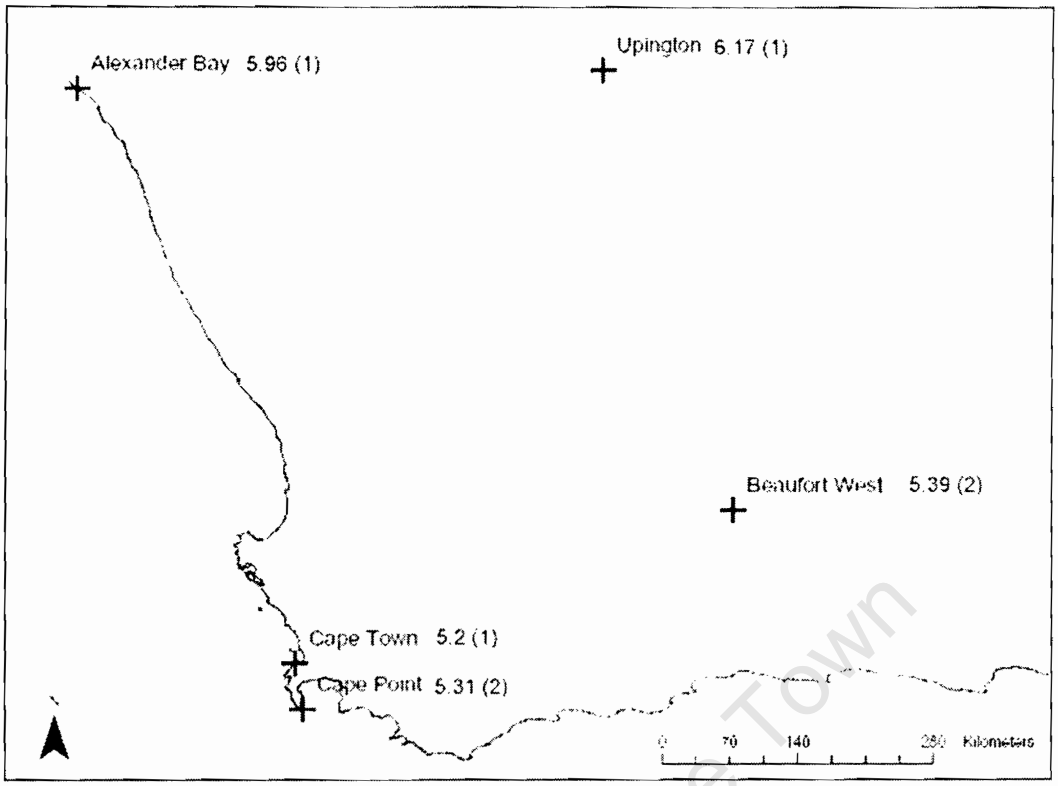


Figure 1.3. Location of stations for daily solar insolation recordings and yearly averages (kWh/m^2/day) graphed in Figure 1.4.

Source 1. World Radiation Data Centre (WRDC) (http://wrdc-mgo.nrel.gov/)

Source 2. NASA Surface meteorology and Solar Energy (**http://eosweb.larc.nasa.gov/sse/**)

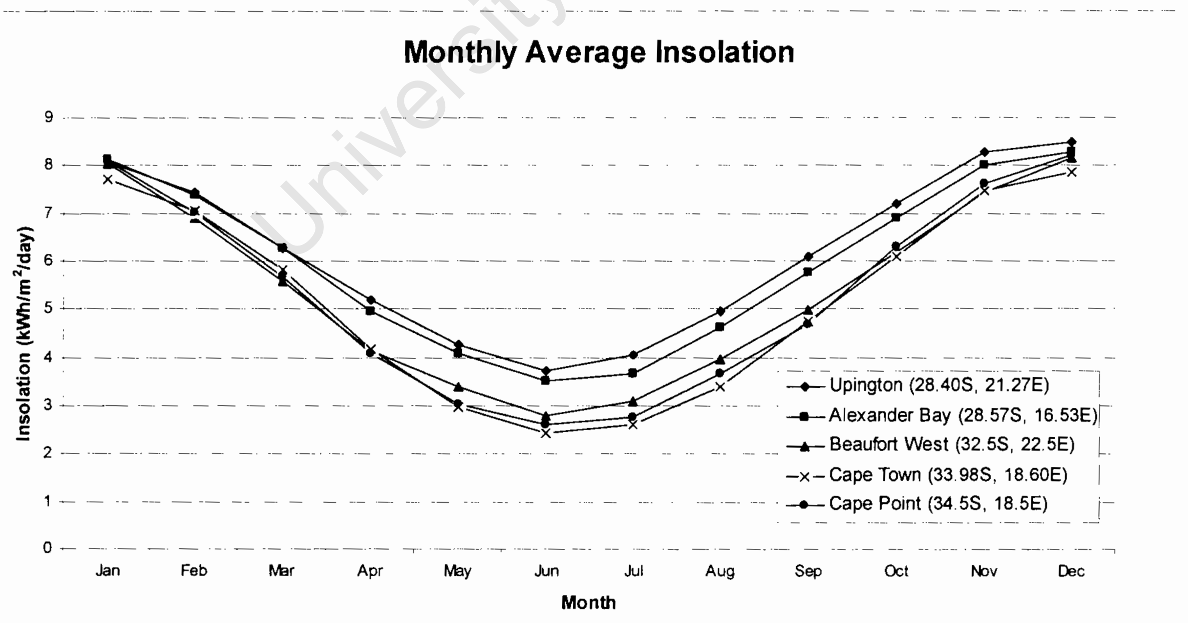


Figure 1.4. Monthly Average Insolation values for the five sites listed.

1.3. The commercial kelp harvesting industry

Around the world, the collection and harvesting of natural kelp resources is commonplace in most areas where large beds occur. This section looks at international harvesting policies in a sample of four countries to show differences in harvesting policy, namely the United States of America, Canada, India and Ireland (based in part on Hillmann, 2005) are briefly reviewed before dealing with the South African industry.

1.3.1 Global commercial harvesting management

United States of America: Alaska, Washington, Oregon, Maine and California

Permits, issued by Alaska Fish & Game, are required for processors, buyers, and harvesters of aquatic plants and aquatic plant farmers. The permit must include species and method of harvesting (which is restricted to one or more fishing districts). Additionally, harvest is by mechanical cutting or handpicking only and plants must be removed from the water at the time of harvest. Commercial harvest of seaweed from aquatic lands (including privately owned tidelands) is prohibited, except upon mutual approval by WADNR (Washington Department of Natural Resources) and WDFW (Washington Department of Freshwater). Only *Macrocystis* sp. may be harvested. As a result, a number of kelp beds are excluded from harvesting. All coastal lands between the vegetation line and mean low water are part of Oregon's Ocean Shore Recreation Area and thus are held in trust for the public. The State Lands Commission owns title to the intertidal and subtidal lands below the mean high tide line. Lease terms will not exceed 20 years, compared to ten years in South Africa. Leased kelp must be harvested by cutting, except if removed loose; and must be harvested at a depth of less than 4 ft below surface water (at time of cutting). If collecting bull kelp (*Nereocystis*) for human consumption, the limit is 2 tons (4,000 lbs) per year and the entire plant must be harvested.

Canada: British Columbia

A license is required to harvest marine plants for commercial purposes. Only Canadian citizens, persons who have or are serving in the Canadian Armed Forces; or persons lawfully admitted to Canada as permanent residents are entitled to apply for and obtain a license. These licenses do not grant the privilege of harvesting on privately owned intertidal land or land leased from Land and Water British Columbia. *No more than 20%* of the total biomass of a marine plant bed may be harvested. A royalty per ton wet weight harvested is levied, depending on the species harvested. In addition, there is an annual licensing fee. The method of harvesting *Macrocystis integrifolia* involves the kelp fronds or stalks being severed cleanly, tears or partial tears of the holdfast from the substrate is prohibited; only individual fronds are to be cut and must not be harvested in water deeper than 5 feet below the surface at any time.

India

Permits are required from the Department of Forests and Department of Wildlife for industrial scale harvesting. Most harvesting is by coastal fisher folk on a small scale and is also done illegally i.e. without a permit. Harvesting is done by hand (picking) and regulations recommended this is done after spores are shed to ensure successive recruitment of species in each locality.

Ireland

A foreshore permit for harvesting and collection on land and seabed between high water of ordinary or medium tides and the 12 mile limit) must be obtained from the Department of the Marine and Natural Resources. Currently, only harvesting by hand is permitted. The industry self-regulates sustainable practice of *Ascophyllum* (one of the two commercially harvested species) and a stump of 15 cm is left for regeneration.

1.3.2 Kelp harvesting in South Africa

Kelp harvesting in South Africa is primarily directed at two species of large brown seaweeds, *Ecklonia maxima* and *Laminaria pallida*. Beach-cast kelp of both species have been collected since at least 1953 in quantities have fluctuated with market demand, but they reached a maximum of about 5 000 tons (dry weight in 1977, Anderson *et al.* 1989) and was approximately 1000 tons in 2003 (Troell *et al.* 2006). Competition from overseas producers has at various times resulted in a downturn in the demand for South African kelp for alginate extraction. Fresh kelp has been harvested since 1979 in relatively small quantities for the production of a liquid plant-growth stimulant, Kelpak™ (Anderson *et al.* 2003). The product contains cytokinins that have been shown to improve the growth and quality of various food and horticultural crops. The recent growth of the abalone farming industry has created further demand for freshly harvested kelp. An increasing proportion of fresh beach-cast frond material (*Ecklonia maxima*) is now supplied as abalone feed. Whole plants are harvested in one Concession Area (near Simons Town, Cape Peninsula) for processing as a plant growth stimulant which is widely used in agriculture and horticulture (Stirk & van Staden, 2004). Recently, large amounts up to 5000 T fresh weight in 2004) of fresh fronds are harvested for abalone feed (Anderson *et al.* 2003, Troell *et al.* 2006). Besides these uses, smaller

quantities of material are used in cosmetics, herbal supplements, and in fertilizer (Anderson *et al.* 2003, Critchley & Ohno, 1998 and Critchley *et al.*,1998).
The South African abalone cultivation industry has developed rapidly and is now the largest producer outside Asia. With a rapid decline in wild abalone fisheries, farming now dominates the abalone export market in SA. Kelp (mostly *Ecklonia maxima*) constitutes the major feed for farmed abalone (over 13 farms operating, most located in the Western Cape) in South Africa (Troell *et al.* 2006).

The exploitation of commercial seaweeds in South Africa is controlled by means of both a Total Allowable Effort (TAE) and a Total Allowable Catch ("TAC"). However, the principal management tool is effort control and the number of right-holders in each seaweed harvesting area is restricted to one commercial operator for one "functional group" of species. The functional groups are *Gelidium* (3 species), *Gracilaria*, and kelp (*Ecklonia maxima* and *Laminaria pallida*). The Concession Areas which have kelp in them are shown in Figure 1.5. A more detailed Concession Area map with exclusion zones is presented in Chapter 3 (Figure 3.1).

Essentially, each Concession Area is limited to one right-holder, for each functional group of seaweed. The process of applying for seaweed harvesting rights is managed by Marine and Coastal Management (M&CM), a division of the Department of Environmental Affairs and Tourism (DEA&T). In addition, limitations are placed on the amounts that may be harvested. In the case of kelp, an additional control is imposed on harvested (rather than beach-cast) material: a Maximum Sustainable Yield (MSY) is set annually (Anderson *et al.* 2003). The MSY is based on the estimated biomass of kelp in the Concession Area as determined from the total area of kelp beds and the mean biomass of kelp within them. These values are based on kelp beds that reach the surface at low spring tides, and do not take into account the extensive *Laminaria* beds that extend into deeper water. There are two reasons for excluding the deeper beds. Firstly, they have not been quantified in any way, and this is unlikely to be done in the foreseeable future. More importantly, they are not harvested. Harvesters cutting kelp for abalone feed operate from boats, and only cut plants that reach the surface at low tide. One methods involves removal of the whole kelp primary blade and fronds. Alternatively, only the distal fronds are cut. The former method kills the plants, while the later "fronds-only" harvesting allows the fronds to re-grow, and in the long term could produce a 4-5 times greater yield of frond material (Levitt *et al.* 2002). Because the total biomass in each kelp Concession Area must be calculated from the area of the kelp bed and the mean biomass, the last two measures should be accurately measured. In the past, M&CM has used a variety of methods to estimate kelp area. For example, the length of rocky coastline (from 1:50 000 maps) were used to obtain an index of potential kelp habitat, and multiplied by a biomass value for a similar piece of coast. These sorts of estimates are unsatisfactory and one of the main aims of the present study was to combine all available data sources and newly map as many of the gaps as possible.

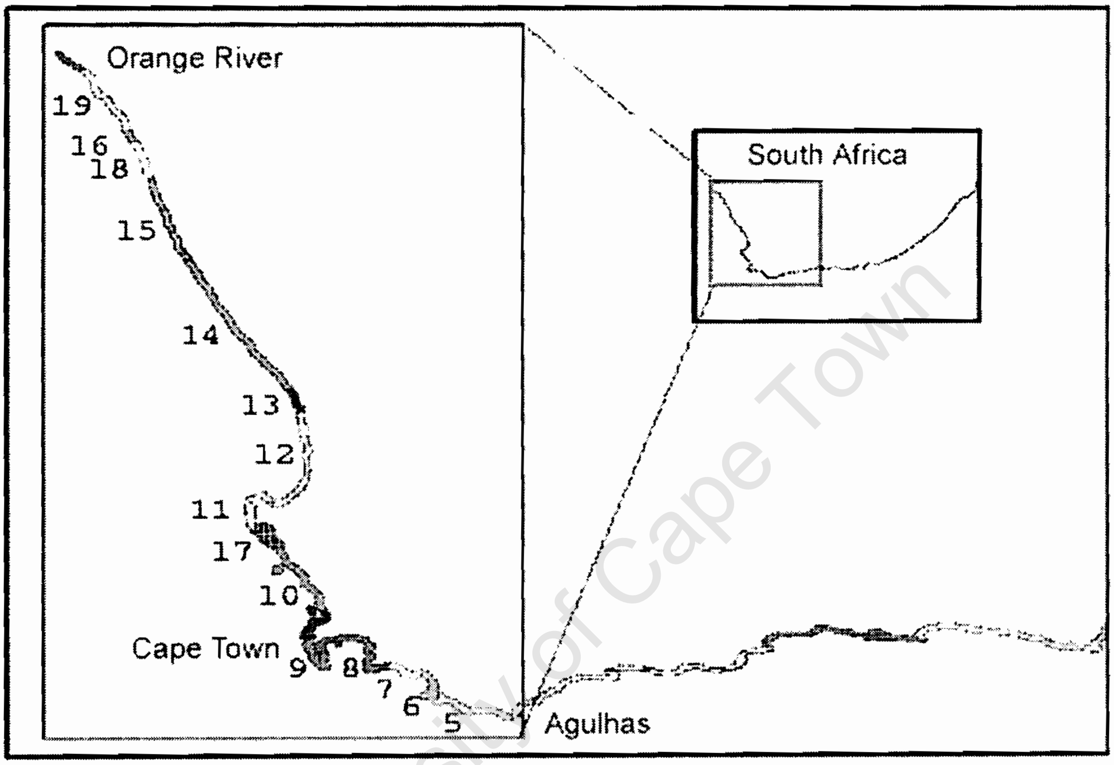


Figure 1.5. West Coast seaweed Concession Areas (more detail given in Figure 3.1).

South Africa currently supplies about six percent of world production of kelp by value, but much of this resource is on the remote northern west coast suffers due to the relatively high cost of transport and logistics (Britz *et al.* 2000). According to a survey done by Southern African Development Community's (SADC) Monitoring, Control and Surveillance of Fishing Activities Programme (Anon 2002b) there are 14 Seaweed Rights holders in the provinces of Northern Cape, Western Cape and Eastern Cape. 60% are owned by Previously Disadvantaged Individuals (PDI) who employ 313 persons (92% of whom are classed as PDI). The value of the industry in 2001 was R 15 – 20 Million. These figures will change during 2006, when harvesting rights for the next 10 years are allocated. A change in regulations will allow harvesters to double their quotas should they harvest kelp fronds in a non-lethal manner. *Ecklonia maxima* is the main resource from Agulhas to Cape Columbine, but *L. pallida* progressively dominates northwards of Cape Columbine (see Figure 1.1).

In South Africa, both beach-cast and fresh kelp is collected (Figure 1.6). Beach cast kelp is collected, bundled and left to dry above the high tide mark, along an access road or footpath. Once dried, the kelp is transported to a stock pile and then milled prior to sale. Freshly cut kelp is transported by row boat or power boat to the shore. Once there, it is loaded onto a tractor and taken directly to the abalone farm to be used as feed.

The commercial harvesting records of South African kelp (from 1986-2003) collected by M&CM are summarized in Table 1.1.

Table 1.1 . Commercial yields of seaweed from natural populations on the coast of South Africa, 1986 – 2003, as reported by concession-holders. The column Kelp (abalone feed) comprises only frond material, but includes both harvested amounts and amounts of fresh fronds collected from beach-casts. All weight in metric tonnes. (from Troell *et al.* 2006).

Year	Kelp (for Kelpak*)	Kelp (beach cast)	Kelp (abalone feed)	Year	Kelp (for Kelpak*)	Kelp (beach cast)	Kelp (abalone feed)
1986	141	2465	0	1995	316	560	23
1987	113	2211	0	1996	495	1523	26
1988	150	2258	0	1997	426	1704	40
1989	202	1253	0	1998	322	1742	391
1990	167	2112	0	1999	273	1443	1502
1991	224	2004	0	2000	609	759	2784
1992	268	1220	1	2001	641	845	5924
1993	268	454	7	2002	701	746	5334
1994	365	433	10	2003	957	1396	5447

Note that the dried kelp values have been included and multiplied by a factor of five to give an approximation of wet mass. Kelpak is a trade name of a plant growth stimulant used in agriculture.

Figure 1.6. Kelp harvesting activities along the west coast of South Africa.

1.3.3 Management Legislation

Worldwide, coastal and marine management has undergone significant changes, as a result of pressure for a more holistic or integrated approach to resource management. During the 1990s strategies and legislation to incorporate new concepts such as the adoption of the principles of sustainable development; application of strategic planning principles; and greater community awareness of management issues; greater community participation in decision making and understanding of global environmental change.

South Africa has undertaken to improve management by providing supportive legislation. All marine resources are controlled by the Marine Living Resources Act (Act 18 of 1998) and subsequent amendments. Its guiding principles are the need for sustainable and equitable utilization of marine resources, the need to promote sustainable development of the fisheries industry, and to protect marine biodiversity together with improved participation of all stakeholders in decision-making processes. Kleinschmidt *et al.* (2003) and Von Sittert (2002, 2003) comment critically on the commercial fishing rights allocation process in South Africa in terms of political equity and economic stability.

The DEA&T authorities are obliged (by legislative bodies that read and enforce the law) to manage harvesting for the best possible balance between minimizing ecological effects and maximizing direct usefulness to humans. This emphasizes the critical need for mapping the resource accurately.

The primary supporting legislation (relevant to the coast) for the rationale for this project includes:

- Sea Shore Act (Act 21 of 1935)
- Environmental Conservation Act (Act 73 of 1989)
- The Constitution of South Africa (Act 108 of 1996)
- National Environmental Management Act (Act 107 of 1998)
- National Policy for Sustainable Coastal Development in South Africa (1998)
- National Environmental Management: Protected Areas Act (Act 57 of 2003)
- The National Environmental Management: Biodiversity Act (Act 10 of 2004)

1.4. Mapping and quantifying kelp resources

1.4.1 Marine inventories

A marine inventory is "the collection of information. In the context of natural resources, inventory requires measurement of objects and features, but no interpretation regarding their importance or value ... Inventory data are typically derived from field surveys, and minimal professional judgment is required other than interpretation of inventory data descriptions and definitions." *Mason & Knight (2001, p 16)*

Douven *et al.* (2003) described how geo-information technology can be used in conjunction with Integrated Coastal Zone Management (ICZM). The benefits lie in the fact that geo-information technology can process large amounts of spatial data and can integrate different types and sources of data. Using a case study of seagrass beds in Banten Bay, Indonesia, they developed a spatial database and seagrass maps by means of overlay analysis. Furthermore, areas that were deemed important as habitat for commercial fish species, or were located near past and planned shoreline developments were delineated. Such spatial analyses are very important to support ICZM decision-making at the district level. A good spatial information infrastructure to collect data and make these data accessible is a pre-requisite to the creation of an inventory.

A Decision Support System (DSS) aims to empower natural resource managers. The current study aims to incorporate the principles laid out in Sarda *et al.* (2005). They suggest that a DSS is composed by: (a) the development of an environmental indicator-based report; (b) the use of a geographical information system (GIS); and (c) the incorporation of different types of graphical packages. Numerous studies have used remote sensing and GIS to compile maps and inventories of kelp habitats. Examples are from the USA are Kvitek *et al.* (2003) and Lathrop *et al.* (2001); and United Kingdom (Connor *et al.*, 2003 and Gold *et al.*, 2003). In colder waters, Komedchikov *et al.* (2003) produced a digital atlas of Russian waters and GIS technology was extended into an environmental inventory in Antarctica (Pang *et al.* 2003). Jónsdóttir *et al.* (2000) produced a GIS based analysis of the benthic community in the Western Arctic Ocean. Often inventories are not merely baseline studies, but may be done for specific outcomes, for example, Frankic (2003) provides the proposed vision for aquaculture development in the Adriatic (Croatia) by producing a macrophyte inventory. The selection of a GIS method and aligned remote sensing tools (aerial infrared photography and Landsat data) along with field surveys used in this thesis was informed by the review of the marine resource inventory literature.

1.4.2 Remote Sensing

Remote sensing refers to capturing information of an object from a distance. This includes aerial photography. This concept has evolved with time and the advancement of technology to include digital media. The use of remote sensing products for biodiversity science and conservation in the twenty first century is reviewed by Drury (1998) and Turner *et al.* (2003).

The review of the current remote sensing literature which follows will focus its application in the coastal marine environment. The Electromagnetic spectrum is summarized in Figure 1.7. The parts of interest in this thesis are the visible and infrared wavelengths of radiation.

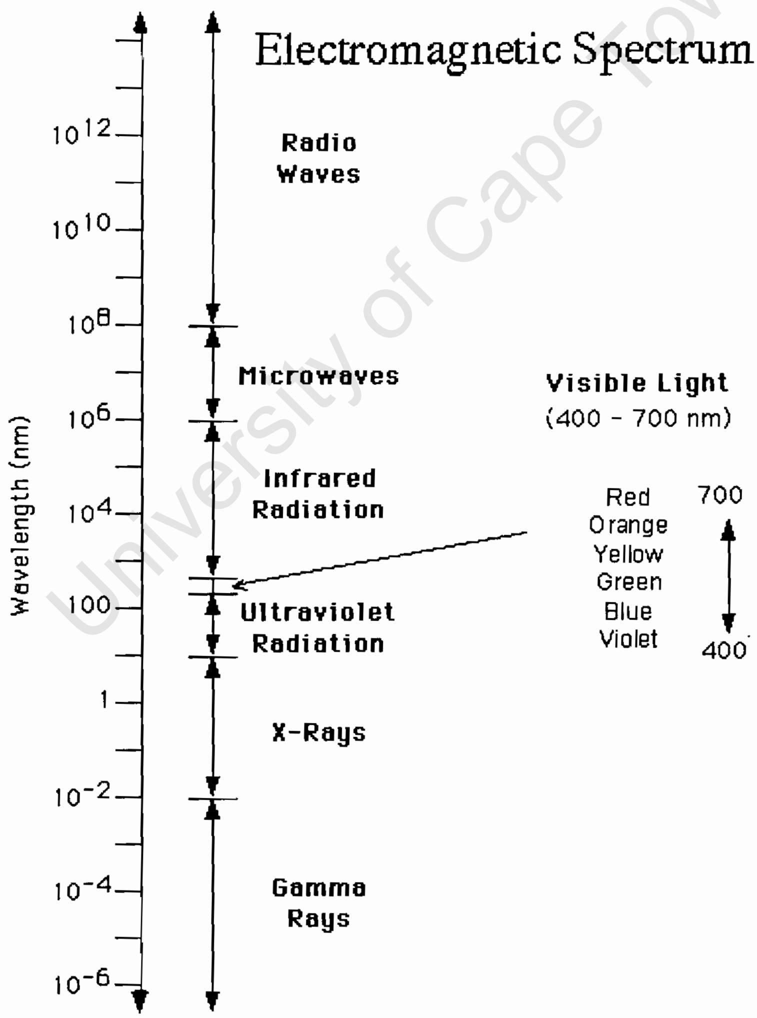


Figure 1.7. Electromagnetic Spectrum (adapted from NASA's Space Education Division, http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html)

Remote Sensing techniques are based on image analysis principles. Satellite sensors measure variations in electromagnetic energy coming from the Earth's surface. Methods used in land based forestry applications (e.g. Banko, 1998) can be adapted to the study of kelp beds, for example in stand density studies. Czaplewski (2003) provides further examples of land forest area calculations done successfully using Landsat data. More details of concepts applied to this thesis have been included in Chapter 2.

Landsat 5/7 data was used in this project to estimate (at 30m resolution) the planimetric area of surface kelp beds. Each band on the Landsat sensors consists of the total radiance measured by the signal detectors mounted on the platform. An image band contains pixels that receive photons, collected between some spectral interval. This signal can be expressed as a voltage whose variation is thus a measure of the photon energy/electron release effect. Liliesand & Liefer (2000, p19) mention the feasibility of "converting this variable voltage signal into an image by using it to drive some electro-optical instrument that produces a light beam output that changes with the voltage." The same principles apply to digital cameras that are sensitive to infrared.

A comprehensive Table of all the Landsat satellites and sensors has been reproduced below in Table 1.2, from NASA (2003). Note that a difference between Landsat 5 and Landsat 7 is in that Band 6 (in the thermal range) has a finer spectral resolution in the latter.

Table 1.2. Landsat Satellites and Sensors (from NASA, 2003)

Satellite	Sensor	Bandwidths	Resolution (m)	Satellite	Sensor	Bandwidths	Resolution (m)
Landsat 4/5	MSS	(4) 0.5 to 0.6	82	Landsat 7	ETM+	(1) 0.45 to 0.52	30
		(5) 0.6 to 0.7	82			(2) 0.52 to 0.60	30
		(6) 0.7 to 0.8	82			(3) 0.63 to 0.69	30
		(7) 0.8 to 1.1	82			(4) 0.76 to 0.90	30
	TM	(1) 0.45 to 0.52	30			(5) 1.55 to 1.75	30
		(2) 0.52 to 0.60	30			(6) 10.4 to 12.5	60
		(3) 0.63 to 0.69	30			(7) 2.08 to 2.35	30
		(4) 0.76 to 0.90	30			PAN 0.50 to 0.90	15
		(5) 1.55 to 1.75	30				
		(6) 10.4 to 12.5	120				
		(7) 2.08 to 2.35	30				

The following data products are available from the Landsat Orthorectified data collection (http://edc.usgs.gov/products/satellite/landsat_ortho.html). The first two have been used in this thesis.

- **Landsat Orthorectified TM**

  Individual scenes may range from 1985 to 1996. These Landsat data have been orthorectified, using geodetic and elevation control data to correct for positional accuracy and relief displacement. Large blocks of Landsat data were adjusted through a patented procedure using pixel correlation to acquire tie-points within the overlap area between adjacent Landsat images.

- **Landsat Orthorectified ETM+**

  The average acquisition date for the Landsat Orthorectified ETM+ data is 2000 (+/- 1 year). All scenes were acquired between 1999 and 2001. These data have been orthorectified for coregistration with the earlier (circa 1990) Landsat TM coverage.

- **Landsat Orthorectified ETM+ Pansharpened**

  These data products consist of pansharpened versions of the ETM+ scenes above. The pansharpening process involved a resolution merging process, which allows the fusion of the higher-resolution panchromatic band (8) with selected lower-resolution multispectral bands (7,4,2) to create a higher-resolution ("pansharpened") color image.

All Landsat Orthorectified data products have been pre-processed according to a standardized set of processing parameters. The processing parameters, format, and media options vary slightly according to product type.

A comprehensive coverage document outlining the thematic/attribute data and its handling is on the United States Geologic Service's website (http://edc.usgs.gov/glis/hyper/guide/landsat_tm). Landsat 4 and 5 carry both the MSS (Multispectral Scanner) and the TM (Thematic Mapper) sensors; however, routine collection of MSS data was terminated in late 1992. The satellite orbits at an altitude of 705 km and provides a 16-day, 233-orbit cycle with a swath overlap that varies from 7 percent at the Equator to nearly 84 percent at 81 degrees north or south latitude. These satellites were designed and operated to collect data over a 185-km swath. The MSS and TM sensors primarily detect reflected radiation from the Earth's surface in the visible and near-infrared

(IR) wavelengths. However, the TM sensor with its seven spectral bands provides more radiometric information than the MSS sensor. The wavelength range for the TM sensor is from the visible, through the mid-IR, into the thermal-IR portion of the electromagnetic spectrum. Sixteen detectors for the visible and mid-IR wavelength bands in the TM sensor provide 16 scan lines on each active scan. Four detectors for the thermal-IR band provide four scan lines on each active scan. The TM sensor has a spatial resolution of 30 meters for bands 1 through 5, and band 7, and a spatial resolution of 120 meters for band 6. Transmission of information is at a rate of 85 Mbps (Lillesand & Kiefer 2000).

Table 1.3. Landsat products (from metadata sheets provided by NASA)

	TM	ETM+	ETM+ Pansharpened
Level of processing	Terrain corrected	Terrain corrected	Terrain corrected
Number of bands	7	9	3 (bands 7,4,2)
Resolution	28.5 m	28.5 m	14.25 m
Projection	Universal Transverse Mercator (UTM)	Universal Transverse Mercator (UTM)	Universal Transverse Mercator (UTM)
Datum	WGS84	WGS84	WGS84
Resampling	Nearest Neighbor	Nearest Neighbor	Cubic Convolution

Richards (1986, p 69) summarizes the two approaches to analyzing image data "...which is available in digital form, spatially quantised into pixels and radiometrically quantised into discrete brightness levels..." The human analyst/interpreter undertakes a visual inspection of the image and performs photo interpretation or image interpretation. Alternatively, quantitative analysis is done by the computer. Chander & Markham (2003) provided reflectance conversion equations in the publication, "Revised Landsat-5 TM Radiometric Calibration Procedures and Postcalibration Dynamic Ranges", whose use is explained in chapter 2 of this thesis.

Other studies that make use of remote sensing techniques along the coastline include Cracknell (1999) and Pelkey *et al.* (2003). Malthus & Mumby (2003) provide a good review of the use of remote sensing in coastal zone research. Phinn *et al.* (2005) approach mapping water quality with an integrated methodology that includes image analysis. Coppin *et al.* (2004) review techniques based on multi-temporal, multi-spectral, satellite-sensor acquired data have demonstrated potential as a means to detect, identify, map and monitor ecosystem changes, irrespective of their causal agents. Robinson-Barker (1988) reviews progress in the 1980's on integration of GIS and RS systems. This work has contemporary value, as it refers to satellites which are still operational.

Enhance interpretation is done by: manipulating the raw data, contrast stretching, edge enhancement, ratioing and supervised classification. Recently, Landsat TM imagery has been used to characterize mine waste in the USA, and could be used in South Africa to determine the impact of increased sediment in the intertidal and sub tidal environment originating from coastal strip mining on kelp beds. This study did not quantify the kelp beds themselves, but the movement of large tracts of marine sediment. Kuehn *et al.* (2000) make use of ratios (such as 3/4, 3/1 and 5/7 for bands 123) and applied a Spectral Angle Mapper (SAM) algorithm in ENVI (The Environment for Visualizing Images) Software to AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) airborne images to achieve better characterization of land degradation. This study adapted these techniques to airborne digital infrared photography.

Remotely sensed images may have one layer or multiple layers. Single layer images are called panchromatic images and multi-layer images are called multispectral images. Panchromatic sensors only measure one portion or band of the electromagnetic spectrum. However, a panchromatic band usually covers a broader band of radiation than a single band of a multispectral image. For example, a panchromatic image may include both green and red reflectance, while the two colors would likely be two separate layers of a multispectral image. Panchromatic images often have a higher spatial resolution (i.e. are spatially more detailed) than multispectral images.

Spectral bands include a set of data file values for a specific portion of the electromagnetic spectrum of reflected light or emitted heat (red, green, blue, near-infrared, infrared, thermal, etc.) or some other user-defined information created by combining or enhancing the original bands, or creating new bands from other sources including vector data types.

Unsupervised training is a computer-automated method of pattern recognition in which some parameters are specified by the user and are used to uncover statistical patterns that are inherent in the data. Histograms are created regularly in remote sensing software. It is a graph of data distribution, or a chart of the number of pixels that have each possible data file value. For a single band of data, the horizontal axis of a histogram graph is the range of all possible data file values. The vertical axis is the number of pixels that have each data value.

1.4.3 Aerial Surveys of coastal marine environments

Various techniques and types of imagery have been used for aerial surveys. Bissett & Zimmerman (2004) give technical details on handling infrared analogue film and conversion to digital media. As a result of the handling difficulties and expense of print media, it was decided to use digital IR photography in this thesis. Aerial seaweed surveys have been done by: Jamison (1971) in California, USA; Sathendranath *et al.* (2004) with CIR photography; De Jong *et al.* (2003) for obtaining biomass values. Fyfe & Israel (1996) mapped *Macrocystis pyrifera* in Otago, New Zealand and Hernández-Carmona *et al.* (1991) investigated the beds of *Macrocystis pyrifera* of the west coast of the Baja California.

Not all acquisition methods are by manned airplanes; Gonçalves *et al* (2004) describe APIAS (an Airborne Photos and Images Attainment System) that makes use of a radio-controlled aircraft, equipped with a conventional camera with a wireless shooting device. Tarr (1993) made use of a helicopter to map South African kelp beds (for the purposes of measuring abalone habitat) near to Danger Point, west of Cape Agulhas.

Valta-Hulkkonen *et al.* (2003) made use of digital false colour aerial photographs of three lakes in the Vuoksi drainage basin, Finland. Differences in trophic state and water quality were used to clarify the reflectance characteristics of various life forms and species of aquatic macrophytes at green, red and near-infrared (NIR)wavelengths. The results indicated that the classification of forms and types of aquatic macrophytes is affected by the density of the vegetation, the openness of the canopies and the amounts, forms and orientations of the leaves. Another Finnish research team (Erkkila & Kalliola, 2004) made use of data from six Landsat TM/ETM+ images from the late 1990s in the Archipelago Sea in the northern Baltic in order to monitor water quality. Single images were enhanced by principal component transformation and multi-temporal image combination was based on unsupervised classification. They concluded that accurate and cost-effective water quality monitoring and forecasting require an integrated monitoring system, consisting of space and airborne surveillance, field surveys and hydrodynamic modeling.

In other parts of Africa, including portions of the coastline, the SAFARI 2000 ER-2 Color-IR Aerial Photography survey (http://www.dfrc.nasa.gov/) was done to provide detailed and spatially extensive documentation by means of 3,046 color-infrared (IR) transparencies collected during the SAFARI 2000 Dry Season Aircraft Campaign in August and September of 2000. However, these are not useful for the coastline, in particular for intertidal zone studies.

This study aims to further the work done by Tarr (1993) and the Seaweed Unit, M&CM, who have taken aerial photograph of kelp beds in order to assess their extent, in South Africa.

1.4.4 Geographical Information Systems (G.I.S.)

The meanings associated with the acronym, GIS need clarification. They include related fields, namely GISytems, GIStudies and GIScience. The term GIS will be used to mean Geographical Information System(s) hereafter. Relational Database Management Systems (DBMS) orientated systems (used in ESRI's ArcView) have been replaced by object-orientated DBMS (such as used in ESRI's ArcGIS) in the late 1990's (Chrisman, 1997). A comprehensive account of the development of applications for GIS up till the 1990's is reviewed in Maguire *et al.* (1991). The theoretical concepts and applications behind the GIS techniques have been documented by Chrisman (1997). The technological, geographic, cartographic and analytical developments in this field over the past decade were discussed by Demers (2000) and Clarke (2001).

In this study, spatial analysis techniques were applied to create a database of kelp beds. Types of operations (after Bernhardsen, 1999 p 234-272) along with examples used in this study include:

1. Logic Operations (set or Boolean algebra) – identifying extrema.
2. Arithmetic Operators (standard operators) – reclassification of image.
3. Statistical Operations (mainly on attribute data) – remotely sensed imagery.
4. Geometric Operations (algorithm based) – centroids and thiessen polygons.
5. Complex Attribute Operations (used Boolean and statistical functions).
6. (Re)Classification (grouping of attributes) – union or merging of themes.
7. Polygon overlay (integrates geometry and attributes) – McHarg Overlay.
8. Network Operations (dependent on topology) – road networks.
9. Connectivity Operations (near neighbour and cluster analysis).
10. Expert Systems (use automated and algorithm based decision making rules).

A number of studies have been done using GIS and other databases in coastal research. For example, Jensen *et al.* (1976, 1980, 1987); Urbanski & Szymelfenig (2003); Congleton *et al.* (1999); Ottaviani *et al.* (2004) ; Chen *et al.* (2005); Guan *et al.* (1999) and Zeidler (1997). GIS techniques and protocols that provide the background for selection of the methods of GIS analysis used in this thesis (see Chapter 2) were obtained from: Smith (2002); Johnston & Davison (2002); Airame *et al.* (2003) and Banks & Skilleter (2002).

It is suggested that the results of the current study be made available on-line. Halldórsdóttir & Þorbergsson (2004) and Elevelda *et al.* (2003) describe the development of an online-database that could provide the framework to accomplish this.

Chapter 2. Data methods and kelp mapping

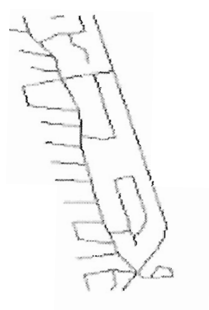
Chapter Outline

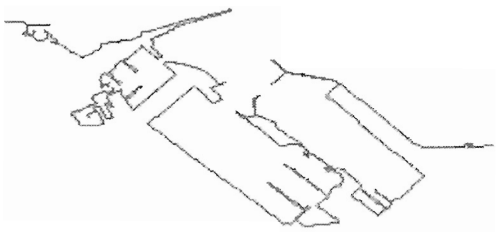
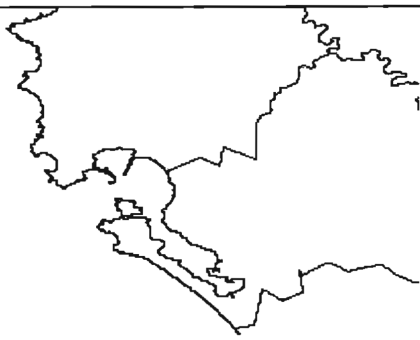
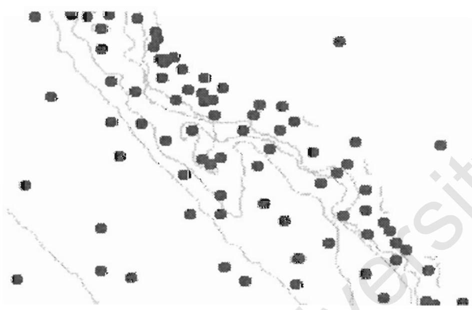
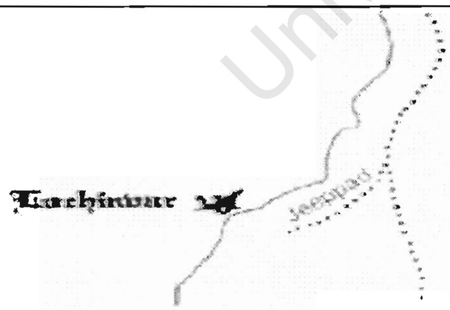
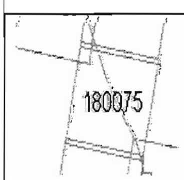
This chapter documents the datasets and research methods, including field surveying techniques and image analysis techniques employed in the creation of the kelp inventory and analysis of commercial harvesting statistics.

2.1. Description of data sources used in this study

The data requirements for this study were geographical datasets captured at the highest resolution possible. Issues of transforming between spatial data projections arose when confronted with the Cape Datum and NAD1983 to Haartebeeshoek WGS84. Although navigational charts are available these do not provide good coastline/intertidal isolines. A national 1:50 000 coastline proved a good starting point for ground truthing as it matches well with 1:50 000 topographic maps. Existing digitized biological data did not match well at a fine spatial scale with digital coastlines. An error of up to 10 meters in the inner fringe of kelp beds in some cases was noted. This was corrected by manual fitting of kelp beds to the coastline verified by field surveys. The reason for the non-overlap of kelp beds and water in the analysis is due to coastline dataset inaccuracies and (in fewer instances) misidentification of non-kelp pixels as being kelp. Non-biological datasets used are listed in Table 2.1 below.

Table 2.1. A list of the spatial databases of non-biological data used in this thesis.

Data type	Data Description	Data Source
	Road Network. Line Vector Data type.	Chief Directorate of Surveys & Mapping (CD:S&M)

	Coastline. Line Vector Data type.	Merge of CD:S&M, NAVY, Cape Town Metropolitan Authority (CCMA)
	South African Towns. Point Vector Data type.	CD:S&M
	Census 2001. Line Vector Data type.	Statistics South Africa
	Soundings, Depth Contours. Line and point Vector Data type.	S.A. Navy
	1:50 000 map series Vector Data type. Raster Data type.	CD:S&M
	WRS2 Path/Row Landsat orbital path. Polygon Vector Data type.	http://landsat7.usgs.gov

The following map (Figure 2.1) shows locations mentioned in the text and sketches out the geographic coverage of the six kelp bed datasets integrated into the kelp inventory, namely Aerial Infrared Photography (1988, 1996, 2005), Landsat 5 (1991), Landsat 7 (2003) and field surveys (2003-2005). A description of each dataset is given in the sections which follow.

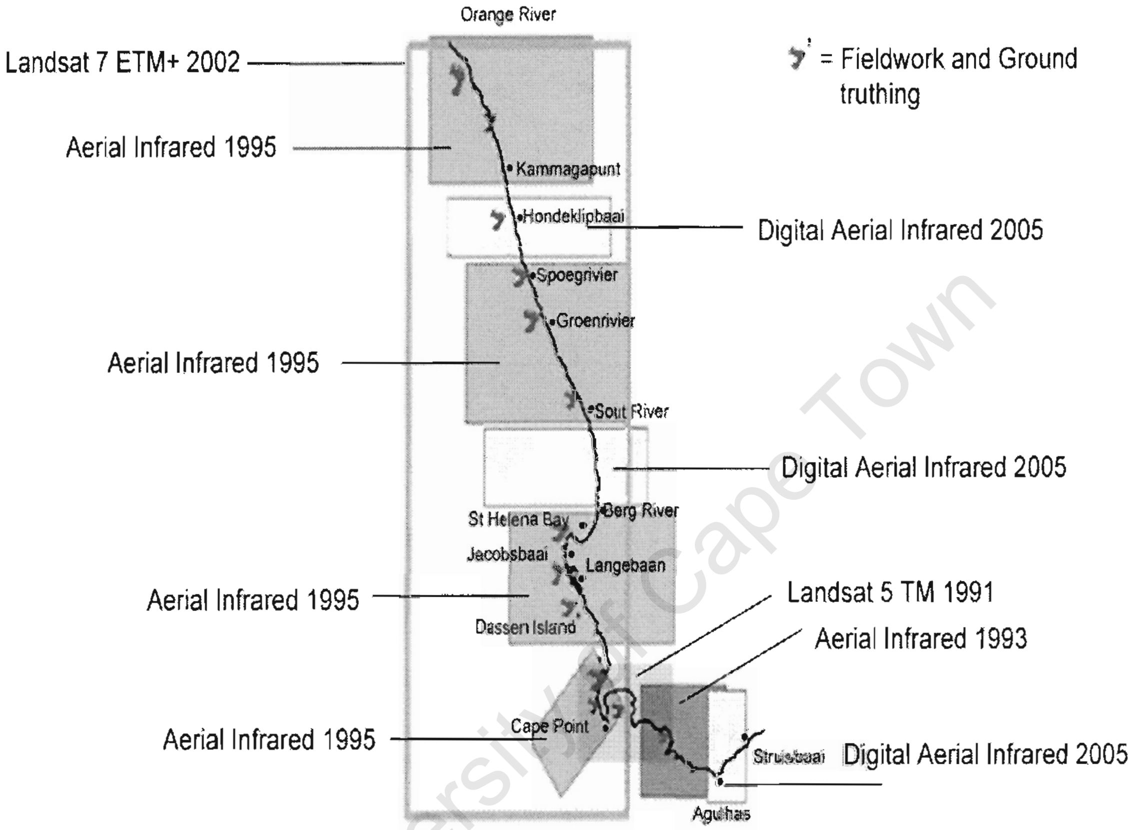


Figure 2.1. Summary sketch of geographical extent of datasets used and locations mentioned in the text.

2.1.1 Previous data and research

Three existing datasets were used in this thesis: Hard copy kelp habitat maps from a Master of Science thesis (Tarr, 1993); M&CM 1996 kelp survey (digitized into vector format); and Landsat 7 ETM+ Imagery (Geospace Pty Ltd., 2002). A description of each follows, with a detailed explanation of refinements performed.

2.1.1.1. Kelp habitat mapping (TARR 1993)

Tarr (1993) produced a series of maps of kelp beds for the purpose of studying abalone habitats. The maps were created from transparencies of 70mm Kodak Aerochrome colour infra-red (using a Pentax 645 SLR camera) from a Bell Jet helicopter during 1988 at an average altitude of 2440m. Figure 2.2 provides the spatial extent of that study which includes the Seaweed Concession Areas 5,6,7,8, and Dyer Island. For this thesis, during 2004, these hardcopy maps were scanned and digitized using on-screen digitizing techniques in ArcGIS 8.3. Individual images were mosaiced and exported into a geodatabase (ArcGIS 8.3). Classes identified were white water, blue water, rock and kelp. The conversion of scanned images of maps was done in ArcMap. The mosaiced images underwent georeferencing, orthorectification and reclassification in ArcGIS 3D Spatial/Image Analyst. Image components were converted from raster to spatial feature files and non-kelp polygons were removed. Kelp polygons were extracted from a unsupervised classification of pixels in the georeferenced imagery. They were compared by visual interpretation of the hardcopy and scanned maps. Examples are given in Figures 2.3 and 2.4.

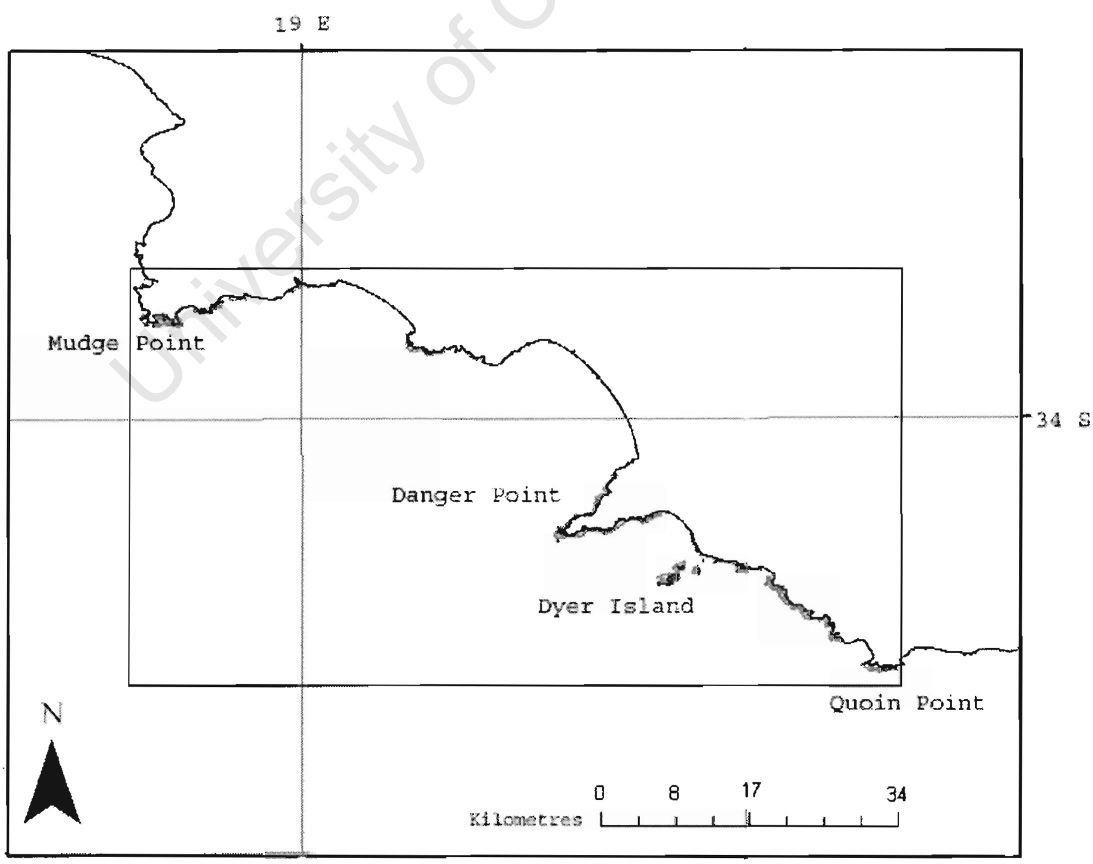


Figure 2.2. Location map of areas surveyed by Tarr (1993)

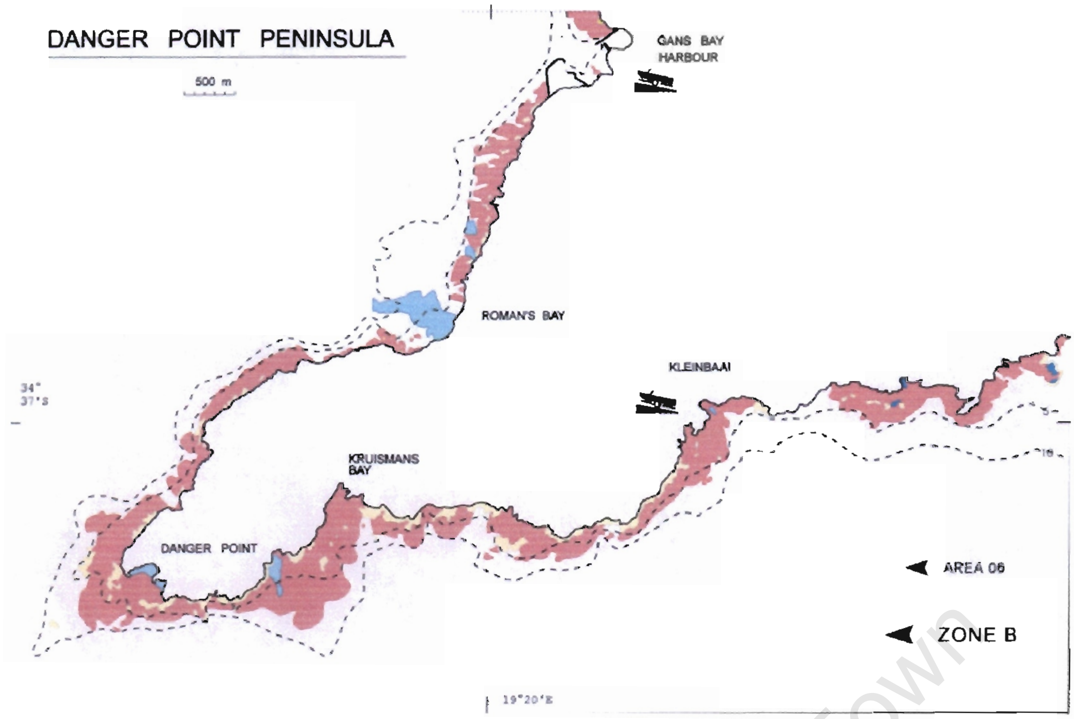


Figure 2.3. Sample image of kelp beds along Danger Point Peninsula (reproduced from Tarr, 1993).

Figure 2.4. Kelp bed vector polygons and coastline of Danger Point Peninsula (extracted from Figure 2.3).

1.1.2 Infrared Aerial print photography (M&CM, 1996 unpublished data)

An aerial photography survey was done by the Seaweed Unit, M&CM using infrared print film in 1996 and 1997. The geographic areas surveyed include (see Figure 2.1):

1. From Simon's Town Harbour, southwards to Smitswinkel Bay; and the kelp beds near to Kommetjie along the Cape Peninsula.
2. From Saldanha Bay, northwards to the Berg River.
3. From the Sout River (31° 15' S, 15° 50' E), northwards to the Spoeg River.
4. Kammagapunt (30° 05' S 17° 10' E), northwards to the Orange River.

This film was printed and enlarged. Kelp beds were interpreted by projecting the slide on a photographic enlarger and tracing kelp beds onto paper laid over 1:10 000 topographic maps. Some years later, these maps were digitized, backed up as shape files, and archived by Terramare Pty (Ltd). Figure 2.5 shows a comparison between manual (visual) and computational identification of kelp beds that was done for a small part of the coast around Port Nolloth done by Sampson *et al.* (2001) prior to the loss of most negatives and all prints. This dataset was cleaned and projected into Haartebeeshoek WGS84 coordinate system.

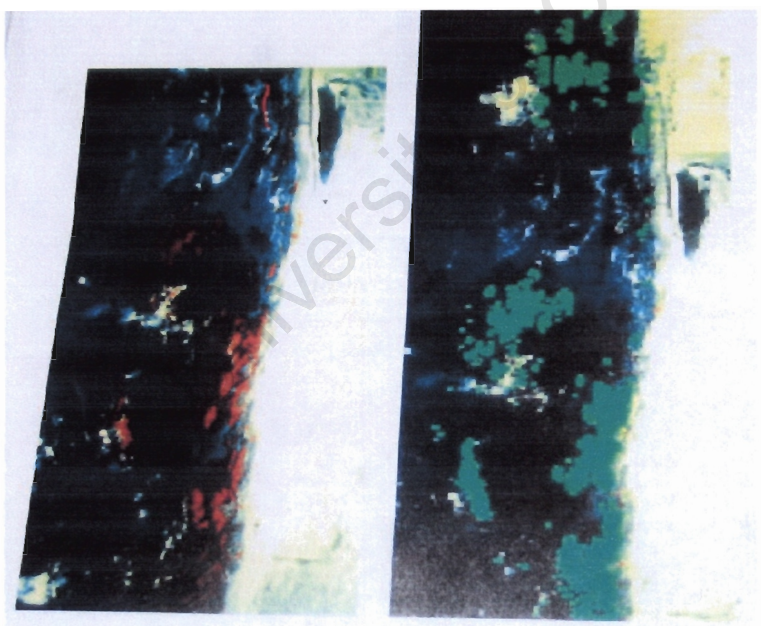


Figure 2.5. On the left, IR Aerial Image with IR band shown in red; on the right, Raster Image with kelp shown in green (scanned from Sampson *et al.*, 2001).

2.1.1.3 Landsat 7 ETM+ (2002)

Landsat 7 ETM+ was used to estimate kelp bed planimetric areas as part of a global study by an American research company, Ocean Imaging (Pty) Ltd. They provided the author with the digital shapefile of kelp beds for parts of South Africa (see Figure 2.1 for overview and Figure 2.7 for detail). Figure 2.6 below provides the footprints of the Landsat 7 satellite covering the coastline of South Africa and Namibia that was used to select possible images for interpretation. This dataset could be used in future studies of the kelp beds along the Namibian coastline, not covered in the present study.

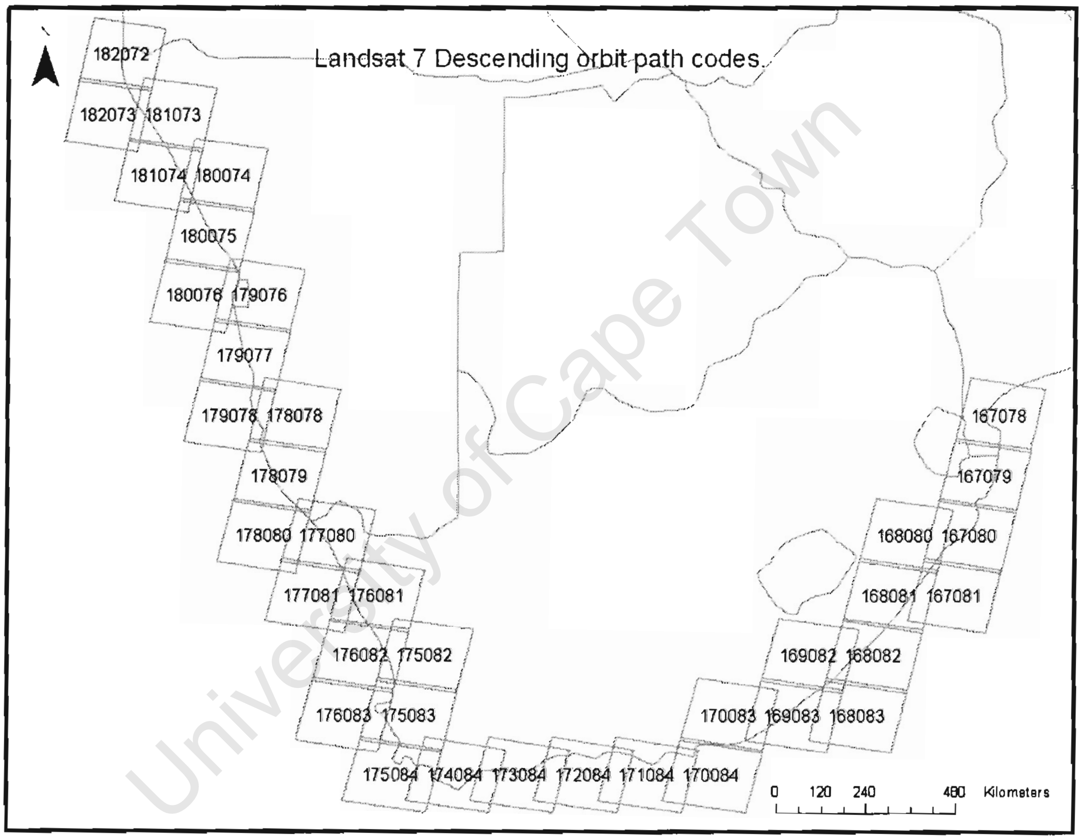


Figure 2.6. Landsat 7 Descending Orbital Path codes and footprints along the coastline of South Africa and Namibia.

A sample of the kelp polygons derived from the Landsat 7 ETM+ dataset is provided for Danger Point Peninsula in Figure 2.7. Compare the kelp beds presented in Figure 2.7 with those presented in Figure 2.4. Note that the kelp beds are fewer and smaller based on Landsat 7 imagery interpretation. For example, note that none of the kelp beds between Gansbaai and Romans Bay Harbour are present in Landsat 7, but are correctly identified in the Tarr (1993) image.

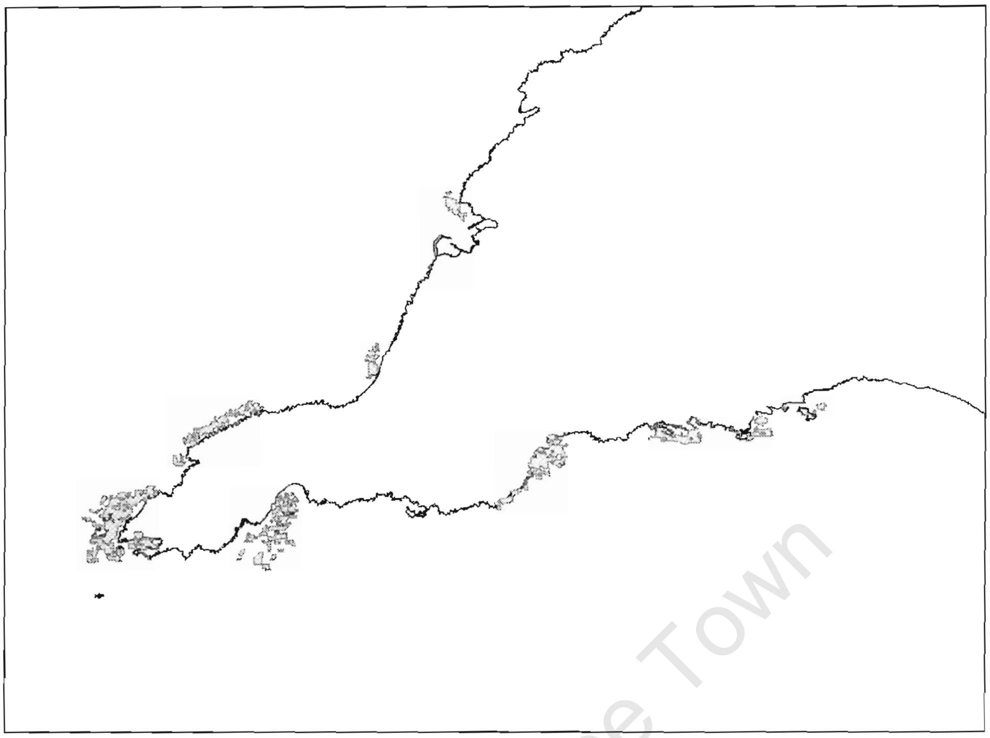


Figure 2.7. Kelp beds of Danger Point Peninsula derived from Landsat 7 ETM+ imagery.

2.1.2 New research

Aerial Colour infrared (CIR) Image acquisition, ground truthing and field work was done between 2003 and 2005.

2.1.2.1 Colour Infrared Aerial photography (2005)

After mapping out the areas of the west coast covered by Tarr (1993) and the 1996 CIR survey, it was decided to fill in the gaps by means of a new survey. This aimed to provide a full coverage of the coastline where kelp occurs. Three high priority gaps in the kelp inventory were selected for an aerial survey. Valta-Hulkkonen *et al.* (2003) successfully made use of green, red and near-infrared (NIR) wavelengths for the discrimination of aquatic macrophyte species. Their research supports the choice of colour infrared (CIR) in this thesis. The government tender process for aerial photography of selected parts of the coastline for the purposes of identifying of kelp beds was initiated by MCM (DEA&T) through an invitation to tender. This document was converted into an official application to tender document which was published by the National State Tender Board (http://www.info.gov.za/tenders/2004/ten2358.pdf). This document requested the tendering company to produce a quote and a number of official forms accompanying the bid: tax clearance certificate, declaration of interest, and preference certificate (containing Historically Disadvantaged Individual (HDI) status of shareholders or partners). HDI is central to the South African procurement policy: "an HDI is a South African citizen who is female, or has a disability, or had no franchise before the national elections in 1994" (Republic of South Africa, 2000). The procedure for closing and adjudication of bids was left up to the adjudication panel. The open and public nature of the closing of the tender enabled bidders to witness that a fair process was adhered to. Thereafter, Geospace International was informed that their bid was successful and they commenced work. A digital camera was preferred over an analogue version used in the 1996 IR aerial survey for increased speed and ease of use in addition to the reduced processing time and improved accuracy.

Geospace International used an integrated digital image photography system namely EnsoMosaic (EM). EM is a digital aerial imaging and image processing system developed by Stora Enso Forest Consulting (Pty) Ltd and the Technical Research Centre of Finland (VTT). EM is a complete set of software for the image acquisition process, from flight planning to geo-referenced and ortho-rectified image mosaics. Geospace developed the onboard photo triggering hardware and software that activates the sensor at appropriate intervals integrating GPS positions. The combination of exposure times as well as gain adjustment per channel allows the operator to adjust individual band histograms in flight. The GPS data are differentially corrected to sub meter quality. The EM software performs image rectification and joins the images into a mosaic using Bundle Block Adjustment. The location of the images is measured with the GPS during the flight and, as a result, the output mosaics can be processed into a real world coordinate system. The Duncantech MS3100 is a Sensor with a colour separating prism with three CCD imaging sensors (1392 X 1040) X3 resolution recording 4 spectral bands between 400 and 1100 nm. The image captured during the process described above is stored in 3 bands namely Infrared, Red and Blue/Green. The Infrared and Red bands are captured by individual monochrome CCDs. The Blue/Green bands are captured on the third CCD that has a Bayes pattern filter on the CCD. The blue and green bands are separated by a post processing process and RGB or CIR images can then compiled by mapping the Infrared, Red , Green and Blue bands in either RGB(Colour) or RIRG(red, infrared, green or CIR). See Figure 2.8 (DuncanTech, 2005)

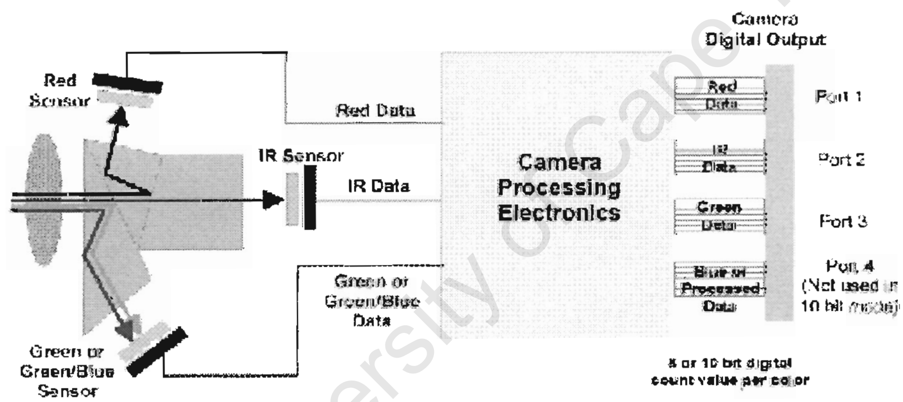


Figure 2.8 The DuncanTech MS3100 Sensor schematic (provided by Geospace Pty Ltd)

The bands used in the final compilation of the mosaics for the study area were IR, Red and Green. Digital imaging has to be performed so that the overlap between successive images (forward overlap) is between 30-60% and between lines (side-lap) at least 20 percent. During the flight the aerial coordinates of each image is captured by means of Real-time differential correction (DGPS). The flight is carried out with the assistance of a GPS controlled moving map, indicating the flight lines as well as the captured images in relation to the flight lines. The software automatically triggers the camera at predetermined intervals and in flight information supplied to the pilot confirms the accuracy of the completed flight lines as well as the positions of the captured images. Despite this ability, infrared film does have limitations in recording sub-surface coastal kelp canopies. Due to its poor water penetration properties of at best two feet (Helgeson 1970); this film will not record kelp that is submerged below the surface due to high winds and seas, high tides, and tidal currents.

The geographic extent of the photography taken in the three areas was:

- **Area One (Figure 2.9)**
  The kelp beds extending from south of Elands Bay (32°20'15"S, 18°10'55"E), northwards to 31°10'0"S, 17°45'30"E. Aerial survey done on 11th March 2005. Low tide was at 09h39 with a tidal height of 0.15m.

- **Area Two (Figure 2.10)**
  The kelp beds between (30°36'S, 17°27'E) and (30°12'S, 17°13'E), an area including Hondeklipbaai. Aerial survey done on 28th March 2005. Low tide was at 10h43 with a tidal height of 0.36m.

- **Area Three (Figure 2.11)**
  The kelp beds between Quoin Point (34°46'S, 19°39'E), extending westwards, past Agulhas, to Struis Bay (34°47'S, 20°01'E). Aerial survey done on 29th March 2005. Low tide was at 11h23 with a tidal height of 0.36m.

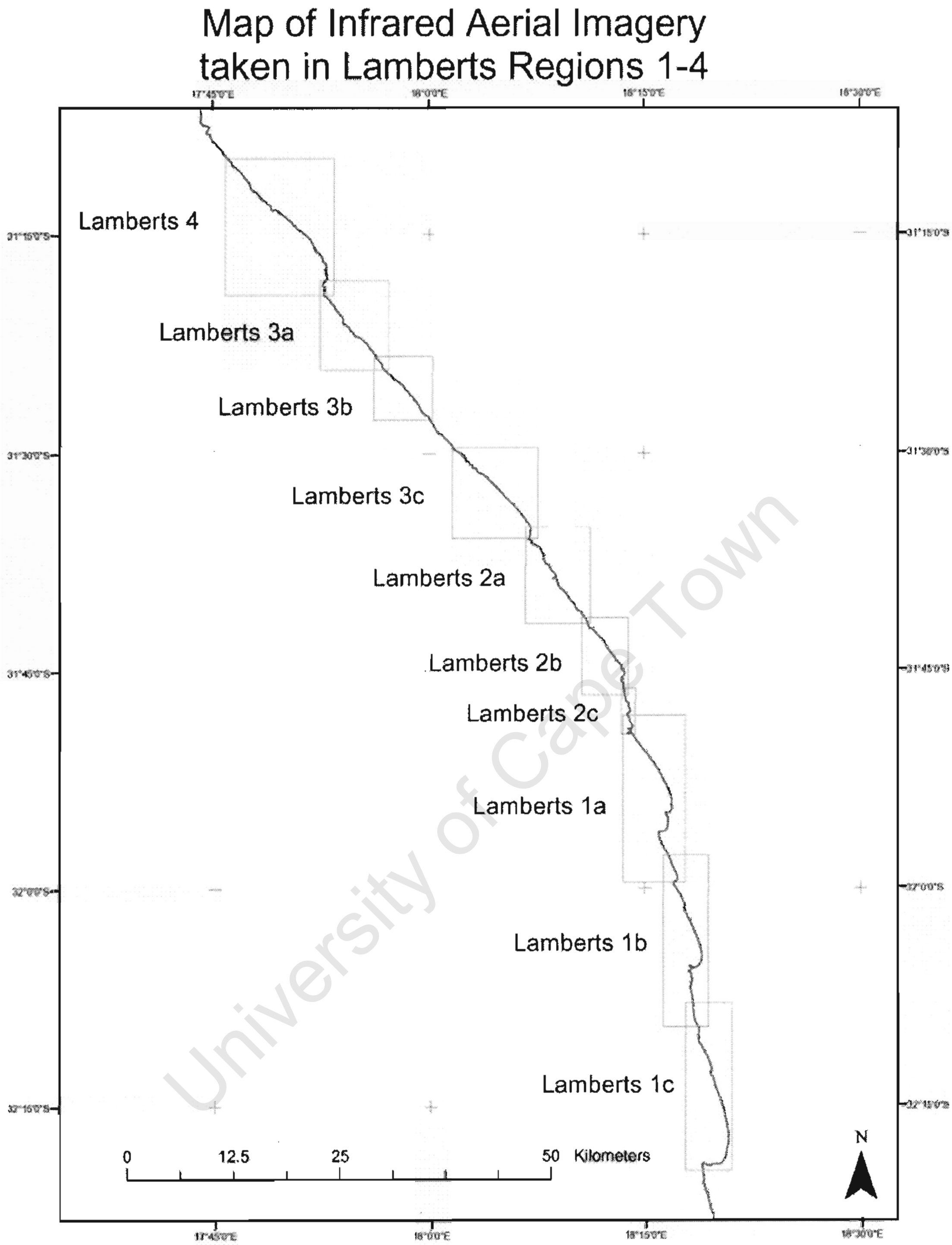


Figure 2.9 Coastline surveyed by Geospace Pty (Ltd) on 11th March 2005. Forms part of the "Lamberts" kelp bed dataset.

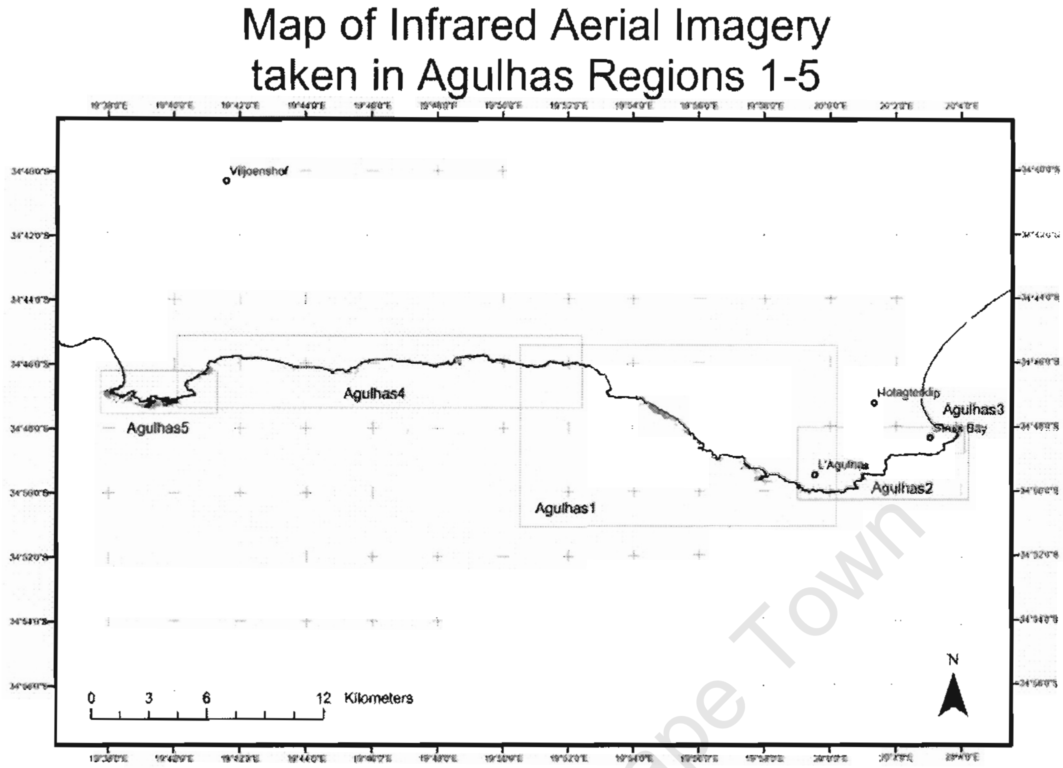


Figure 2.10. Coastline surveyed by Geospace Pty (Ltd) on 28th March 2005. Forms part of the "Agulhas" kelp dataset.

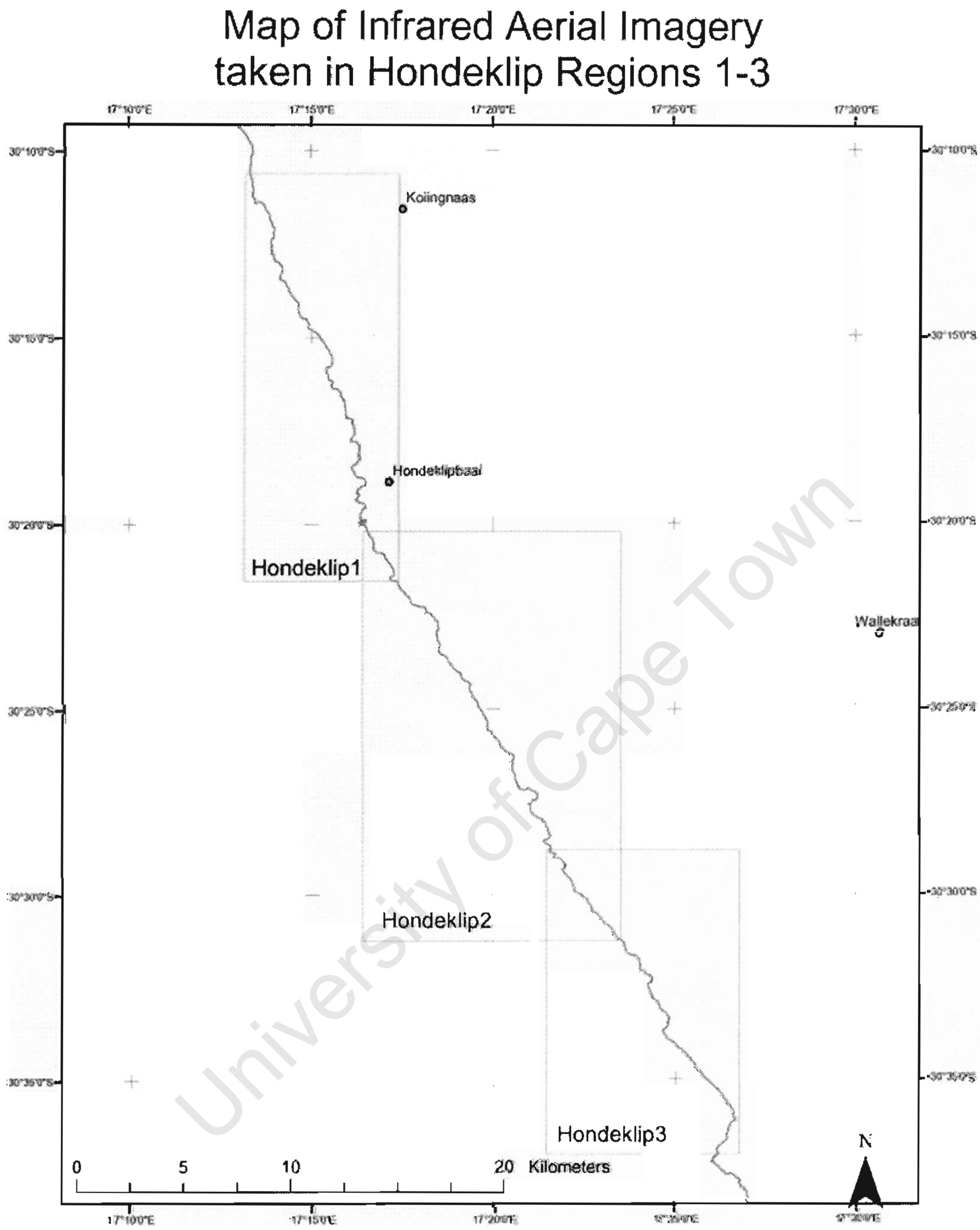


Figure 2.11. Coastline surveyed by Geospace Pty (Ltd) on 29th March 2005. Forms part of the"Hondeklip" kelp bed dataset.

Figures 2.12 and 2.13 provide samples of the imagery. A summary metadata table for the CIR imagery flights and digital processing performed has been included in Appendix 7.

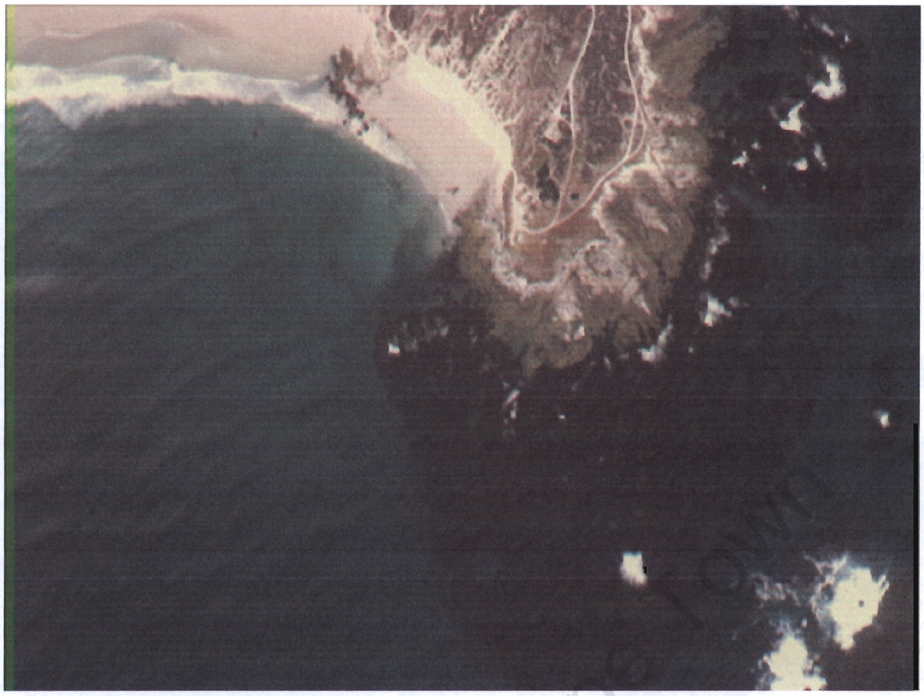


Figure 2.12. Example of non-georeferenced RGB image (corrected in-flight).

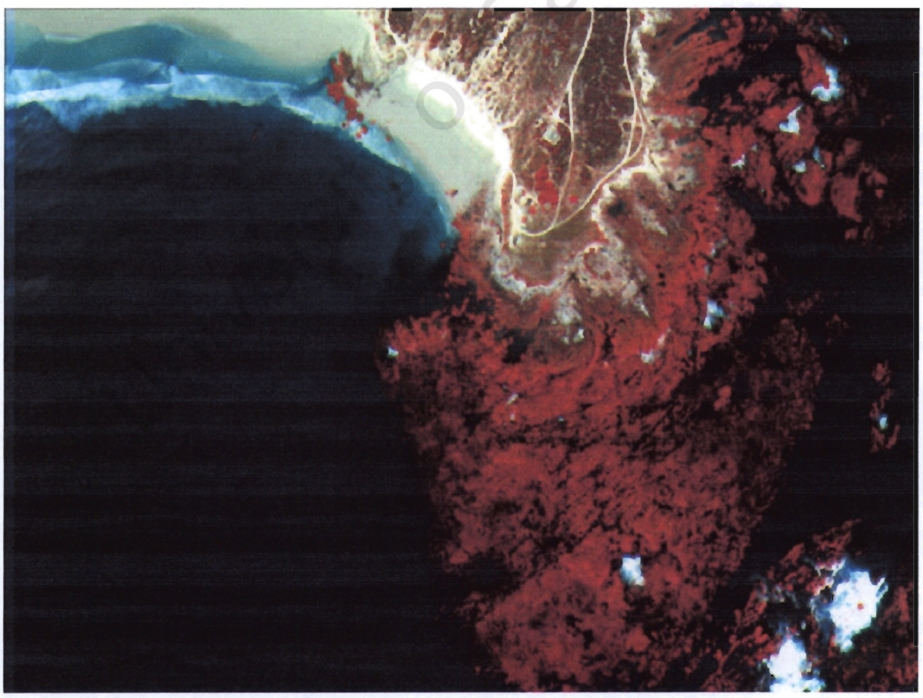


Figure 2.13. Example of non-georeferenced CIR image selected from the RGB image (after blue exclusion) and IR fusion. (Note kelp beds appear red).

The analysis performed on the imagery was done using ENVI 4.0 on a workstation in the Department of Environmental and Geographical Science, University of Cape Town.

The two (kelp and white-water) selected Region of Interest (ROI) pairs underwent the Jeffries-Matusita and Transformed Divergence separability tests. These values can range from 0 to 2.0 and indicate how well the selected ROI pairs are statistically separate. Values greater than 1.9 indicate that the ROI pairs have good separability. For ROI pairs with lower separability values, the separability may be improved by editing the ROIs or by selecting new ROIs. For ROI pairs with very low separability values (less than 1), may be combined into a single ROI. For more information, see Richards (1986, 1999). Both ROI separability tests gave a value close to 2.

The data were explored using a number of supervised classification methods including Parallelepiped, Minimum Distance, Mahalanobis Distance, Maximum Likelihood, Spectral Angle Mapper and Binary Encoding classification methods. The preferred supervised classification method is the Spectral Angle Mapper (SAM). This is a pixel-based spectral classification technique that uses an n-dimensional angle (in this case n, the number of bands, =3) to match pixels to reference spectra. The algorithm determines the spectral similarity between two spectra by calculating the angle between the spectra, treating them as vectors in a space with dimensionality equal to the number of bands (3 bands: IR, Green, Red). This technique, when used on reflectance data, is relatively insensitive to illumination and albedo effects. Endmember spectra used by SAM can come from ASCII files, spectral libraries, or can be extracted directly from the image (as ROI average spectra). SAM compares the angle between the endmember spectrum vector and each pixel vector in n-dimensional space. Smaller angles represent closer matches to the reference spectrum. Pixels further away than the specified maximum angle threshold in radians are not classified. This step produces a "rule image" (see Figure 2.14). Kruse *et al.* (1993) describe the characteristics of SAM in greater detail. Other studies have also successfully employed SAM classifications in the marine environment. For example, Hunter & Power (2002) produced two candidate techniques: the Maximum Likelihood Classifier (MLC) and the Spectral Angle Mapper (SAM). In that study, SAM was applied on hyperspectral data, but has been used for CIR data in this study. An example of a piece of coastline with sandy beaches and rocky platforms with kelp offshore and white water is given in Figure 2.16. The SAM analysis performed on that image is presented in Figure 2.17. Note that the intertidal seaweeds are not identified.

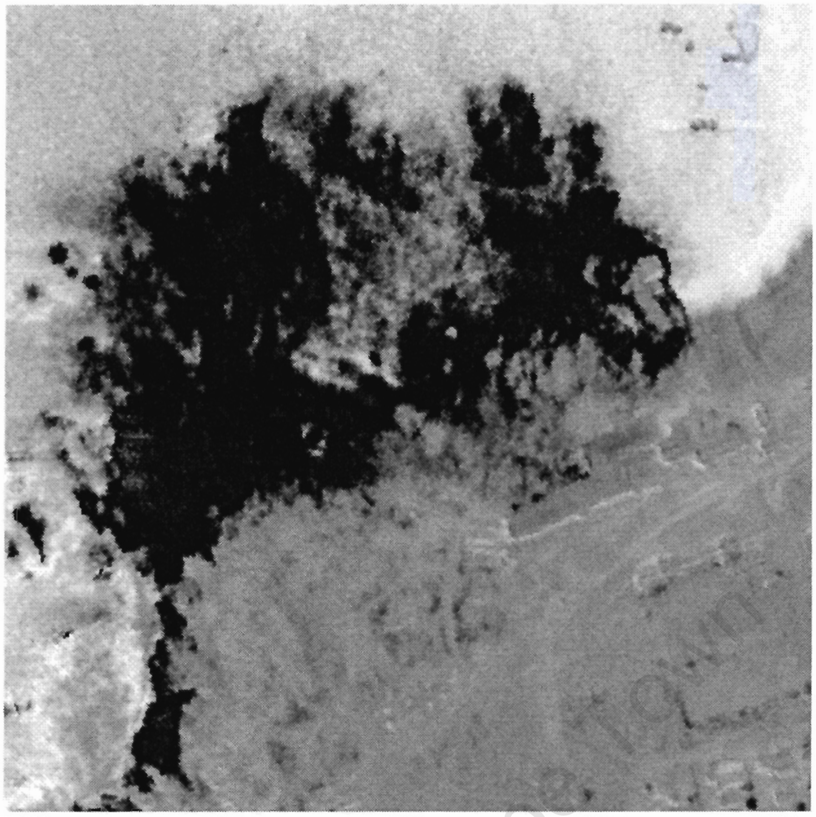


Figure 2.14. Rule Image. Note that the dark areas are closer to reference spectrum and white areas are the furthest away.

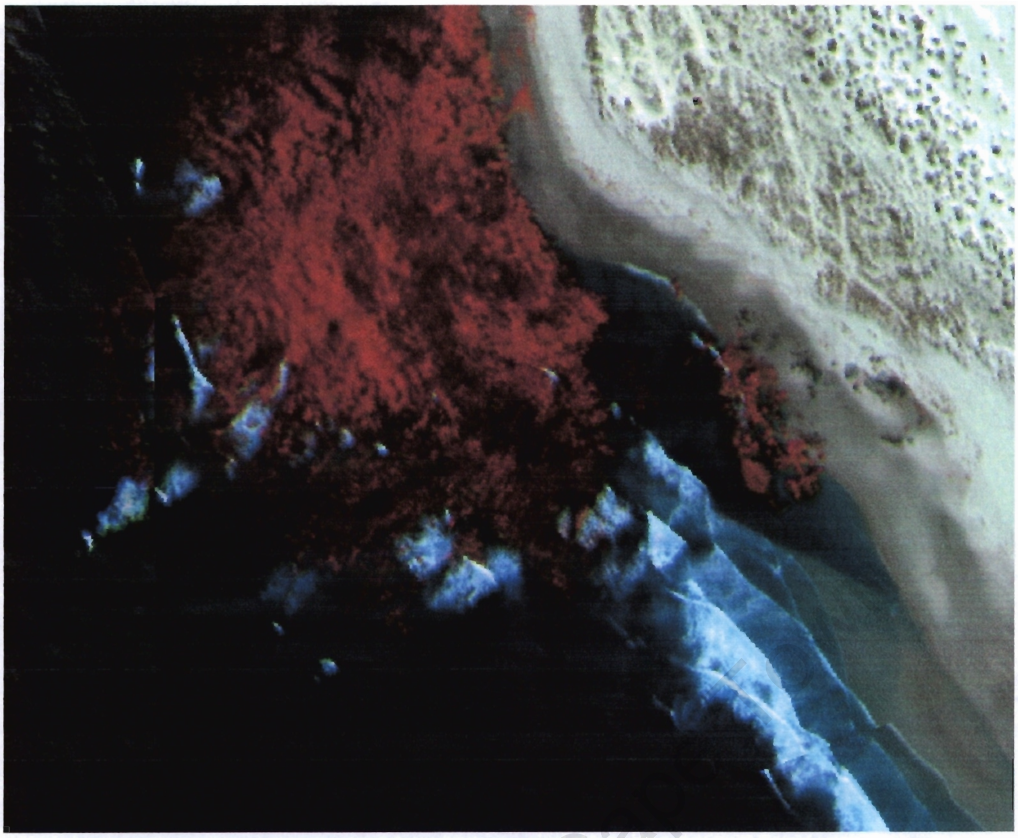


Figure 2.15. Sample of CIR imagery on which the SAM was run (see Figure 2.16)

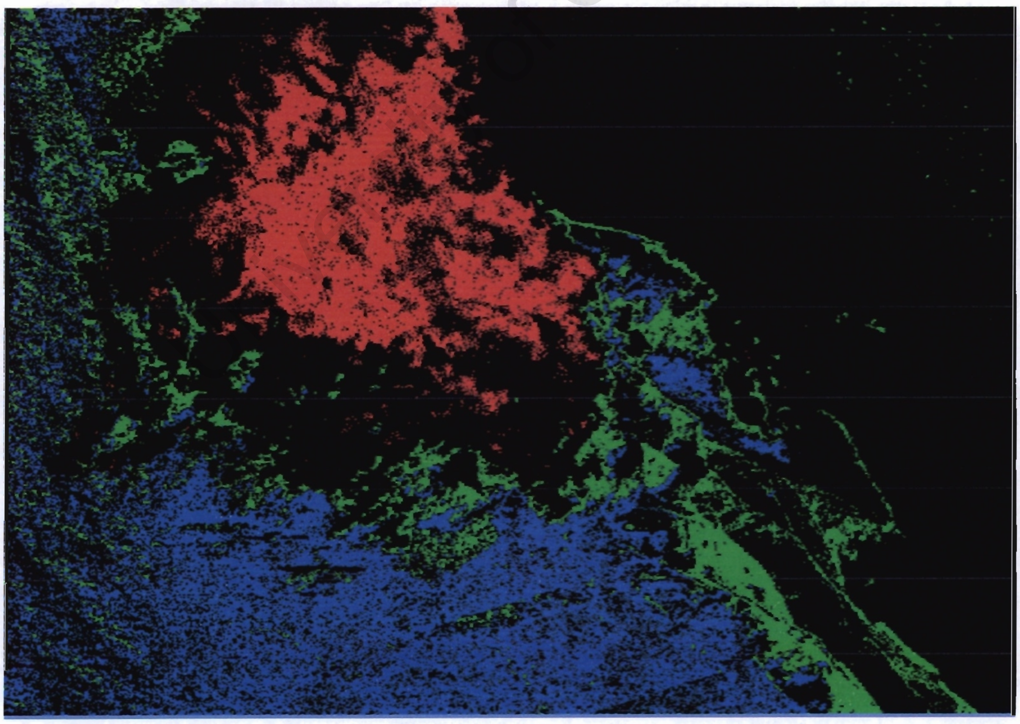


Figure 2.16. Results of Spectral Angle Mapper (SAM) Analysis. Red areas are kelp, green are white water, blue are dark water, and black unclassified.

2.1.2.2 LANDSAT 5 (1991)

Data from satellites have become more accessible as organizations (eg. Earthwatch, European Space Agency, NASA) integrate and catalogue the vast number of satellite images and data. Satellite images are becoming cheaper, particularly older images that have contemporary value for time-series analyses. Obtaining older images allows for a baseline to be set for a particular study, so that later images can be compared. To this end, Landsat 5 images were obtained from the Tropical Rain Forest Information Center's Orthorectified Landsat Atlas Series and analyzed with the aim of identifying kelp beds.

The Thematic Mapper (TM) sensor aboard Landsat 5 is a multispectral scanning instrument designed to achieve higher image resolution, sharper spectral separation, improved geometric fidelity, and greater radiometric accuracy and resolution than the MSS sensor and has a spatial resolution of 30 m. The TM data are scanned simultaneously in seven spectral bands. Band 6 scans thermal (heat) infrared radiation, but has a coarser spatial resolution of 120m. The spectral range of bands, spatial resolution and application to the coastal environment for the Thematic Mapper (TM) sensor are presented in Table 2.2 (after Bernhardsen, 1999). All TM bands are quantised as 8 bit data.

Table 2.2. Characteristics of the 7 Landsat Thematic Mapper bands.

Band	Wavelength Interval (μm)	Spectral Response	Applications
1	0,45-0,52	Blue-Green	Good water body penetration for coastal water mapping. Useful for distinguishing soil from vegetation
2	0,52-0,60	Green	Measures green reflectance peak of vegetation. Useful for detecting infrastructure features
3	0,63-0,69	Red	Senses chlorophyll absorption region aiding in plant species differentiation.
4	0,76-0,90	Near-IR	Delineates water bodies and determining healthy vegetation
5	1,55-1,75	Mid-IR	Indicative of vegetation moisture content and soil moisture
6	10,40-12,50	Thermal-IR	Thermal mapping applications
7	2,08-2,35	Mid-IR	Discrimination of mineral and rock types

When three bands are viewed together using the red, green, and blue color guns of a computer monitor, one may discern even more information.

The most common Landsat TM band combinations and their marine applications mapped to the RGB channels (after NASA 2003):

TM 3,2,1 ('natural color') creates a 'natural color' image from the visible bands that is useful in bathymetric and coastal studies.

TM 4,3,2 ('infrared color') is similar in appearance to color infrared aerial photography and may be used in: detailed vegetation and crop analysis; Wetland studies and urban development and land use studies (useful in masking out urban structures).

TM 4,5,3 Location of inland water bodies and land/water boundaries.

TM 7,4,2 Analysis of soil and vegetation moisture conditions.

TM 5,4,3 Separation of urban and rural land use and Identification of land/water boundaries.

2.1.2.2.1. Kelp Mapping Using Landsat 5 TM imagery

A Landsat 5 TM image was used to investigate whether marine macrophyte vegetation (kelp) could be identified. The image name is "p175r84_5t910629.TM-EarthSat-Orthorectified". It was acquired on the 29th June 1991 along path 175 and row 84 (see Figure 2.17 below). The image header information has been documented in Appendix 6. The coastline that has been captured extends from north of Table Bay Harbour, around Cape Point, to east of Danger Point; but not including Dyer Island. The Concession Areas that fall within this geographic area are: 7; 8; 9; 5 Exclusion West; 6 Danger Point; 6 Exclusion East; 6 Exclusion West; 6 Northern Section; 7 Exclusion East; 7 Exclusion West; 8 Stony Point Ex; and Between 8 and 9. The low tide height on the 29th June 1991, at Simons Town Harbour, was 0.41m at 10h29; and was two days after full moon.

Although TM has a resolution of 30m, narrower features may be visualized if they contrast strongly with their surrounding pixels. Objects may not be distinguished from one another if they do not contrast strongly enough from their neighbours (Liliesand & Liefer 2000, p403).

The methods employed and selection rationale in the analysis of Landsat 5 Tm data is summarized in the following 10 points. Further sections in this chapter detail the steps taken and algorithms used.

1. Appropriate Landsat Image selection (based on cloud cover and timing of tidal height).
2. Acquisition of imagery from the Tropical Rain Forest Information Center (free data for the use by African scientists).
3. Image Enhancement (cleaning up of unused parts of the image).
4. Radiometric Correction (DN to Radiance to Reflectance values).
5. Spectral Masking (removal of Land and sub-photic zones from the analysis).
6. Visual assessment of classified bands and resultant stacked image.
7. Image Classification (unsupervised methods, supervised Spectral Angle Mapper and visual interpretation).
8. Selection of pixels matching spectral library of kelp reflectance.
9. Class aggregation and area calculations.
10. Class export to shapefile and integration into kelp inventory.

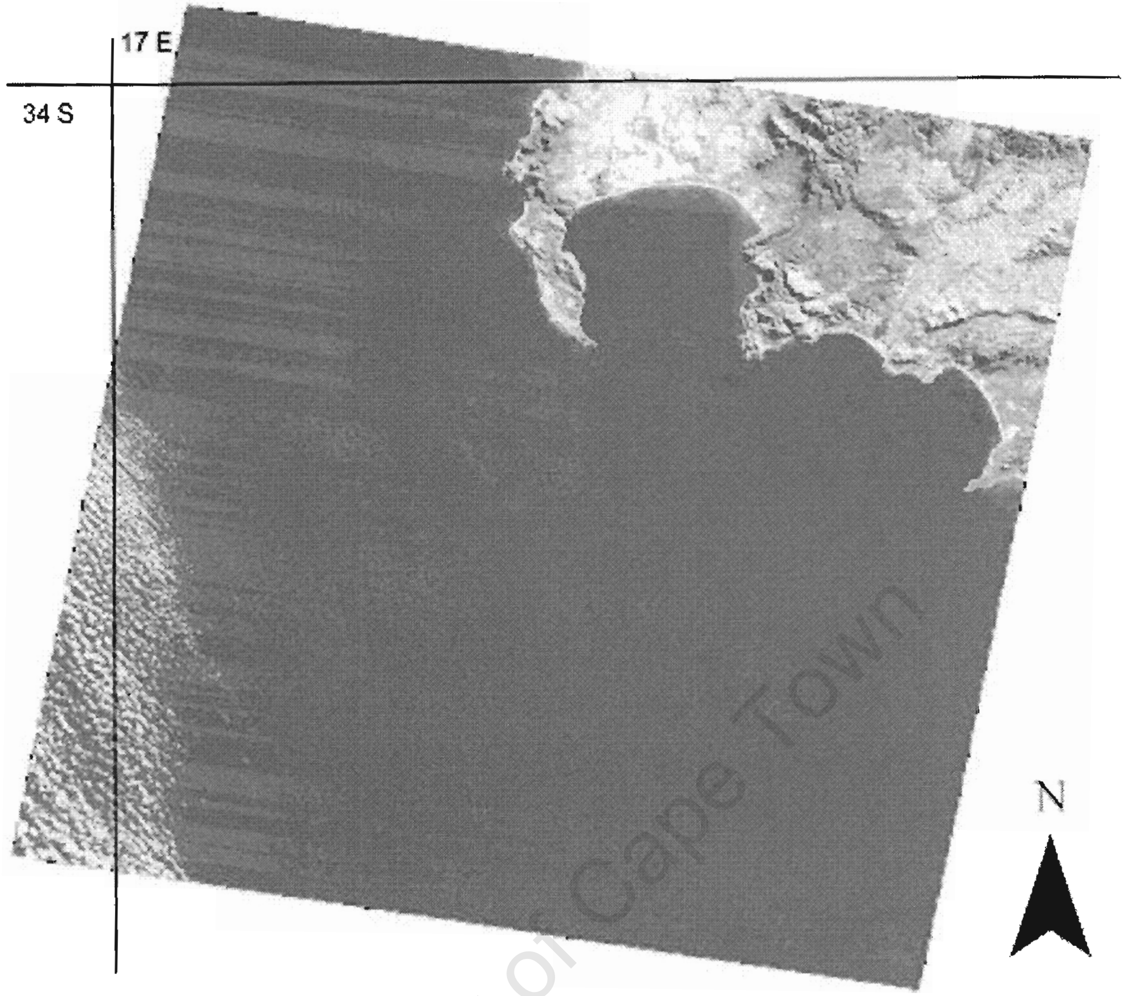


Figure 2.17. Landsat 5 Image used in this study (p175r84_5t910629.TM-EarthSat-Orthorectified).

2.1.2.2.2 Preprocessing: radiometric normalization

A first order normalization is a conversion from scene dependent radiance to an independent variable reflectance. This allows for comparisons with other areas and time periods. It forms the basis of all higher levels of radiometric corrections. A satellite sensor measures radiance at the sensor itself, not surface reflectance from the target. In other words, the sensor is only measuring the intensity of light when it hits the detector surface. The units for this measurement are typically watts per steradian square metre (Wm^{-2} sr^{-1}).

The rationale for including visual interpretation along with supervised and unsupervised classification methods is the backbone of remote sensing when aerial photographs were the only remotely sensed images available. Advances in technology have made a tremendous contribution to remote sensing through the introduction of new digital sensors and improved algorithms to process imagery. The classified map products, however, have not significantly increased in quality. The value of visual interpretation in the process of integrating historical (analogue maps and photographs) with modern digital satellite-acquired imagery is shown in a study by Ciavola *et al.* (1999) involving satellite imagery and water environments.

The process of radiometric correction involves the conversion of Digital Number (DN) into radiance values followed by the transformation into actual reflectance values. This allows for the comparison with other datasets and the use of spectral libraries to aid in the classification procedure. Table 2.3 provides the Landsat 5 post calibration ranges for the 7 bands used.

Table 2.3 Preprocessing values from Chander *et al.* (2004). Note: Landsat 5 Postcalibration Dynamic Spectral Radiances, Lmin, Lmax in $W/(m^2.sr.um)$.

Band	Lmin	Lmax	G(rescale)	B(rescale)	1/G(rescale)
1	-1.52	152.1	0.602431	-1.52	1.65
2	-2.84	296.81	1.1751	-2.84	0.85
3	-1.17	204.3	0.805765	-1.17	1.24
4	1.51	206.2	0.814549	-1.51	4.23
5	-0.37	27.19	0.108078	-0.37	9.25
7	-0.15	14.38	0.5698	-0.15	17.55

A description of the radiometric normalization follows:

Landsat 5 Radiance ($W.m^{-2}.sr^{-1}$) = DN / Calibration coefficient ....(1)

Where, DN = digital number; calibration coefficients for bands for images acquired. However, the radiance values were not available for this image, so they had to be calculated. Thus,

Landsat ETM+ Radiance ($W\ m^{-2}\ \mu m^{-1}$) = gain * DN + offset...............................(2)

Which may be expressed, for Landsat 5 TM, as (Price, 1987; Markham & Barker, 1987):

Radiance = ((LMAX-LMIN)/(QCALMAX-QCALMIN)) * (QCAL-QCALMIN) + LMIN ....(3)

DN is the Digital Number for each pixel of the image, LMAX and LMIN are the calibration constants, and QCALMAX and QCALMIN are the highest and the lowest points of the range of rescaled radiance in DN.

For Landsat 5, the QCALMAX is 255 and the QCALMIN is zero

Spectral Radiance values for the 7 bands were written in ENVI's ION™ script language, simplified from Equation 2 above:

BAND 1: (0.609 * fix(b1) - 0.15)

BAND 2: (1.18836 * fix (b2) -0.28)

BAND 3: (0.81768 * fix (b3) -0.12)

BAND 4: (0.8254 * fix (b4) -0.15)

BAND 5: (0.108908 * fix (b5) -0.037)

BAND 6: (0.0619048 * fix (b6) + 0.1238)

BAND 7: (0.05758 * fix (b7) - 0.015)

In order to convert from Radiance to Reflectance (from Chander & Markham, 2003)

$$\rho p = (\pi * L_\lambda * d^2) / (ESUN\lambda * \cos \theta) \quad \text{......} \quad (4)$$

where L_λ is at satellite spectral radiance which is the outgoing radiation energy of the band observed at the top of atmosphere by the satellite, d is the Earth-Sun distance in astronomical units, ESUNλ is mean solar exoatmospheric irradiances (W m^{-2} μm^{-1}) for the band λ, and cosθ is the cosine of the solar incident angle. Supposing a horizontal land surface is flat, the cosine of solar incident angle (cosθ) can be calculated from the Sun Elevation cos(90-SunElevation). The Sun elevation angle for the image is in the header file.

Radiation intensity from the sun is dependent on the distance between earth and sun, and the solar elevation (90 – solar zenith angle). Normalized variable reflectance describes the ability of a surface to absorb or reflect radiation from a certain wavelength. Spectral reflectance equations employed in ENVI to calculate radiance. A sample equation for Band 1 is (based on equation 4):

(π * ((0.609 * fix(b1)) - 0.15) * (1.0166 * 1.0166)) / (1957 * 0.6333192030863)

Note the command "fix" extends the Dynamic range of values stored in each pixel from -32768 to + 32767. This allows for larger numbers to be computed.

An example of the spreadsheet created for Digital Number equal to "5" is given in Table 2.4. Note that Band 6 (thermal Band) was not included in this analysis, as it requires in-situ field measurements (which were not done at time of image capture) of temperature for corrections to be done.

Table 2.4. Example of spreadsheet used for Landsat 5 Radiometric Normalization.

Band	Gain	Bias	LMIN	LMAX	QCALMIN	QCALMAX	QCAL = DN	L=spectral radiance	ESUN	Reflectance
1	0.00398	-0.01	-0.15	152.1	0	250	5	2.895	1957	0.007584
2	0.00964	-0.0232	-0.28	296.81	0	250	5	5.6618	1826	0.015896
3	0.0054	-0.0078	-0.12	204.3	0	250	5	3.9684	1554	0.013092
4	0.01043	-0.0193	-0.15	206.2	0	250	5	3.977	1036	0.01968
5	0.00235	-0.008	-0.037	27.19	0	250	5	0.5075	215	0.012102
6			0.1238	15.6		250	5			
7	0.00154	-0.004	-0.015	14.38	0	250	5	0.2729	80.67	0.017343

The ENVI software was used to create regions of interest (ROI) in order to collect similar pixels into groups for further classification. The resulting clases were: water, bare rock, kelp and intertidal seaweeds. Scattergrams of any two bands aided in the selection of ROIs that appeared to have good separation.

The classification method involved the creation of a spatial mask. Masking of input images is very important in the normalization of coastal imagery. In coastal imagery, digital number (DN) values tend to be much greater for land surfaces than for water surfaces. If these brighter land surfaces are included in the normalization process, the mean and standard deviation values within individual scattering angle bands will be greatly affected; this influence will have adverse affects on the output normalized image. Deysher *et al.* (1997) provide a model example, however, the principles outlined above were used to make a purpose specific mask.

1. A 3 kilometer buffer was created to eliminate unnecessary pixels that would slow down computational time of over 2000 images.
2. The land was masked out by a manual process of land-pixel identification and masking procedure.

3. The mask was applied to each of the bands in the image

The training of the classification protocol included use of spectral libraries. Werdell & Roesler (2003) reported that the spectral shape of the kelp albedo did not vary significantly between samples, although the brightness varied by a factor of two. The values presented in that study (Figure 2.18) were used to create the spectral library. Although that study was done for *Laminaria* sp., it provided the best in-situ measurements of reflectance of kelp. Future studies should make use of in-situ species-specific reflectance values for the particular study site under investigation.

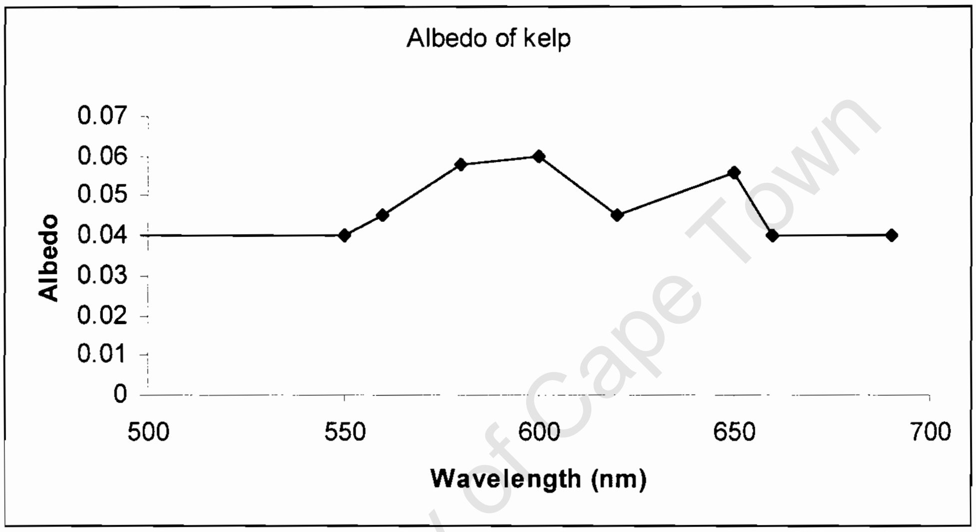


Figure 2.18. Albedo of kelp (*Laminaria* sp.) used to create spectral reflectance library (based on Werdell & Roesler, 2003).

"Absorption by Chl a and c and fucoxanthin results in a reflectance window in the 560- to 660-nm range. Kelp fronds are very thick (>2 mm) and thus the spectral bands in which pigments absorb are virtually nonreflective." Werdell & Roesler (2003, p562).

A ENVI header file created from Figure 2.18 as follows:

```
ENVI
description = {  New spectral library file [Mon Dec 19 15:00:45 2005]}
samples = 9
lines   = 1
bands   = 1
header offset = 0
file type = ENVI Spectral Library
data type = 5
interleave = bsq
sensor type = Unknown
byte order = 0
wavelength units = Nanometers
reflectance scale factor = 1.000000
z plot titles = {Wavelength, Value}
band names = { Spectral Library}
spectra names = { kelp}
wavelength = { 400.000000, 550.000000, 560.000000, 580.000000,
600.000000, 620.000000,  650.000000, 660.000000, 690.000000}
```

1.2.2.3. Unsupervised classifications

An ISODATA unsupervised classification following a Normalised Vegetation Index (NDVI) was performed on the imagery, using band math of the form:

```
FUNCTION p175r84_5t910629.TM-EarthSat-Orthorectified, b1, b2
   NDVI_float = (float(b1) - b2) / (float(b1) + b2)
   b1 = BYTSCL(NDVI_float, min = -1.0, max = 1.0)
   RETURN, b1
 END
```

The results are presented in Chapter 3. This unsupervised classification was compared with the SAM supervised classifications. A sample from Danger Point (Figure 2.19) is presented here:

Figure 2.19. Sample of Landsat 5 image (RGB, 321) analysis with kelp beds (identified in red) at Danger Point.

2.1.2.2.4 Supervised classification (SAM)

Methodology for using SAM is given in Purkis *et al.* (2002). In the absence of a training set of ground-truth data, it was found that by applying bispectral and principal components plots of satellite radiance, pixels corresponding to sand and deep water could be recognized. A further description of the Spectral Angle Mapper (SAM) may be found in the 2005 CIR survey methods section.

2.1.2.3 Field surveys and ground truthing (2003-2005)

Ground truthing of the edge of kelp beds was done either by ski boat or, with greater accuracy, by sea kayak for areas along the Cape Peninsula. The process involved the collection of GPS data (Garmin X12 Recreational GPS unit used). The DNR Garmin Extension software (created and maintained by the Minnesota Department of Natural Resources, MIS Bureau, GIS Section) was used to upload the GPS data into ArcGIS. Other sites that were ground truthed included Groen River to Spoeg River (shoreline transects), Port Nolloth (kelp bed and shore transects), Jacobsbaai (kelp bed transect), Cape Peninsula (sea kayak), Dassen Island (ski boat) and Danger Point (ski boat).

2.1.2.4 Port Nolloth (2004)

Certain kelp beds along the shore of South Africa where chosen as sites for the ground truthing of imagery obtained. A site at Port Nolloth was surveyed between 09 - 11 March 2004. Figure 2.20 is a photograph of the transect line, near an abalone farm. The floating quadrat method involves a 1x1 metre square PVC pipe that floats on the surface of the water. It was used to count the number of heads at the surface per square metre. The plants in each of the quadrats were also removed for biomass determination. Every plant removed was cut into the different components (stipe weight, stipe length, primary blade, distal fronds, basal fronds) and each weighed or measured separately. 1m^2 floating quadrats were used to count the number of plants in different size classes for population structure determination. The kelp biomass results are presented in chapter 3.

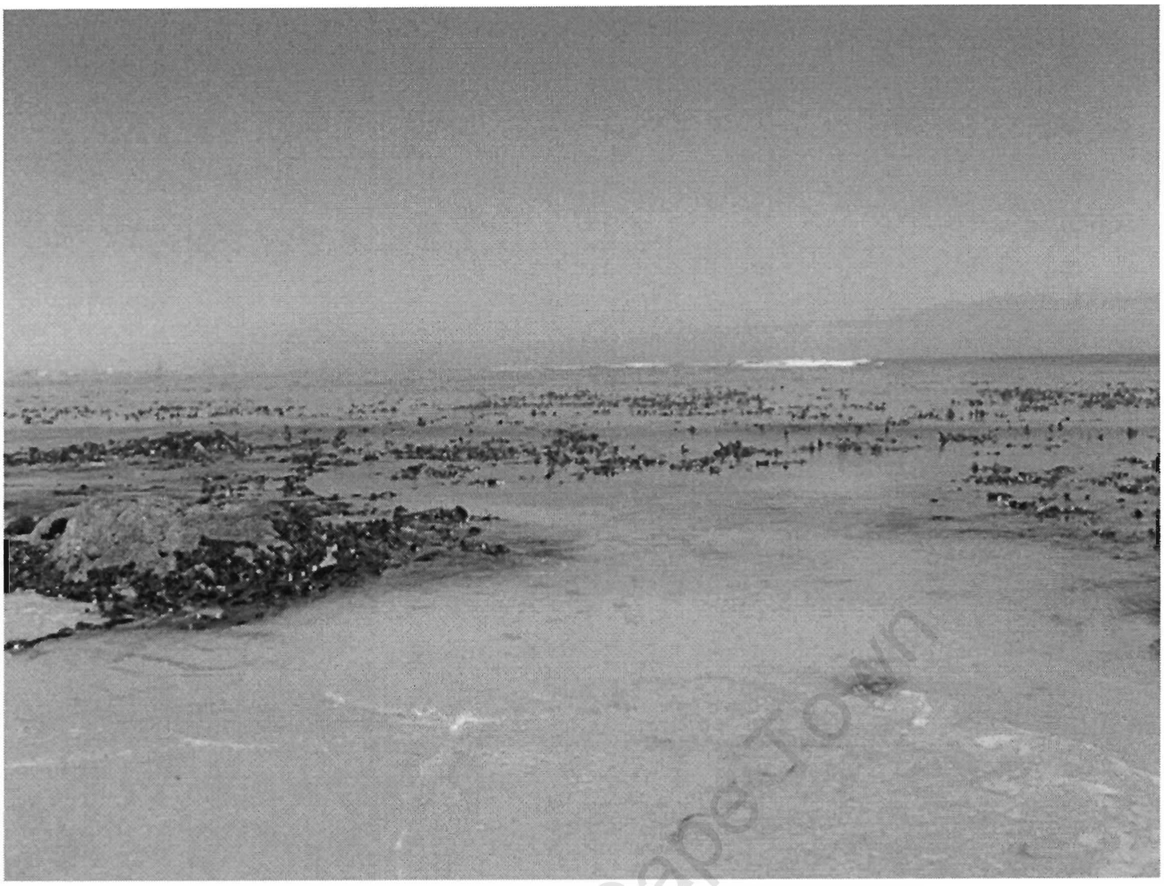


Figure 2.20. Photograph of the Port Nolloth biomass survey transect line site.

2.1.2.5 Dassen Island (2004)

Dassen Island was surveyed by boat because there were no images available and the resource needed to be quantified. This kelp survey aimed to fill a gap in the kelp database and demonstrate how detailed survey work could be done. Secondly, it aimed to contribute towards the ecological management objectives laid out in the management plan (Wolfaardt, 2000), namely Section 4.9, the proclamation of a marine reserve around the island:

> "Management has recently used the Provincial Ordinance (Ordinance 19 of 1974) to extend the boundary of the reserve 500 metres seaward (Government Gazette, 22 January 1999, No. 5/1999). The Manager must draw up a policy document proposing how the new marine component of the reserve is going to be managed, and arrange a workshop between the relevant authorities to discuss a management strategy for these areas." (Wolfaardt 2000, p2)

Mapping of kelp beds by GPS and ski boat was done for Dassen Island during spring low tide on 25 November 2003. Dassen Island is located approximately 55 km north west of Cape Town, 33 km south west of Saldanha Bay, in the southwestern Cape. It has a latitude of 33°25'S and a longitude of 18°06'E. A comprehensive management plan for Dassen Island has been compiled by Wolfaardt (2000). Dassen Island was an example of a gap in the kelp inventory. Observations and measurements of the kelp beds from a ski-boat were done over spring low tide on the 25th November 2003. A Garmin GPS was used to plot the track and waypoint notes in order to map the seaward boundary of kelp. Part of the coastline was ground truthed near to the shoreline. A process to digitally reconstruct the spatial information (see Figure 2.21) and attribute information and building up the database with the area/biomass calculations was undertaken.

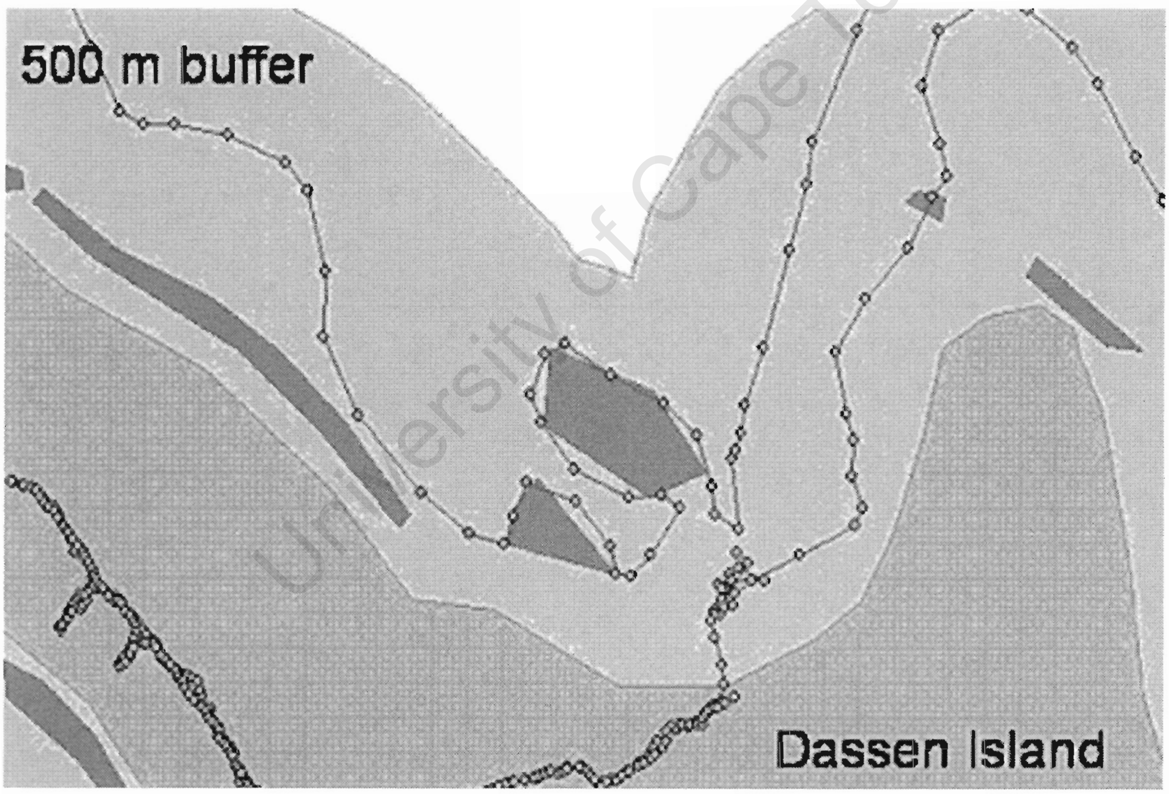


Figure 2.21. Scheme of GPS points, tracks and kelp polygons (darker areas offshore) of a part of the survey of Dassen Island. 200m buffer around island.

2.2. GIS and RS Platform, Database and Analysis

The GIS software used to create the geodatabase was ESRI's ArcGIS 8.2, ArcView 3.3 and ENVI 4.0, provided by the Department of Botany and Department of Environmental and Geographic Science, University of Cape Town. In addition to the extensions to ArcGIS (such as 3D Analyst and ArcGIS to ENVI converter), the following three programs proved useful:

- Polytool 3.6 for ArcGIS (by Johannes Weigel, weigel@ecogis.de) had the following commands: polyline, polygon, shape, ftheme, halve, part, exact, precise, rectangle, circle, point, bezier, spline, arrow, center, three, click, line, centerline, reiver, street, cut, split, axis, mid-line, center.
- ET GeoTools 9.0 - released 14.07.2004 ET GeoSoft.
- ECW - ER Mapper Enhanced Compression Wavelet is a proprietary compression technique registered to Earth Resource Mapping, Inc.

The conceptual framework (see Figure 2.22) of the structure of database was obtained from an online-database for environmental data in Iceland (Halldórsdóttir & Þorbergsson, 2004). Elevelda *et al.* (2003) worked on a European Commission funded project that developed a European Virtual Coastal and Marine Data Warehouse named CoastBase that is designed to improve data and information search and exchange. The intent was to create a database with high level of usability that could be brought online in a similar manner as those laid out by Elevelda *et al.* (2003).

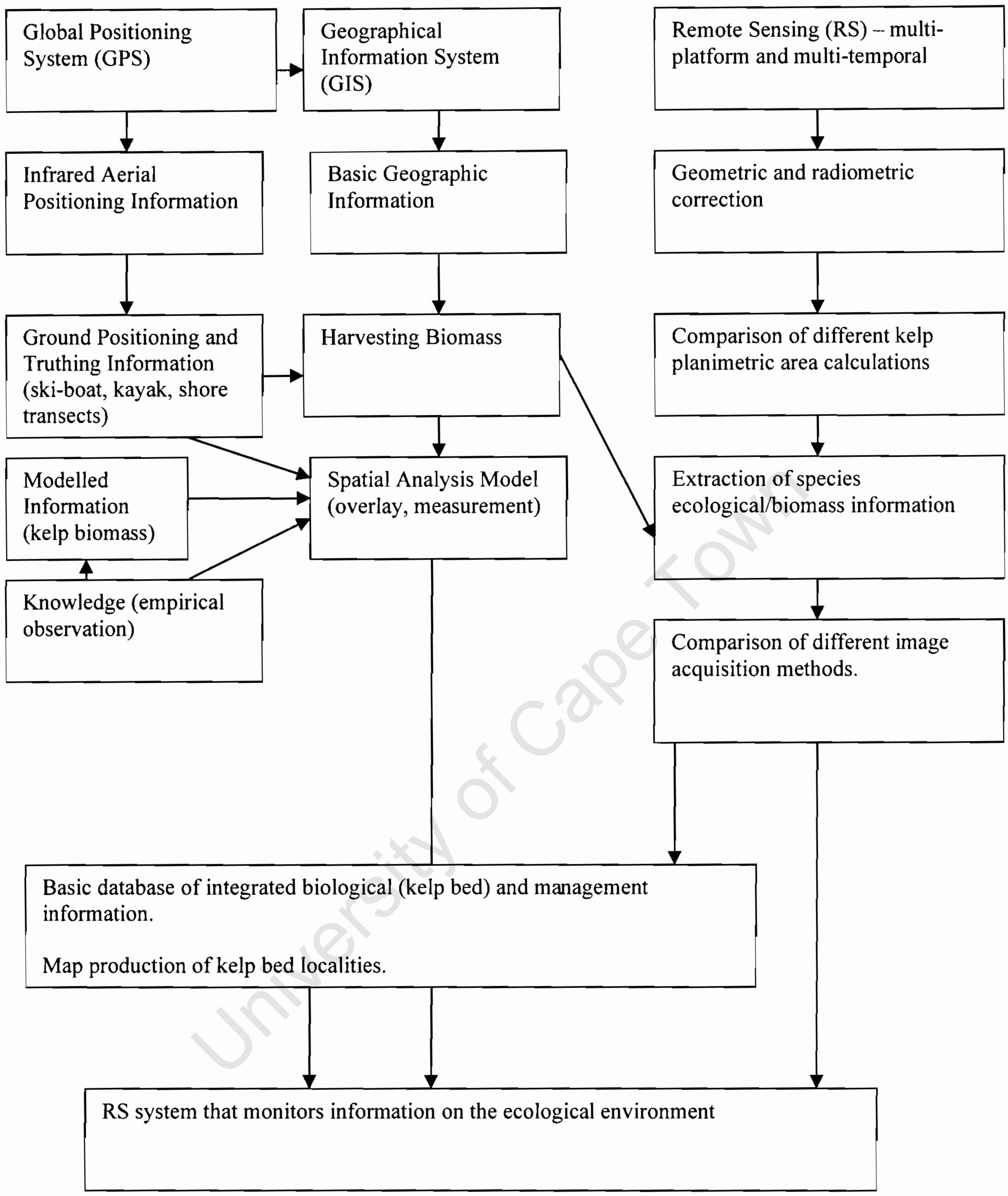


Figure 2.22. Scheme of the process of developing the kelp inventory.

ESRI (2004, p24-26) provided details on the mathematical equation of both geographic (NAD83 and WGS84) transformation procedures required to convert all datasets into WGS84. Visual Basic code used in spatial data creation has been provided in appendix 5.

2.3. Biomass estimation methods

Biomass and productivity/ production measures have a variety of units, such as volume, carbon content or energy content. The most practical unit for the purposes of this study was the mass per area (usually in kilograms per square metre). This was chosen based on the biomass statistics reported in the literature. Basic data exploration and descriptive statistics were done in Statistica 7.0.

A hurdle to the calculation of kelp bed biomass is that: “Canopy cover area or abundance however, is only a measure of the relative abundance of kelp beds and does not provide an overall estimate of the biomass or density of the submerged kelp beds.” (Edyvane 2003, p40). The solution lies in correlating surface area to kelp bed biomass at a local scale.

Biomass Figures used in this study came from a variety of sources published (e.g. Levitt *et al.*, 1992, 2002) and unpublished data collected by the Seaweed unit (M&CM) and fieldwork done by the author. A complete list is presented in Chapter 3.There are two methods of biomass collection and estimation. The first is by destructive sampling of whole plants and weighing of their individual parts (fronds, primary blade and stipe). Secondly is the floating quadrat method, a random sampling method is applied to a kelp bed over a 2-3 hour period that starts 1.5 hours before and after low tide, and the number of heads of kelp of the species present within the quadrant counted. Results of field collection and seasonal analyses are presented in chapter 3.

2.4. Commercial harvesting statistics

The Seaweed Unit (M&CM) maintains harvesting records of the amount of seaweed species harvested and their wet weights. These records are submitted by seaweed concession holders on a monthly basis. These data were incorporated into a database and summarized using Microsoft Excel and Statistica 7.0. Besides basic descriptive statistics used, Kruskal-Wallis ANOVA and Median Test (as per Siegel & Castellan, 1988) was applied to see if there were seasonal trends visible within and between seaweed Concession Areas.

2.5. Mapping limitations

The series of four photographs (Figure 2.23) taken north of the Spoeg River (30° 42’ S, 17° 29’E) show how white water can cover kelp beds and hamper the accurate recognition of the kelp beds by aerial survey. Examples of kelps losing their fronds and thereby resulting in less surface coverage by photosynthetic material that is visible to a surveying infrared device has been documented in north western USA, early last century by Peters (1914): The *Neurocystis* kelps "..have lost part or all of their fronds, and the rounded shiny pneumatocyst bulb suggests the term "bald-headed" more than 2/3 of fronds missing in some cases". *Ecklonia maxima* loses its fronds in summer when the water is calm for long periods. A high density of such plants would result in significantly lower biomass and reduced visibility from the air (see Figure 2.24).

Figure 2.23. Series of four photographs showing water conditions (white foam) in a bay.

Figure 2.24. "Bald-headed kelp" near to the harbour at Port Nolloth.

Chapter 3. South African kelp inventory

Chapter Outline

This chapter documents the results of fieldwork, research and data analysis following the application of the methods presented in the previous chapter. The kelp biomass figures collected in-situ and from the literature for various parts of the coast are presented together with a summary of the kelp bed areas in each Concession Area and showing harvestable and protected stretches of the west coast of South Africa. That summary is accompanied by an appendix of maps of parts of the coastline which have kelp beds, layered with each of the relevant survey results (one or more of each of: Landsat 5; Landsat 7; and CIR 1993, 1997 or 2005) and appropriate land-based infrastructure. A comparison of methods provides insights into the survey methods. This chapter is concluded with a discussion of the results.

3.1. Results

3.1.1. Kelp biomass

The kelp distribution maps are based in seaweed Concession Areas (Figure 3.1). Areas that have been excluded (for conservation purposes) from harvesting permits are indicated by either a lack of concession number (prefixed with “CA”) or with the word “exclusion”. These areas have formed the geographic unit on which the kelp distribution maps have been based. The maps of the kelp beds (included in Appendix 8) are preceded by: a map explaining the topographic details and icons used; a map of the coastline with reference map reference numbers; and a Table providing a map index of survey methods and areas covered.

The diamond area is not open to the public and is the preserve of diamond mining operators. The Groen-Spoeg Exclusion is an area that is soon to be designated as a Marine Protected Area (MPA). The Lamberts-Groothoek Exclusion has been excluded from harvestable seaweed Concession Areas for conservation purposes. The Langebaan Lagoon and surrounds is part of a National Park, and therefore excluded. The area between seaweed Concession Areas 9 and 10 has been excluded for historical reasons – it is an area between Sea Point and Blouberg of high public sensitivity. The area between 8 and 9 has almost no attached kelp, and mostly sand beaches and is a ecologically sensitive, highly populated area along the Cape Peninsula False Bay coast.

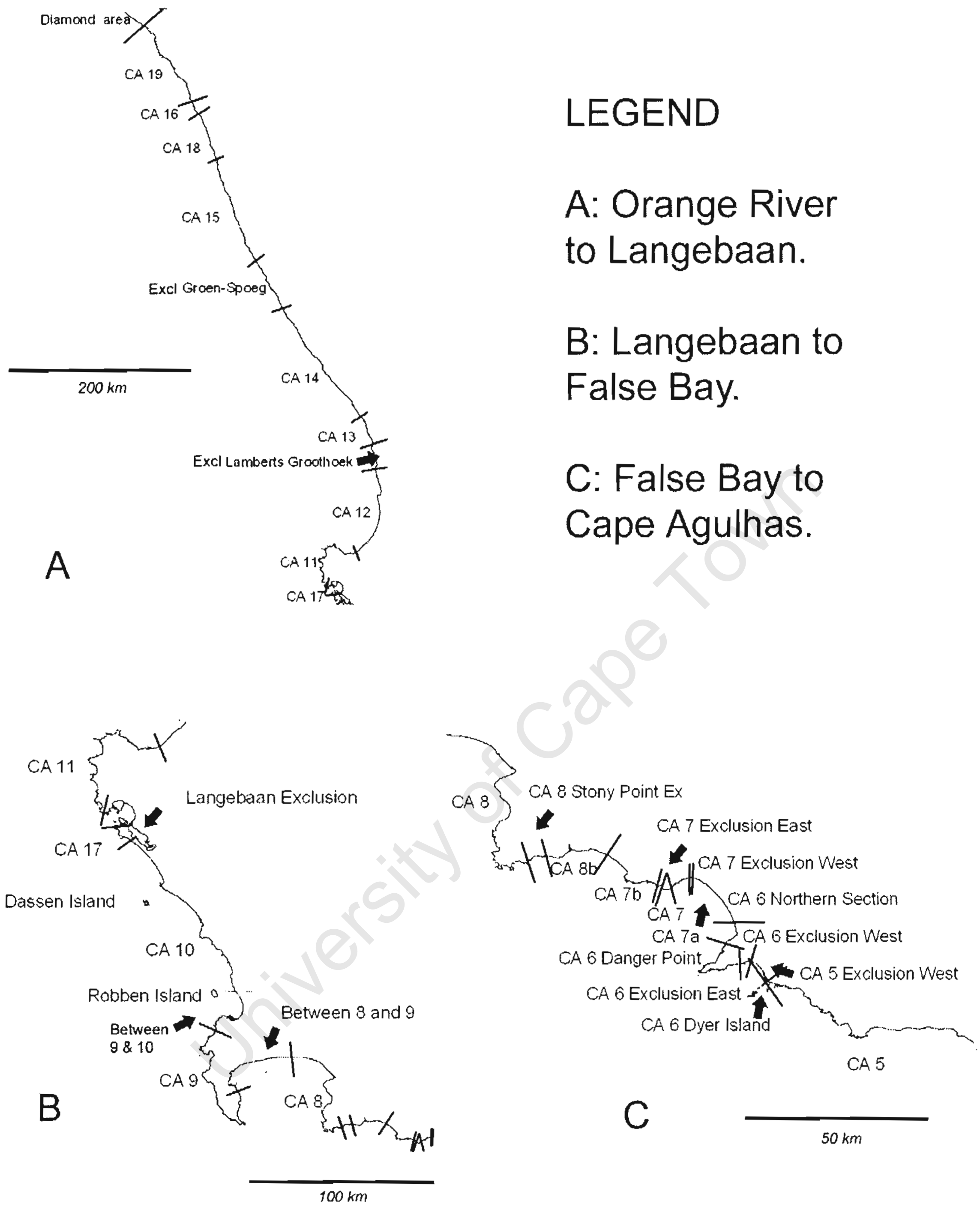


Figure 3.1. Scheme of kelp Concession Areas (numbered) and exclusion areas (un-numbered) from Cape Agulhas to the Orange River. Note. Scale of three diagrams varies.

The 'exclusion zones' areas 5 – 8 are stipulated in the permit conditions for each Concession Area. These were either to protect small existing MPA's (e.g. Betty's Bay MPA) or were to leave about 10% of each Concession Area free from harvesting in order to maintain areas of old, mature kelp beds (local "harvesting' reserves). Mature kelp stands have high biomass of epiphytes that are important in the ecology of the kelp beds (Anderson *et al.* 2006).

Table 3.1 contains the kelp biomass figures, averaged over all kelp species for a particular geographic region along the west coast of South Africa. The following should be noted about the method of biomass estimation used in the studies listed in Table 3.1 Some studies conducted transects within the kelp bed at representative densities. There is a large difference between some of the studies that shows both the variability within kelp beds and between neighboring and nearby kelp beds. This could be due to the observed seasonality in kelp bed biomass and different sites. Furthermore, discrepancies between estimates could be due to the method of surveying and transect line choice. For example, Field *et al.* (1980) used a transect that ran from the subtidal fringe to the deepest extent of the kelp, including all substrata in between. This method would include the often extensive beds of *Laminaria pallida* beds in deep water. M&CM data, however, is based on quadrats of *Ecklonia maxima* beds that reach the surface. These are relatively shallow and dense and represent those areas that are harvestable by hand from a boat.

Kelp biomass is spatially very variable. Some kelp beds are dense, others less so for a number of reasons, including substratum topography, presence or absence of sand and grazers. Biomass is temporally variable (Levitt *et al.* 2002) and can change by 50% or more with seasons. Levitt *et al.* (2002) produced estimates of kelp biomass for the Danger Point area based on dive and quadrat surveys over many years (1992 – 1997).

Overall, the biomass of different stretches of the coastline are highly variable. For example, Kwaaibaai (Jacobsbaai) has values of 10.7 $kg/m^2 \pm 3.5$ (Rothman, 2006) compared with 3.6 kg/m^2 (M&CM, 1997).

Table 3.1. Kelp biomass figures by area from the literature, some with standard error ranges.

Kelp	Biomass (kg/m2)	Reference
Kreeftebaai/Saldanha	0.8	Field *et al.* (1980)
Melkbosstrand	2.84	Field *et al.* (1980)
Sea Point, Cape Peninsula	1.68	Field *et al.* (1980)
Oudekraal, Cape Peninsula	1.68	Field *et al.* (1977)
Kommetjie, Cape Peninsula	7.01	Field *et al.* (1980)
Kommetjie, Cape Peninsula	7.9	Simons & Jarman (1981)
Olifantsbos, Cape Peninsula	5.95	Field *et al.* (1980)
Betty's Bay	4.9	Field *et al.* (1980)
Danger Point (North)	9.22	Levitt *et al.* (2002)
Danger Point (South)	5.71	Levitt *et al.* (2002)
Slangkoppunt	3.8	Levitt *et al.* (1992)
Sandkop (Port Nolloth)	17.8	Levitt *et al.* (1992)
Stillbaai (Port Nolloth)	14.2	Levitt *et al.* (1992)
Owen Island (Port Nolloth)	24	Levitt *et al.* (1992)
Oubeep (Port Nolloth)	19.1	Levitt *et al.* (1992)
Soetwater (Cape Town)	15.2	Levitt *et al.* (1992)
Danger Point (Gansbaai)	13.8	Levitt *et al.* (1992)
Kwaaibaai, Jacobsbaai	10.7 ± 3.25	Rothman (2006)
Kwaaibaai, Jacobsbaai	3.6 ± 3.4	MCM (1997, unpublished)
Mauritzbaai, Jacobsbaai	10.3 ± 1.73	Rothman (2006)
Mauritzbaai, Jacobsbaai	2.4 ± 1.6	MCM (1997, unpublished)
'Pump House', Jacobsbaai	11.1 ± 2.68	Rothman (2006)
'Pump House', Jacobsbaai	2.4 ± 1.7	MCM (1997, unpublished)
Olifantsbos 1, Cape Peninsula	14.4 ± 3.79	Rothman (2006)
Olifantsbos 2, Cape Peninsula	15.1 ± 3.05	Rothman (2006)
Soetwater, Cape Peninsula	17 ± 4.97	Rothman (2006)
Glencairn, Cape Peninsula	10 ± 1.53	Rothman (2006)
Kommetjie, Cape Peninsula	21.3 ± 4.26	Rothman (2006)

3.1.2. Kelp standing crop

The results of the areas calculated by the different methods and datasets are presented in this section. The area of surface kelp by Concession Area are tabulated and presented as maps (Appendix 8). Additionally, an estimate of the standing stock is given. These values have been calculated using biomass values, as presented in Table 3.2. A short discussion of the observed trends follows each section.

Table 3.2. Locations and area (in hectares) of kelp calculated using different methods.

Location	Landsat 7	Landsat 5	Aerial IR (1996)	Tarr (1993)	CIR (2005)
5	79.66			497.48	370.5
7	15.05	81.77		223.75	
8	30.57	133.31		322.52	
9	64.12	249.23	185.3		
11	108.19		617.95		
12	11.74				15.9
13	9.67				10.8
14			206.64		100.51
15	22.57		732.22		320 *
16			206.44		
17			17.92		
18			976		
19			254.95		
10 Exclusion Proposed	0.4				
5 Exclusion East					2.3
5 Exclusion West	2.79	0.41		7.19	
6 Danger Point	114.81	125.09		383.24	
6 Dyer Island	205.11			223.19	
6 Exclusion East	6.55	4.73		43.54	
6 Exclusion West		2.36		28.94	
6 Northern Section		2.84		2.92	
7 Exclusion East		4.58		15.77	
7 Exclusion West		2.92		4.4	
8 Stony Point Exclusion	7.91	44.55		90.19	
Between 8 and 9		18.16	20.64		
Dassen Island	5.02				
Groen-Spoeg			71.94		16.01
					27.6
Lamberts Groothoek					
Robben Island	11.24				

* Only half of Concession Area 15 was surveyed in 2005.

The kelp biomass, by Concession Area, used to calculate the standing crop (Table 3.4) is presented in Table 3.3. The three data sources are Levitt *et al.* (2002), M&CM (2001) and Rothman (2006, unpublished MSc thesis). The kelp biomass differs considerably along the coast, with values ranging from 3 – 10.7 kg/m^2. The northern parts of the West Coast (Concession Areas 11-19) have the lowest biomass values. Whereas, the Cape Peninsula and Danger Point (Southwest coast) have higher values (9-10kg/m^2)

Table 3.3. Kelp biomass used in the calculation of standing crop of surface kelp.

Concession Area	kg/m2	Source
5	5.71	Levitt *et al.* (2002)
7	6.35	M&CM (2001)
8	6.35	M&CM (2001)
9	6.35	M&CM (2001)
11	10.7	Rothman (2006)
12	3	M&CM (2001)
13	3	M&CM (2001)
14	3	M&CM (2001)
15	3	M&CM (2001)
16	3	M&CM (2001)
17	3	M&CM (2001)
18	3	M&CM (2001)
19	3	M&CM (2001)
6 Danger Point	9.22	Levitt *et al.* (2002)
6 Dyer Island	5.71	Levitt *et al.* (2002)

The standing crop of kelp, by Concession Area, is presented in Table 3.4. The third area (Groen-Spoeg) that has been surveyed by both methods provides estimates of 2158 tonnes (Aerial IR 1996) and 480 tonnes (CIR 2005). These results are an order of magnitude different, but this is probably due to the second survey covering the entire Groen-Spoeg area, where as the Aerial IR (1996) only covered a part of that area.

The different survey methods provide radically different estimates of kelp visible at the surface on and around a spring low tide. Landsat 5 & 7 provides lower estimates than the three aerial photography methods. For example, in Concession Area 7, Landsat 7 estimates 956 Ha, which is approximately five times less than Landsat 5, which in turn is about three times less than the 14208 Ha calculated from Tarr (1993). In Concession Area 15, the two IR methods estimate a kelp area of, on average, 20 000 Ha; which is over twenty times more than the Landsat 7 estimate.

Table 3.4. Estimates of biomass (in tonnes) of kelp, by survey method, for each seaweed Concession Area. Note, blank cells were unsurveyed by the corresponding method.

Location	Landsat 7	Landsat 5	Aerial IR (1996)	Tarr (1993)	CIR (2005)
5	4549			28406	21156
7	956	5192		14208	
8	1941	8465		20480	
9	4072	15826	11767		
11	11576		66121		
12	352				477
13	290				324
14			6199		3015
15	677		21967		9600
16			6193		
17			538		
18			29280		
19			7649		
10 Exclusion Proposed	26				
5 Exclusion East					131
5 Exclusion West	159	23		411	
6 Danger Point	10585	11533		35335	
6 Dyer Island	11712			12744	
6 Exclusion East	604	436		4014	
6 Exclusion West		218		2668	
6 Northern Section		262		269	
7 Exclusion East		422		1454	
7 Exclusion West		269		406	
8 Stony Point Exclusion	729	4108		8316	
Between 8 and 9					
Dassen Island	151				
Groen-Spoeg			2158		480
Lamberts Groothoek					828
Robben Island	337				

Concession Areas were originally demarcated using an estimate of kelp derived from the length of rocky shoreline, as stated in Jackson & Lipschitz (1984). Table 3.5 provides the length of rocky shoreline and combines this information with Table 3.2 to provide an estimate of kelp area (in hectares) per kilometer of coastline for each of the seaweed concession areas. Note that there is a high variability between methods; and that within a method there is a poor correlation between rocky shoreline and kelp present in any particular area. There is a large difference in length of rocky coastline between Concession Areas. Area 12 has 1.25 km, whereas Area 15 has 104.5 km. This table aims to highlight the concession areas that have large kelp beds, whilst taking the length of rocky coastline into account. Area 16 & 18 estimates by Aerial (1996) are unreasonably high (41 & 53 Ha/km).

Table 3.5. Length of rocky shoreline of South Africa and kelp for Kelp Concession Areas. Based on the Coastal Sensitivity Atlas (Jackson & Lipschitz, 1984). The total rocky coastline is a sum of exposed rocky headlands (ERH) and wave cut rocky platforms (WRP).

Concession Area	Total (km)	Kelp Abundance (Ha/km)				
		Landsat 7	Landsat 5	Aerial IR (1996)	Tarr (1993)	CIR (2005)
19	48.5			5.3		
16	5			41.3		
18	18.25			53.5		
15	104.5	0.2		7.0		3.06
14	63.75			3.2		1.58
13	4.25	2.3				2.54
12	1.25	9.4				12.72
11	28.75	3.8		21.5		
10	24.25					
9	58.75	1.1	4.2	3.2		
8	38.25	1.0	4.6		10.8	
7	17.75	0.8	5.0		13.7	
6 (excluding Dyer Island)	22.25	5.5	6.1		20.6	
5	38.75	2.1	0.0		13.0	9.56

3.1.3. Comparison of datasets

3.1.3.1 Spatial data overlap within colour infrared aerial survey done in 2005.

An aerial survey of three areas along the west coast was flown in 2005. The geographical coverage is shown in Chapter 2, Figure 2.1. Maps of the sites surveyed are presented in Chapter 2 (Figure 2.9 - 2.11). Note that areas of partial overlap provide a second pass over that area. Table 3.6 tabulates the difference between these two passes over a particular area – which is the overlap between two images (e.g. 2.94 for Lamberts 3a and Lamberts 4). The dissimilarity index (D.I.) is the area of the lesser estimate divide by the area of the second (larger) estimate. Lamberts 1a and Lamberts 2c show the greatest similarity in identifying the same area of kelp. This gives a greater level of confidence in the estimation being a true reflection of the real world kelp bed.

Table 3.6. Comparison of kelp areas in overlap regions of the aerial photography done in 2005. A higher D.I. indicates greater dissimilarity between images. D.I. = 1 indicates complete similarity.

Name	Area (Ha)	Dissimilarity	Name	Area (Ha)	Dissimilarity
Lamberts 3a	0.8083		Lamberts 1a	5.7236	
Lamberts 4	0.3453	2.34	Lamberts 1b	10.9455	1.92
Lamberts 3a	0.168		Hondeklip 2	4.1521	
Lamberts 3b	0.4873	2.94	Hondeklip 3	4.6919	1.36
Lamberts 1a	3.1023		Hondeklip 1	1.6644	
Lamberts 2c	3.0731	1.01	Hondeklip 2	1.9082	1.14
Lamberts 2b	0.0013		Agulhas 4	1.584	
Lamberts 2c	0.0005	2.56	Agulhas 5	0.363	4.36
Lamberts 2a	0.4056		Agulhas 1	0.6766	
Lamberts 3c	0.745	1.85	Agulhas 4	1.6794	2.5
Lamberts 2a	0.0781		Agulhas 2	0.5957	
Lamberts 2b	0.0426	1.83	Agulhas 3	0.1461	4.08
Lamberts 1b	2.0817				
Lamberts 1c	2.0993	1.01			

3.1.3.2 Spatial data overlap of Landsat 7 (2003) and Field survey (2005) of Dassen Island.

Dassen Island was surveyed using Landsat 7 ETM+ and a total of 5 hectares was described as kelp. Fieldwork, however, showed there to be 27 hectares of surface kelp. Figure 3.4 shows the areas of overlap between the two surveys. The beds on the west side of the island were identified by only one survey. The spatial and kelp information has been included in Appendix 8. Figure 3.2 below summarises the kelp bed information from Dassen Island. Assuming an average standing biomass of 5-10 kg/m^2; the total biomass is 1135 - 2270 tonnes. Harvesting of 10 % of total biomass per annum equates to 114 - 227 tonnes available to the kelp harvester. However, the majority of this standing stock is within the 500m reserve. Additionally, the location of Dassen Island is prohibitively far from the main shoreline for commercial exploitation to be viable. The *Macrocystis angustifolia* bed has been excluded from calculations, as it is a rare species and not commercially harvested. Figure 3.3 illustrates the main base rock types of Dassen Island and they are: biotite- and tourmaline-granites. The sandstone and ferricrete weather to form sandy beaches on the north coast (House bay). The type of substrate is a determinant of kelp recruitment.

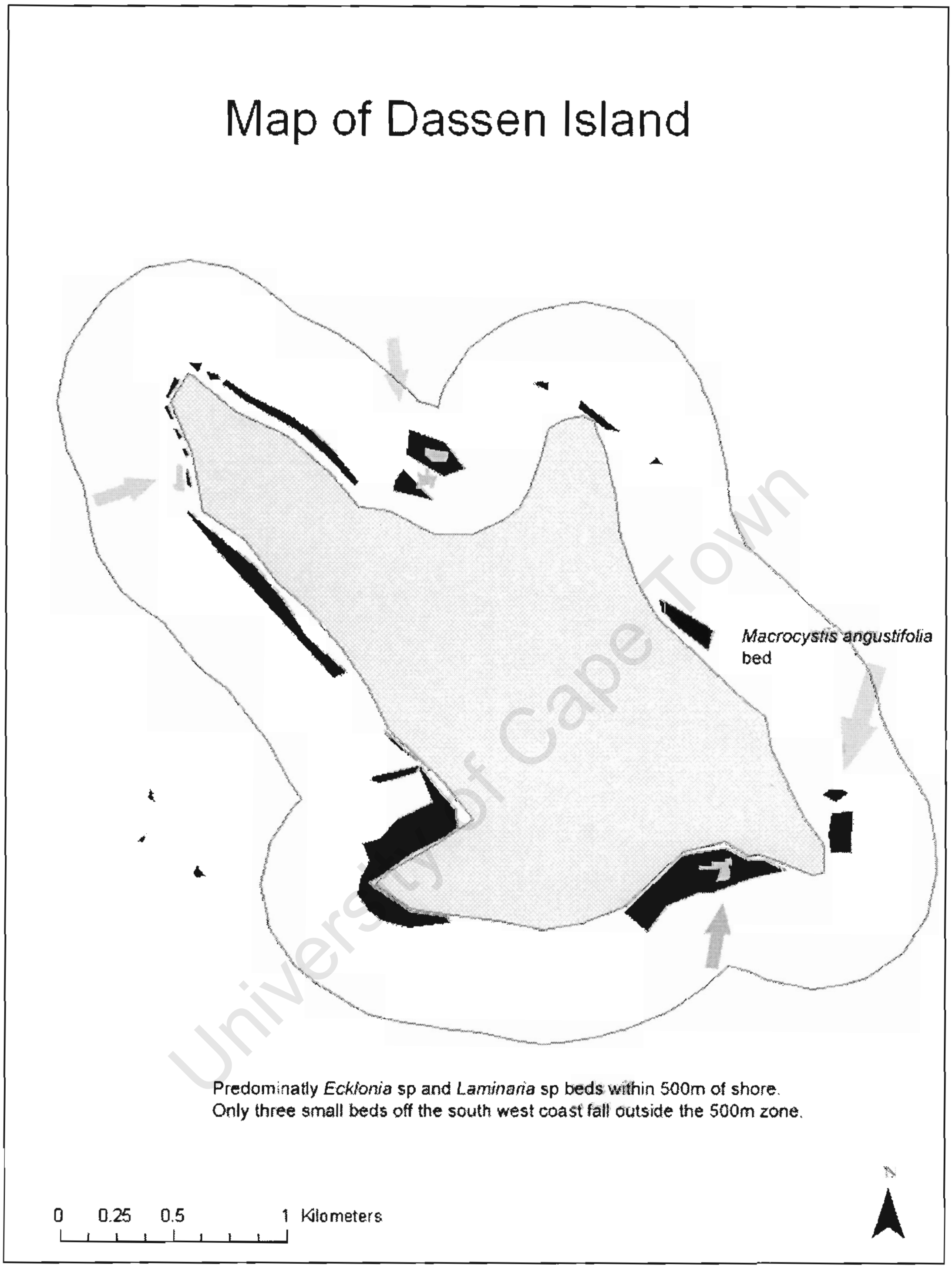


Figure 3.2. Map of Dassen Island showing the kelp beds identified during a field survey (Black). Harvesting within 500m of the island is forbidden. The four kelp beds (Grey) identified by Landsat 7 ETM+ are pointed out by the three smaller arrows.

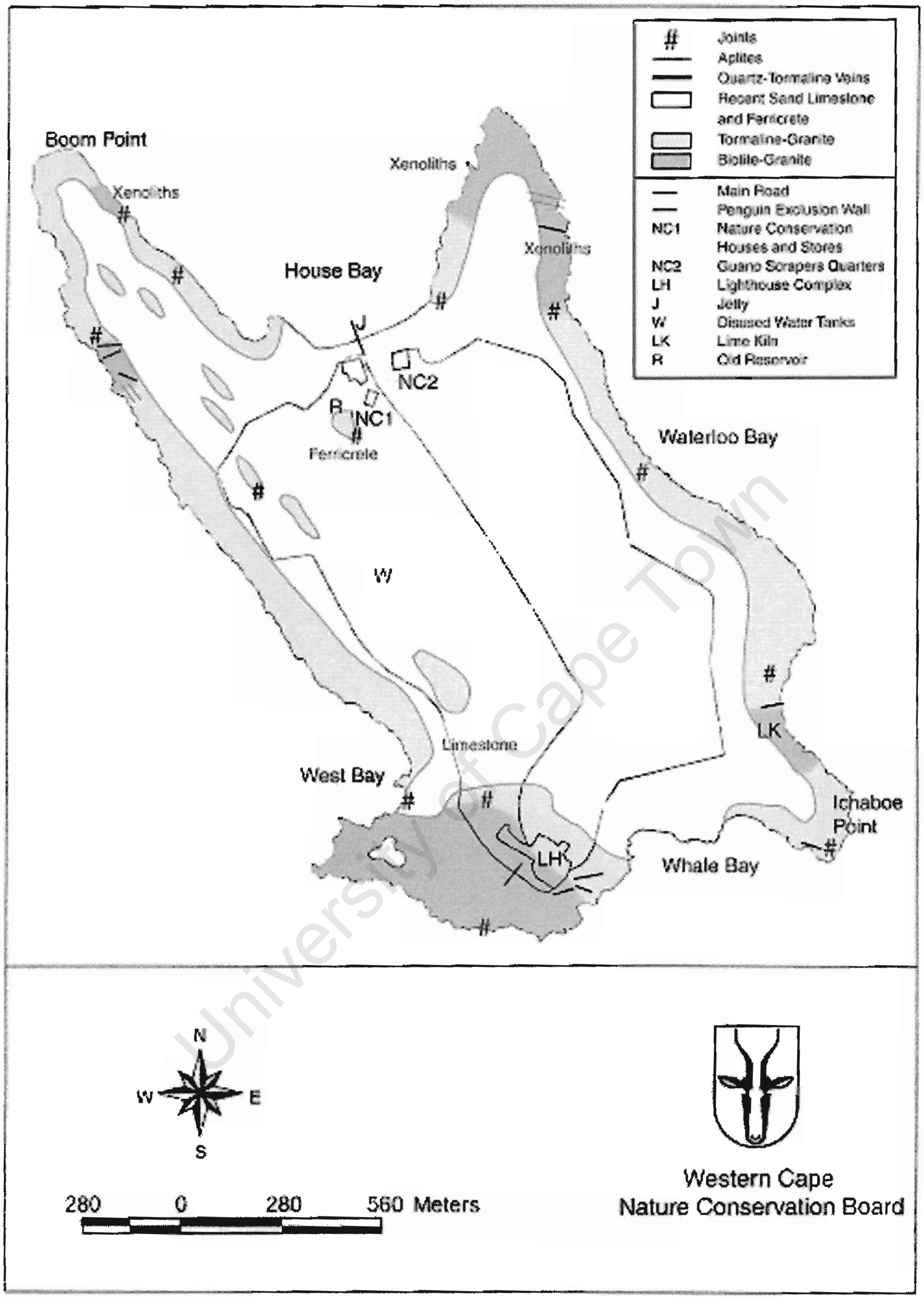


Figure 3.3. Geology of Dassen Island (Wolfaart 2000. p6)

3.1.3.3 Spatial data overlap of Concession Areas 9 -15.

The following table (Table 3.7) aims to give an indication of how two methods compare. Kelp beds, identified by a particular method, that are within 30 metres from kelp beds in another dataset are considered to be overlapping. This measure gives an indication of where the two methods are both finding kelp to be present at a particular point. For example, the CIR (1996) survey for Concession Area 11 identified 361.1 Ha of 618 Ha (58%) of kelp that was within 30 metres of kelp identified by Landsat 7; which in turn only estimated there to be 102.8 Ha for the same area. There is little agreement between Landsat and Aerial photography. However, both CIR methods identify 94% -100% of all the kelp beds identified by Landsat 7. The portions of the coast that were ground truthed are shown in the kelp beds maps in Appendix 8.

Table 3.7. Area of kelp (hectares), as a percentage, in each concession area where there is a partial overlap between datasets that allows for a comparison of the survey methods.

Concession Area	CIR 1996	CIR 2005	Landsat 7
9	63/240 (15%)		60/64 (94%)
11	361/618 (58%)		102/108 (95%)
12		14/16 (88%)	11/11 (100%)
13		4/10 (41%)	10/10 (100%)
14	24/207 (12%)	1.6 /32 (2%)	
15	49/732 (7%)		23/23 (100%)

3.1.4. Commercial kelp harvesting statistics by Concession Area.

The demand for kelp increased over the period 1988 to 2003. Figure 3.4 illustrates the increased demand for fresh cut kelp sold to abalone farms as feed. The kelp collected as beach cast has fluctuated, with a dip in the mid 1990s, followed by an increase in collection in the late 1990s.

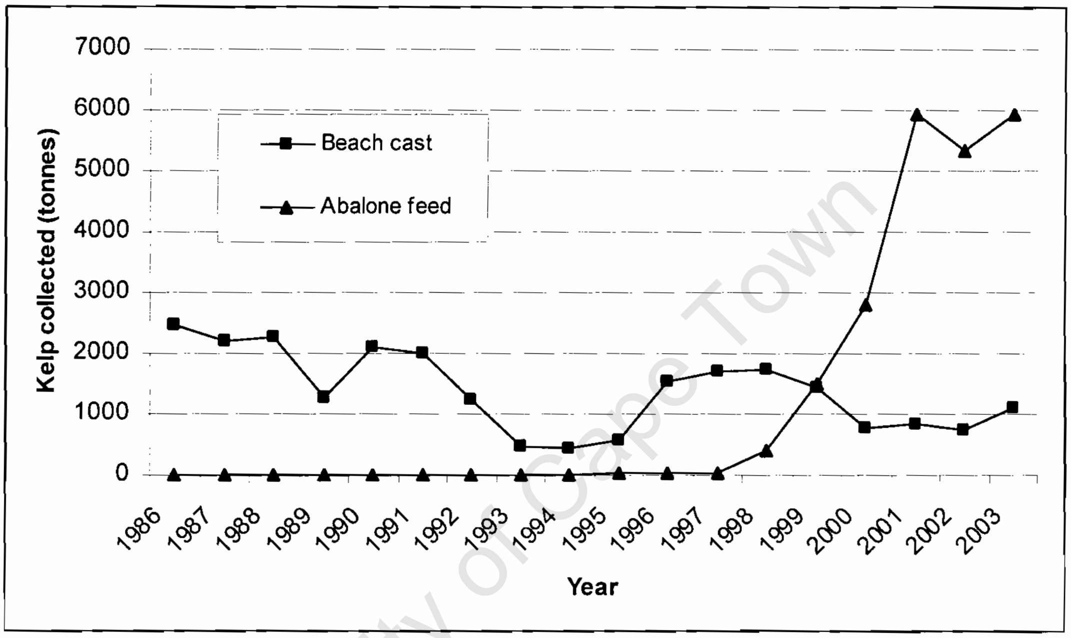


Figure 3.4. Commercial yields of seaweed from natural populations on the coast of South Africa, 1986–2003, as reported by concession-holders (adapted from Troell *et al.*, 2006).

The monthly trends in kelp harvesting are presented in Figure 3.5 below. There is year round harvesting of fresh and beach cast kelp, with a slight dip in collection during the winter months.

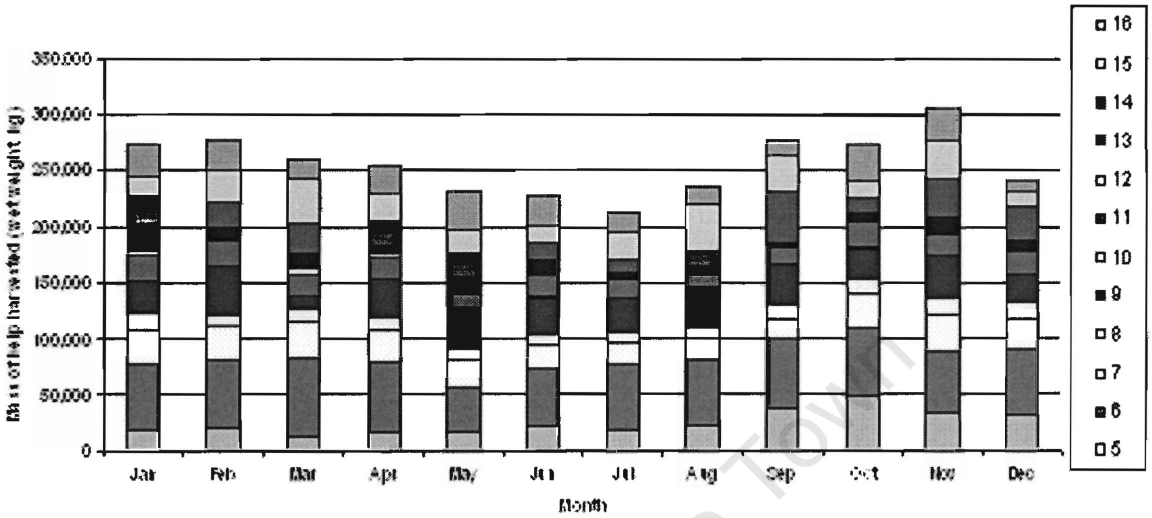


Figure 3.5. Reported annual average mass of kelp harvested (excluding beach cast) in each Concession Area between 1998 and 2003 showing the seasonal nature of harvesting. (Based on spreadsheets from Marine and Coastal Management (MCM), DEA&T, RSA)

Table 3.8 shows the total amount of kelp that is allowed to be harvested to per Concession Area from 2006 onwards under current regulations (M&CM, 2005). Note that in Concession Area 6, twice the tonnage is harvestable but the fronds must be sustainably harvested. Kelp plants may not be killed. Note that there is a huge difference in quotas between Concession Areas.

Table 3.9 shows the amount (fresh weight) of fresh and beach cast kelp was collected in 2003 in each of the Concession Areas. Note that the percentage of kelp collected in relation to the standing crop is given. The amount harvested varies between concession areas, up to about 99% in Concession Area 12.

Table 3.8. Harvestable amounts of kelp (in tonnes) per Concession Area in South Africa from 2006 onwards (M&CM, 2005). Note that in Concession Area 6 twice the amount may be harvested if a non-lethal fronds only harvesting method is used.

Concession Area	Fronds Only	Whole plant
5	1313	2625
6	4350	3318 (mainland), 1032 (Dyer Is.)
7	736	1472
8	1024	2048
9	1030	2060
10	94	188
11	1510	3019
12	70	141
13	60	120
14	216	531
15	1020	2040
16	220	439
17	Beach cast only.	0
18	835	1670
19	220	440

Table 3.9. Kelp resources along the South African west coast and their utilization records during 2003 (adapted from Troell *et al.*, 2006).

Concession Area	Kelp MSY	Kelp Harvest (f wt)	Kelp Harvest as % of MSY	Beach Cast
5	1165	696	60	0
6	2680	897	33	362
7	644	348	54	192
8	956	951	99	0
9	1030	0	0	0
10	0	0	0	0
11	1550	1158	75	9
12	15	0	0	29
13	32	0	0	126
14	478	0	0	177
15	784	0	0	129
16	564	0	0	77
18	137	0	0	0
19	364	0	0	0
Total	10399	4050		1101

3.2. Discussion

3.2.1 Kelp biomass and standing crop

The Seaweed Unit (M&CM) has ongoing surveys of the biomass of kelp beds along the coastline. This will improve the estimates given in Tables 3.1 and 3.3. The biomass estimates for the kelp beds along the west coast are highly variable. Very different results are obtained by the different methods. However, there is a good correlation (around 50 – 100% error) between the two CIR methods.

The colour infrared survey (1996, 2005) estimates that the south west coast has a higher concentration of kelp beds than the coast further north (Table 3.5). This supports the MSYs set for the seaweed Concession Areas by M&CM (Table 3.9).

Dassen Island

It is suggested that the geomorphological features of Dassen Island determine the location of kelp beds. Kelp sporophytes colonize sand-free solid substrates. Areas that are suitable for this are the east, south and west coasts of Dassen Island. The main base rock types include: biotite- and tourmaline-granites See Figure 3.3). The sandstone and ferricrete weather to form sandy beaches on the north coast (House bay). This is an unsuitable surface for kelp growth, as is seen in Figure 3.2. There are areas of the coast that have tourmaline-granite base rock, however, much of the west coast substrate is covered in sand and this precludes the recruitment of kelp. The presence of a single *Macrocystis angustifolia* bed on the south-east coast, north of Icaboe Point, is probably due shelter from swell, as that part of the island is on the leeward side of prevailing winds in both summer and winter, as Wolfaardt (2000, p7) explains below:

> "Northerly and north-westerly winds predominate in winter. In summer southerly and south-westerly winds dominate. The incidence of calms is greatest in the spring months, from September until November."

The small bed of *Macrocystis angustifolia* is located in the lee of Dassen Island, similarly to the location of larger beds of this species in the lee of Robben Island (Anderson, R.J. *pers. comm.*) These kelp bed maps will provide managers with increased information on the protection of sub-tidal habitats.

3.2.2. Comparison of datasets

The Landsat 5 TM and Landsat 7 ETM+ data is readily obtainable, but is of little use in the identification of kelp beds on a scale that is useful for estimating the extent of the kelp resource. In some cases there is a good correlation between Landsat 5 and Tarr (1993), for example in Concession Area 6 Northern Section (2.84 and 2.92 Ha, respectively, in Table 3.2). However, in other areas, such as Area 7, there is a four fold difference (81.7 and 223.8, respectively). Nevertheless, Landsat 5 proved to be more accurate at identifying the *presence* of kelp than Landsat 7. This is probably due to the Landsat 5 imagery being captured two days after a Spring Low Tide and the radiometric normalization that was done on the imagery. Landsat 7, however, failed to identify large kelp beds (e.g. Dassen Island and other parts of the west coast). Table 3.8, summarized from Table 3.2, shows Landsat 5 (1991) and Landsat 7 ETM+ (2003). Overall, Landsat 5 found approximately three times more kelp than Landsat 7; with the exception of Area 5 (Exclusion West).

Landsat is useful in identifying the presence, but not quantity, of kelp beds. CIR found all (94% -100%) the kelp beds identified by Landsat 7 (see Table 3.7).

3.2.3. Commercial harvesting statistics

The Concession Areas are harvested with different intensities. They share a common harvesting trend that is seasonal (see Figure 3.5). However, some Concession Areas are reaching the limits of their quotas. Area 11 (75%) and Area 12 (99%) are the most intensively harvested (Table 3.9). This demand is driven by the expanding abalone farming industry (Troell *et al.,* 2006).

Chapter 4. Micromanagement of kelp on a bed by bed basis

4.1. Introduction

The scale of management refers to the spatial and temporal resolution at which data about the resource and its use by right's holders is collected. There are a number of issues around the collection of biological information of the kelp beds that were covered in Chapter 2 & 3. This chapter aims to examine if a different scale of kelp management by Marine and Coastal Management and Seaweed Concession Right's Holders could improve management practice. The term "micromanagement" refers to the bed–by-bed harvesting, observation and management techniques and periodicity employed in the case study. It is compared to the large or macro-scale management by spatially larger Seaweed Concession Areas that is currently the reigning scale of management. The research questions posed are: (1) is there evidence of harvester preference of kelp harvesting site? (2) Should each kelp bed be managed (on a bed-by-bed basis), or should a delineated piece of coastline be managed based on a generalized model of biomass and harvesting intensity?

Jacobsbaai Sea Products (JSP) is a private mariculture company, whose primary source of business is land-based farming of abalone. It is based on the outskirts of the town of Jacobsbaai, St Helena Bay on the west coast of South Africa (see Figure 4.1). Until the end of 2005 the company employed a sub-contractor who harvested on their behalf. They paid a levy to the rights-holder, Maribus Industries Pty (Ltd), on the mass of kelp harvested in Concession Area 11. Since then, JSP is one of three shareholders in a company (Verdino Ltd.) who has the harvesting rights to seaweed Concession Areas 11 and 12. JSP has kept meticulous records of harvests in each kelp bed within the part of area 11 that they work. This level of private micro-management of part of a kelp resource is unusual, yet commendable, in South Africa. The aim of this chapter is to provide analyses of the detailed harvesting records and see whether there is a pattern in the temporal (seasonal) and spatial harvesting practices; and whether this is sustainable. Additionally, with the combination of ground biomass surveys, to see if an estimate of the state of the kelp beds can be provided. An understanding of the harvesting pressure on the kelp habitat could be gained by combining this information with standing stock estimates (based on the 1996 Aerial IR photography presented in Chapter 3).

Beach cast kelp is collected on days when the sea is too rough to send out boats, and on days after a storm has dislodged kelp holdfasts and whole kelp washe ashore. Fresh kelp is harvested from an inflatable boat. The kelp beds in the vicinity of Jacobsbaai are dominated by *Ecklonia maxima* and *Laminaria pallida*. There are a few very small patches of *Macrocystis angustifolia* near Pump House (see Figure 4.1). Only *Ecklonia maxima* is harvested, but whole heads are removed. The coastline of the study area is varied and consists of sandy beaches, rocky platforms and boulder strewn beaches. The degree of exposure varies between bays. Examples of a sheltered and exposed bay are given in Figures 4.2 and 4.3.

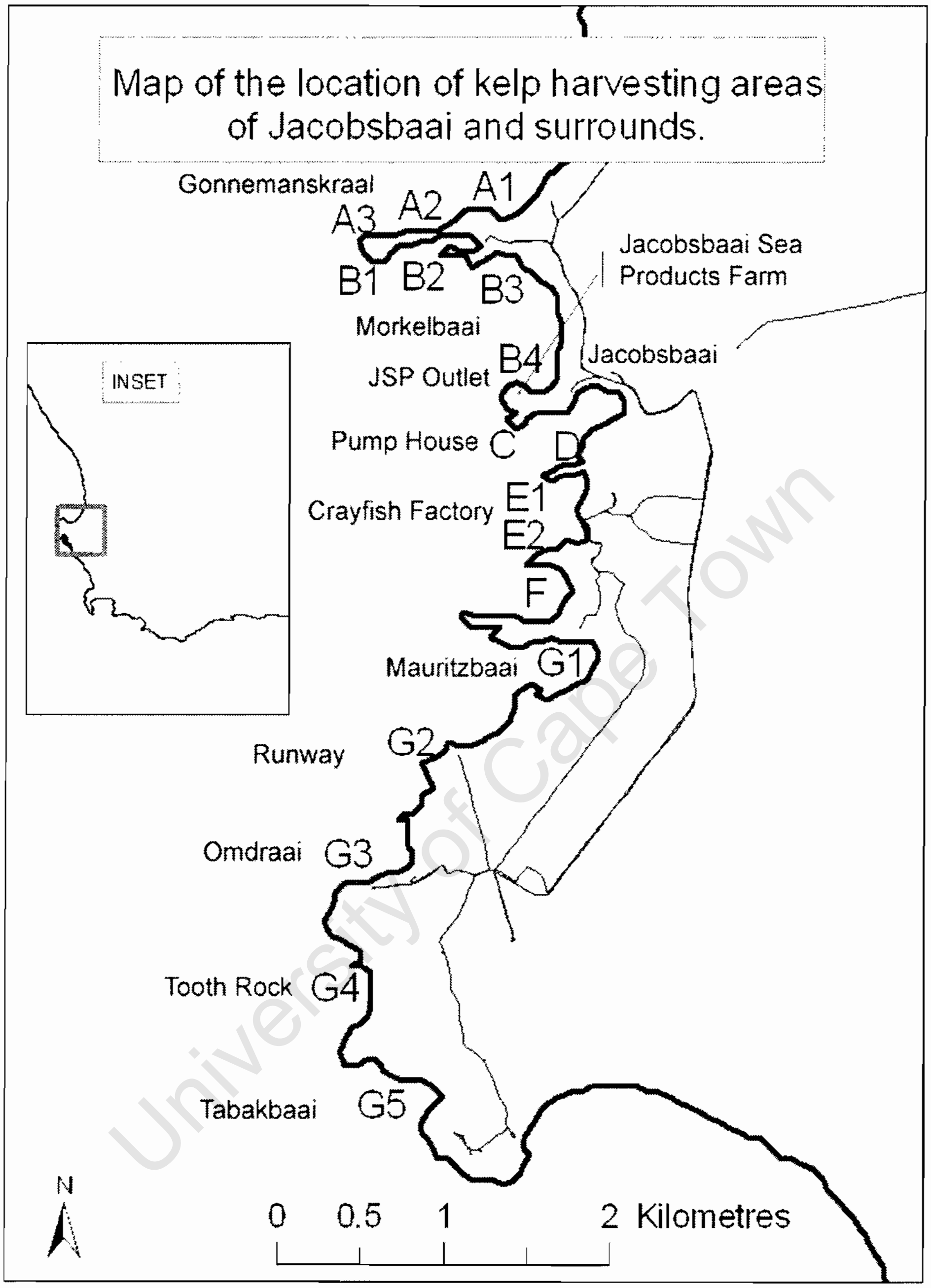


Figure 4.1. Map of the location of kelp harvesting areas of Jacobsbaai and the surrounding area, bays harvested are labeled alphabetically as per JSP's kelp bed demarcation system.

Figure 4.2. Rough bay north of Tabakbaai which remains unharvested year round.

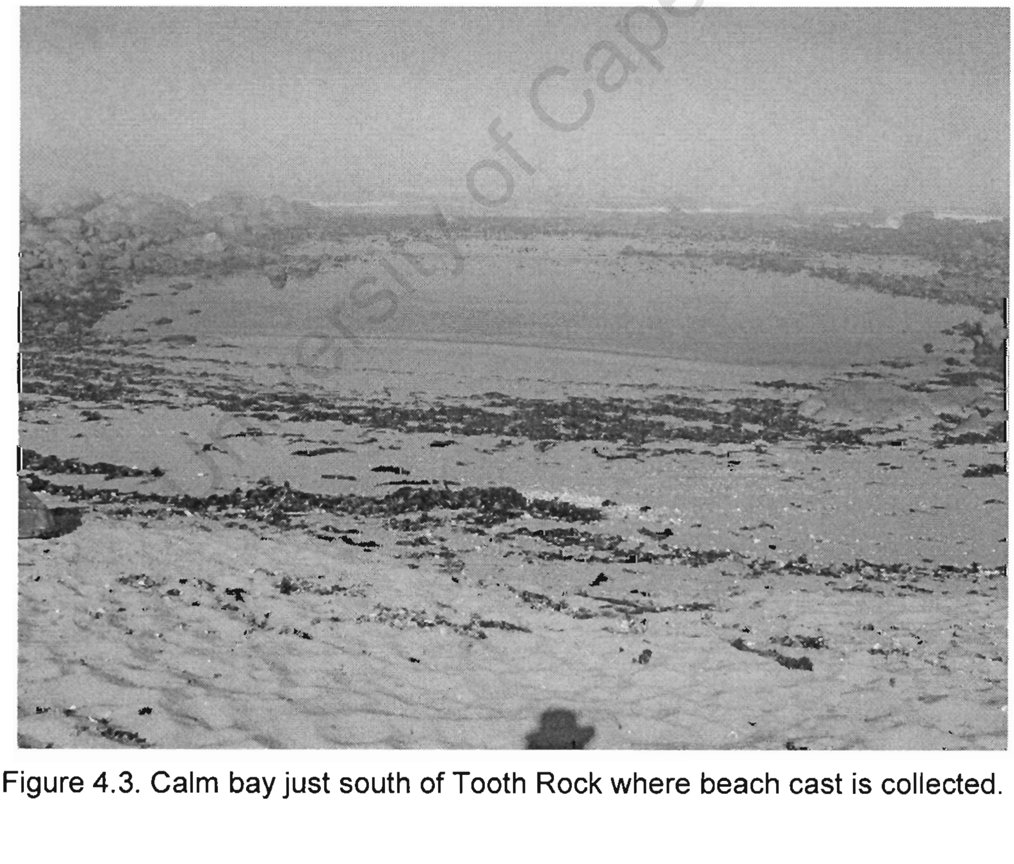


Figure 4.3. Calm bay just south of Tooth Rock where beach cast is collected.

4.2. Methods

4.2.1 Kelp biomass estimation

Kelp bed area data (which forms part of the Kelp Inventory discussed in Chapter 2) were derived from the infrared aerial survey done by the Seaweed Unit, Marine & Coastal Management (M&CM) in 1996. Additionally, Jacobsbaai Sea Products obtained aerial digital colour images of the area during an aerial survey in 2003. However, kelp bed size or density can not be extracted from these images, as they are not georeferenced or orthorectified and are subject to various problems (listed in Chapter 2). An example is the photograph (Figure 4.4 taken by JSP 2003) where sun glint obscures the surface features over the water. This image can not be used in digital image analysis of water features because technical information about acquisition has not been recorded. However, land features are clearly visible. These photographs were useful in identifying kelp beds during discussions with harvesters.

Figure 4.4. Sun glint (that obscures surface kelp beds to the observer) over the calm water near the crayfish factory (photo courtesy of JSP).

4.2.2 Morphometrics of kelp in Jacobsbaai

There are a number of sources for biomass and morphological measurements of *Ecklonia* and *Laminaria* individuals from areas near to Jacobsbaai. The method of data collection involved 1x1 metre bottom and floating quadrat sampling at the following sites in 2001 by the Seaweed Unit, M&CM and in 2005 by the author with the support of the Seaweed Unit. At each site, quadrats were places at 2-3 meters intervals in a series of lines across the kelp beds.

- Kwaaibaai 04/12/2001
- Mauritzbaai 04/12/2001
- Pump house 05/12/2001
- Mauritzbaai 25/01/2005
- Pump house 26/01/2005
- Surf Bay 25/01/2005

4.2.3 Commercial harvesting trends (1996 – 2004)

Jacobsbaai Sea Products (JSP) provided the kelp harvesting data for the period 1996 to 2004. The data were recorded daily and summed to give monthly records. See Figure 4.1 for site locations. Friedman ANOVA and Kendall Coefficient of Concordance analyses, using Statistica 7.0, were done to test for any variation in the site selection for harvesting and collection of kelp.

4.3. Results

4.3.1 Kelp Biomass

The area of sub-surface (kelp identified as being submerged, yet visible from the air, at low tide) and surface (floating fronds distinguishable as being above the surface of the water) kelp, calculated from Aerial Photography (see previous chapter) taken in 1997, in each of the study areas outlined in Figure 4.1 is shown in Table 4.1 below. A total of over 400 hectares of kelp is accessible to boat harvesting. That is more than half of the kelp in seaweed Concession Area 11 (617.95 Ha). The largest kelp beds are found in Mauritzbaai (G1) and Jacobsbaai (D). Assuming a kelp density of 3.6 kg/m^2 (see Table 4.2), the total kelp standing crop of the study site is 14930 tonnes. The current kelp quota for seaweed concession 11 is 1510 tonnes, which is approximately 10% of standing crop (see Table 3.3, Chapter 3).

Table 4.1. Area (Ha) of kelp beds (surface and subsurface) at selected sites at Jacobsbaai.

Area	Total (Ha)
Gonnemanskraal (A1)	13.24
Gonnemanskraal (A2)	43.62
Gonnemanskraal (A3)	20
Morkelbaai (B2)	15.38
Morkelbaai (B3)	11.86
Morkelbaai (B4)	12.23
Pump House (C)	5.97
Jacobsbaai (D)	72.23
Crayfish Factory (E1)	2.81
Crayfish Factory (E2)	3.16
(F)	47.29
Mauritzbaai (G1)	107.52
Runway (G2)	14.33
Omdraai (G3)	10.54
Tooth Rock (G4)	19.81
Tabakbaai (G5)	14.7
Grand Total	414.7

Once the surface area of kelp is known, the biomass of kelp at the surface needs to be surveyed. Kwaaibaai has the highest density as shown by the average mass of kelp per square metre obtained during a survey by M&CM in 2001 (with 95% Confidence Intervals).

- Kwaaibaai 3.6 kg/m^2 ± 3.4 kg/m^2
- Mauritzbaai 2.4 kg/m^2 ± 1.6 kg/m^2
- Pump House 2.4 kg/m^2 ± 1.7 kg/m^2

Another biomass assessment method is to take a floating quadrat and count the number of primary blades at the surface of the water at and around the time of low tide. The results (with 95% Confidence Intervals) of these observations done in 2005 for:

- Kwaaibaai 3.4 heads ± 1.4
- Mauritzbaai 3.3 heads ± 1.5
- Pump House 5.3 heads ± 2.1

4.3.3 Commercial kelp harvesting trends (1996 – 2004)

The commercial harvesting records received from JSP have been summarized below in Table 4.3. There is a considerable monthly variability in the harvesting of sites. Area G1 (see Figure 4.1 for location) is the most intensively harvested area (on average over 10 tonnes a month). Most of the beach cast kelp is obtained from area A (Gonnesmanskraal) – which comprises a rocky headland with kelp beds that is adjacent to a long stretch of sandy beach. On the other hand, area G4 (0.4 tonnes a month) and G5 (0.8 tonnes a month) are the least harvested, as these areas are further away from Jacobsbaai and the JSP farm and harvesting would incur a greater transport and time cost to the company.

Table 4.3. Average monthly harvest and beach cast collection records of kelp obtained by JSP for 1996-2004 (mass units are tonnes)

Place	Number of months beds harvested	Average harvest (T/month)	Confidence -95%	Confidence +95%
Gonnemanskraal (A) cast	72	6.5	4.38	8.51
Morkelbaai (B) cast	72	1	0.67	1.41
Pump House (C) cast	72	0.4	0.25	0.60
Total cast	108	8.8	7.15	10.41
Gonnemanskraal (A) harvest	106	5.4	4.16	6.70
Morkelbaai (B) harvest	101	3.2	2.26	4.05
Pump House (C) harvest	97	1.1	0.54	1.80
Jacobsbaai (D) harvest	97	3.8	0.13	0.63
Crayfish Factory(E) harvest	105	4.2	2.82	5.52
(F) harvest	108	2.5	1.64	3.28
Mauritzbaai (G1) harvest	36	10.7	8.58	12.90
Runway (G2) harvest	32	3.6	2.10	5.01
Omdraai (G3) harvest	28	3.4	1.82	4.92
Tooth Rock (G4) harvest	25	0.4	-0.21	1.03
Tabakbaai (G5) harvest	25	0.8	0.12	1.55
Total (harvest)	108	21.3	17.99	24.69
Total (harvest + cast)	108	30.3	26.56	33.99

Initially, JSP collected more beach cast than fresh material in 1996. There has been a steady increase in annual kelp harvest by JSP up until 2001; thereafter it leveled off (Figure 4.5). This has been accompanied by a drop in beach cast collection until 1999, after which more beach cast (100 – 200 tonnes) was collected each year. Currently, beach cast collection is under 100 tonnes annually, with fresh harvested about 5 times more.

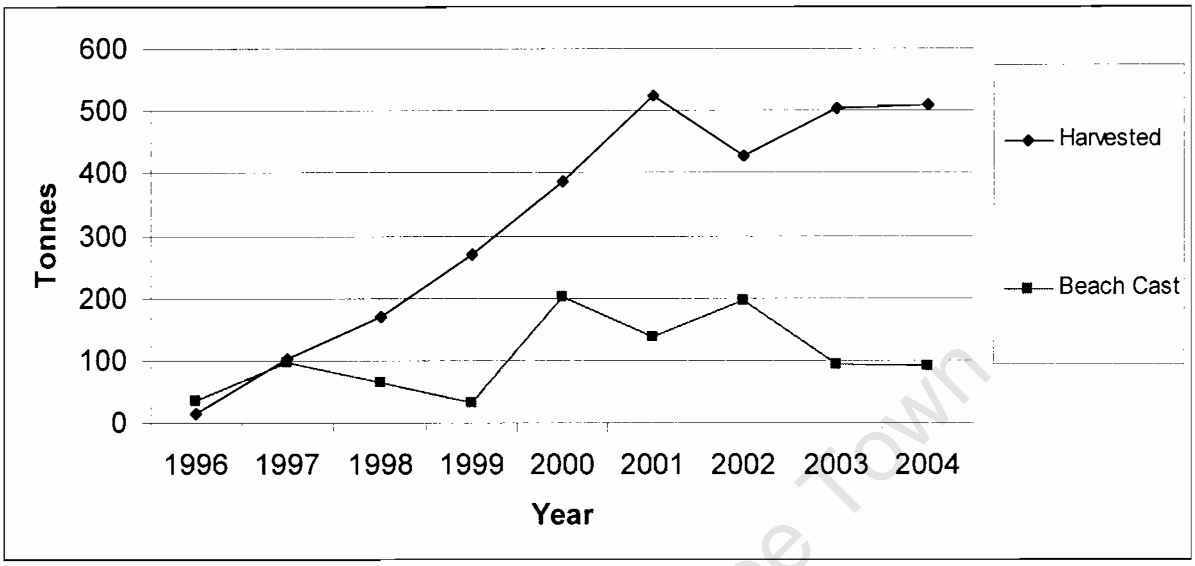


Figure 4.5. Annual harvested and beach cast kelp records (in tonnes) for Jacobsbaai Sea Products from 1996 -2004.

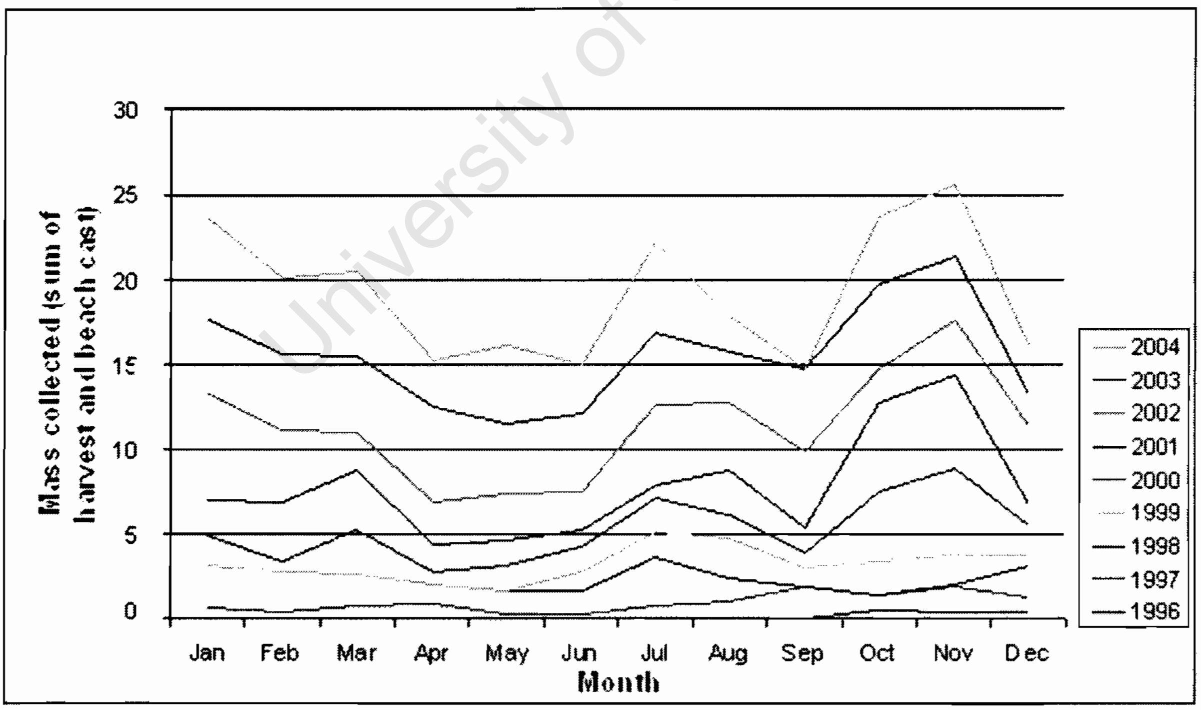


Figure 4.6. Monthly kelp production (harvest and beach cast collection in tonnes) for Jacobsbaai Sea Products from 1996 -2004.

The seasonal trend in kelp collection is visible in the graph of monthly kelp collection (see Figure 4.6). Kelp collection peaks in early summer (October/November/January) and during winter (July). A contributing factor to this observed trend is that there has been an increase in the mass of fresh kelp collected, as expanding abalone farms required more feed.

4.3.3.1 Beach cast kelp collection

There are three areas (namely, areas Gonnemanskraal (A), Morkelbaai (B) and Pump House (C) in Figure 4.1) from which beach cast is collected. Friedman ANOVA statistics done on these data (N =12, df =2) showed that obvious significant different amounts of kelp were collected from different beaches in any given year (p - values range from 0.00001 to 0.16987). However, between years this beach preference changed. For example, in 1996, Area C was preferred over the other two and between 400% and 800% as much kelp was collected. The following year saw area A being the preferred beach collection point. From 2001 onwards, beach cast kelp was only collected from Area A.

Seasonal variation in beach cast collection is a function of climatic conditions (wave action) and kelp harvester preference. The results of the ANOVA test run on the monthly beach cast records show that there is very little difference in beach cast area selection in March, June and August over the six years. However, in all other months, Area A is the preferred location for beach cast collection. Although, there is no statistically significant difference ($p > 0.15$) in all cases).

The dependence of beach cast collectors on available beach cast from area A (Gonnemanskraal) is shown in Figure 4.8. More kelp is collected during the months May to September – this is the winter season which is characterised by storms and an increase in wash up.

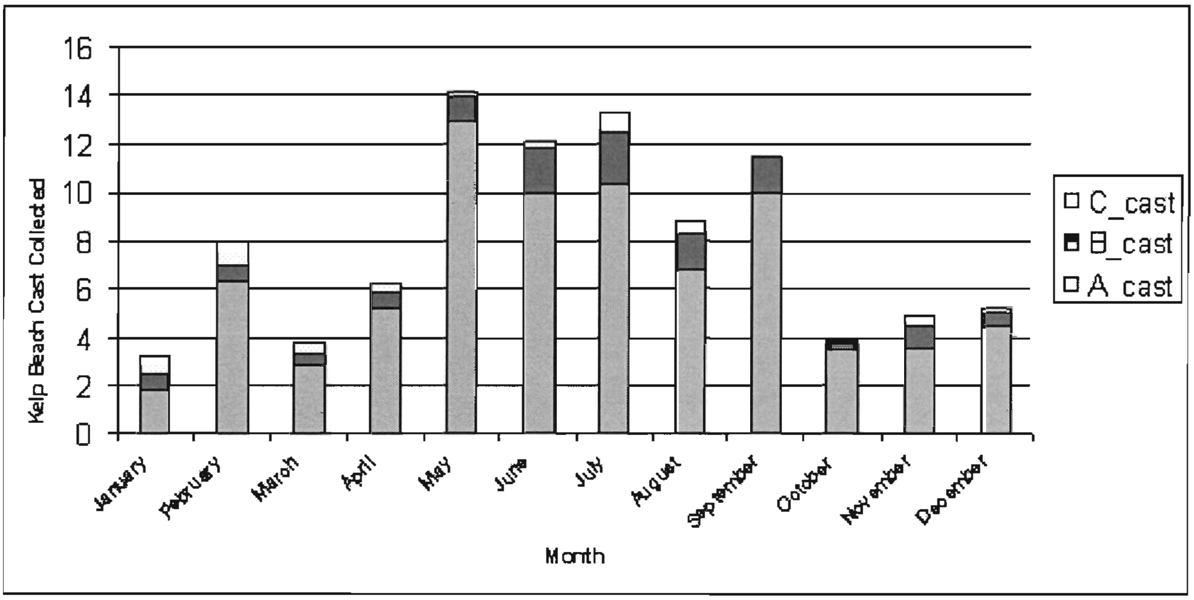


Figure 4.8. Amount of beach cast kelp collected (in tonnes) from the three sites at Jacobsbaai from 1996 - 2001.

4.3.3.2. Harvested kelp

Table 4.5 and Figure 4.9 document the monthly records of fresh kelp harvested. The curve is smoother than that of the beach cast dataset above, as fresh kelp can be accessible when sea conditions allow for boat harvesting. Not all bays are harvested every month. There is no statistical significant difference between site selections during any given month, with the exception of June – where only 5 out of the 11 sites were harvested.

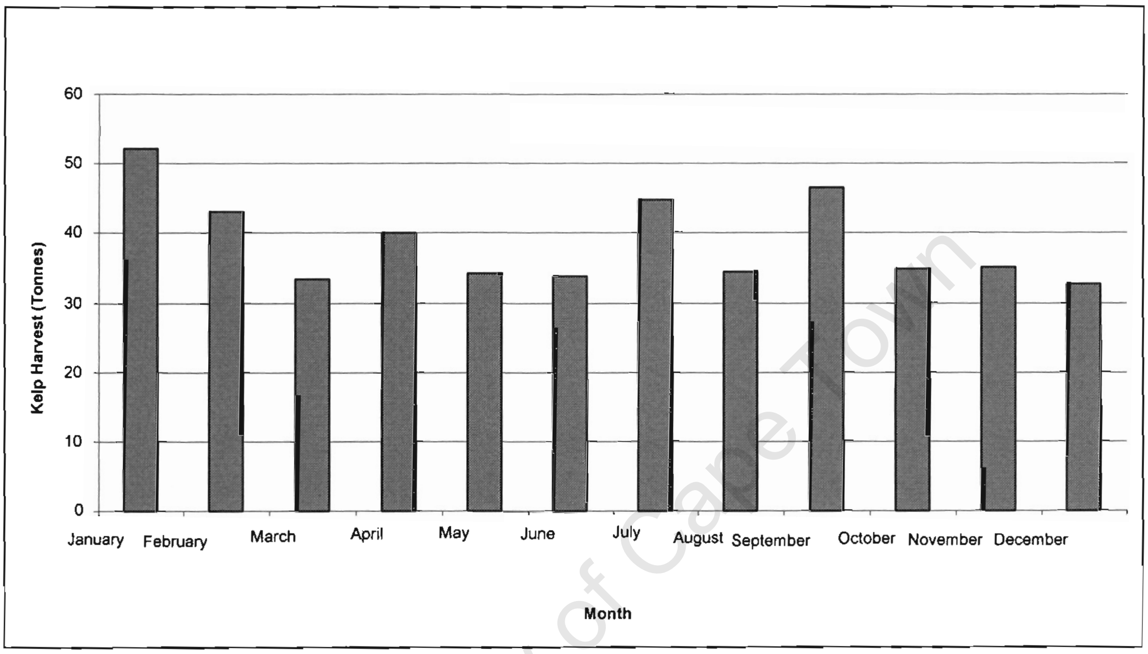


Figure 4.9. Mean monthly kelp harvested at Jacobsbaai between 1996 and 2004.

Table 4.5. Biomass of kelp beds (surface and subsurface), assuming 3.4 kg/m^2 at selected sites at Jacobsbaai.

Area	Total mass (T)	Area	Total mass (T)
Gonnemanskraal (A1)	476.64	(F)	1702.44
Gonnemanskraal (A2)	1570.32	Mauritzbaai (G1)	3870.72
Gonnemanskraal (A3)	720	Runway (G2)	515.88
Morkelbaai (B2)	553.68	Omdraai (G3)	379.44
Morkelbaai (B3)	426.96	Tooth Rock (G4)	713.16
Morkelbaai (B4)	440.28	Tabakbaai (G5)	529.2
Pump House (C)	214.92		
Jacobsbaai (D)	2600.28	Total	14929.2
Crayfish Factory (E1)	101.16		
Crayfish Factory (E2)	113.76		

Table 4.6 presents the amount of fresh and beach cast harvested as a percentage of kelp biomass as estimated from aerial photography. Note that the average kelp biomass is 3.6 kg/m^2 (based on a dive survey in 2001, see section 3.1 in this chapter). The amount of kelp harvested, as a percentage of standing crop (as calculated from 1996 aerial photography) increases year on year. In 2004, about 3.4 % of the standing crop was harvested. There is a range from 0.3 % to 6.7 % from the individual sites. The exception is Crayfish Factory (E) which has harvesting values between 10.1 % and 62.6 %. These values must be an anomaly, which is probably a result of incorrect initial kelp area coverage in this small bay (lowest standing stock of all sites). Furthermore, some sites (sites G1 – G5) were not harvested prior to 2002.

Table 4.6. Percentage of surface standing crop (as per 1996 aerial photography) harvested by area and year, based on tables 4.1 and 4.5 (above).

	1996	1997	1998	1999	2000	2001	2002	2003	2004
Gonnemanskraal (A)	0.2%	2.4%	3.4%	1.0%	1.7%	0.2%	4.4%	4.6%	2.8%
Morkelbaai (B)	0.3%	1.4%	3.6%	1.7%	3.1%	4.7%	1.9%	2.3%	3.4%
Pump House (C)	1.9%	7.9%	10.6%	6.4%	3.8%	9.3%		7.9%	4.7%
Jacobsbaai (D)				0.3%	0.0%	0.9%		0.1%	0.1%
Crayfish Factory (E)				10.1%	23.7%	62.6%	25.6%	42.7%	39.0%
(F)				0.5%	5.3%	3.1%	0.6%	2.2%	4.0%
Mauritzbaai (G1)							2.7%	3.4%	3.9%
Runway (G2)							9.8%	5.5%	6.7%
Omdraai (G3)							9.6%	8.5%	6.7%
Tooth Rock (G4)							1.0%		0.5%
Tabakbaai (G5)							3.3%	0.3%	0.3%
G total				2.8%	2.4%	3.7%			
Grand Total	0.1%	0.7%	1.1%	1.8%	2.6%	3.5%	2.9%	3.4%	3.4%

4.4. Discussion

4.4.1 Harvesting practices and results (1996-2004)

This study made use of the commercial kelp harvesting records maintained by JSP and biomass statistics to gain insights into the seasonal trends in preference for types of kelp collected and the preferred harvesting localities. The average monthly harvest is 30.3 tonnes (95%CI: 26.56 - 33.99, see Table 4.3). There is a clear seasonal trend of increased harvesting in mid winter and early summer. Note that there has been a year on year increase in harvested kelp from Concession Area 11. This trend follows the expansion of the abalone farm which drives the demand for kelp in the area. On the other hand, beach cast collection peaks in winter (Table 4.8). This is due to the winter storms which dislodge kelp plants and the incoming tide casts them ashore. The amount of kelp harvested by boat peaks in summer (Figure 4.9). This is due to beach cast becoming less available and the increased demand for fresh kelp due to beach cast and collected kelp losing its feed quality in the summer heat. Kelp is harvested more regularly and surplus is not kept overnight if it begins to rot.

The harvesting pressure has increased, but remains within kelp harvesting quotas for the Concession Area 11. Approximately 500 tonnes of kelp is harvested per year, this is about one-third of the quota (1510 tonnes) allocated to the whole area, which contains two other kelp harvesting companies. The kelp harvested per month from each concession area (see Table 4.3) varies by 2 – 3 tons. This indicates that the kelp beds are visited regularly and harvested with a similar intensity, although a seasonal trend in harvesting is still apparent (Figure 4.9).

This chapter examines whether a different scale of kelp management is able to improve management practice. The first research question: whether or not there is evidence of harvester preference for kelp harvesting site has been answered. Beach cast is currently preferentially harvested from Area A (Gonnemanskraal), which is the closest beach cast area to the abalone farms. Collection from this area has the lowest logistical costs. This area is located on the edge of a large bay north of Jacobsbaai Sea Products' abalone farm. When taking harvested beds into account, a pattern of intense harvesting of the Crayfish Factory (E) beds seems to be sustainable. However, this is unlikely to be based on accurate data. As mentioned previously, the initial standing crop biomass is probably incorrect for this small bay, which may have been poorly assessed using aerial photography. The bay may have been covered by white water or swell which obscured the surface kelp from the observer (see Chapter 2 for other mapping limitations). Other observations and dive surveys have shown "no visible evidence" of over harvesting impacting on the kelp bed structure (R. J. Anderson *pers. comm.*). However, harvesting is a relatively new activity in the area and it may take decades for effects to become apparent.

4.4.2 Kelp bed management

The health of kelp beds could deteriorate without proper supervisory management. Harvesting outside of sustainable limits could cause a decline in kelp, and in turn other ecological effects. The single rights holder and MSY aim to reduce over exploitation of the kelp resource.

Jacobsbaai Sea Products (JSP) micro-manages the kelp beds from which they derive kelp for abalone feed. They keep accurate records of all collections, in order to prevent over harvesting and help explain any changes that might occur. Aerial photographs were also taken in an attempt to quantify the resource. This is unusual and points in the direction of what should become best practice for kelp resource users. Despite these intentions, some beds are harvested more than others. Table 4.6 shows that as demand for kelp increased after 1999, and so more areas were accessed. This pattern of accessing bays that were further away from the abalone farm (see Figure 4.1) was repeated in 2002, when areas G1 - G5 were harvested for the first time. Areas G1 – G5 provide about 3-5 tons of kelp per month (Table 4.3) which is on par with more closely located beds in Areas B and C.

Management of kelp beds should be on a bed-by-bed basis ('micromanagement'), instead of making use of averaged out surveys and removal statistics over the whole coastline within a seaweed harvesting area. Maintaining monthly kelp records allows for the management of beds by the rights holder. Information and analysis allow for the understanding of seasonal variation in harvests and the geographical intensity. They are able to provide insight for both the commercial exploitation and conservation of the kelp resource. These data can be coupled with kelp bed surveys to provide a snap shot of the state of the kelp beds under harvesting pressure.

It is recommended that current seaweed Concession Areas be maintained. Kelp harvesters and beach cast collectors should maintain tonnage records of the areas (at least at the scale of a bay) that they harvest from. The seaweeds rights administrators could provide rights holders with maps of their areas, with an area demarcation that would allow the harvesters to use a standard naming convention. The results from the detailed records is able to permit the authorities to identify the high use areas in a Concession Area. From this, low/no use areas could be established for either conservation areas or as potential points of entry for new rights holders or expansion of the current rights holder's business.

The generalization of local, small scale surveys to a stretch of coastline that is heterogeneously populated by different ratios of kelp species and coastline substrate type is a method that does not have the rigor that is required in the context of an ever increasing harvesting pressure. The micromanagement of kelp beds by rights holders, keeping government bodies informed, is recommended. The model of management used in Concession Area 11, as described in this chapter, should be extended into the other seaweed (kelp, *Gracilaria* and *Gellidium* Concession Areas).

Chapter 5. General discussion and recommendations

Chapter Outline

This chapter summarises the results of the study. The kelp inventory and commercial harvesting trends are reviewed in the context of the research questions stated at the beginning of this thesis. An evaluation of the relevance of GIS and RS in the current study and for future research concludes this chapter.

5.1. Kelp Inventory review

This is the first study to provide an estimate of kelp area and biomass on the South African coast that is based on accountable, comprehensive mapping, and the first to use GIS to combine map data from a variety of sources, and attempt to fill in the gaps. Most of the stretches of the west coast that have rocky ledge platforms and hard substrates was covered by this study. Information relevant to Tarr's (1993) Infrared aerial print photography (M&CM, unpublished data, 1996); and Landsat 7 ETM+ (2002, Ocean Imaging) were successfully included in a database. New research methods were applied to the data of colour infrared aerial photography of approximately 300km of previously unmapped coastline (2005), Landsat 5 (1991), and field surveys that provided ground truthing (2003-2005).

All these datasets are now integrated into a single ArcGIS geodatabase. Additionally, hardcopy maps of the kelp beds (according to each survey method), coastline, depth isobars, access routes and towns have been produced and included as appendices to this thesis. The database adheres to industry standards of format and may be edited with ease by GIS personnel to produce updated maps.

There are differing degrees of disparity in the planimetric area values for the kelp bed distribution obtained by different methods. Areas that remain unmapped include parts of the Cape Peninsula ("Between 9 & 10"), specifically around the Cape Metropole together with a portion of the Lamberts Bay area (31°30' S).

5.2. Review of Research Questions

5.2.1 What is the distribution of kelp resources?

The kelp resources and transport network has mapped and presented in Appendix 8. The literature and previous surveys were used as a source of kelp bed density figures. Biomass is highly variable within transect, between neighboring sites and other beds further away in terms of number of kelp primary blades at the surface during low tide and in standing biomass. Table 3.1 in chapter 3 provides biomass values. For future studies, the development of a standard recording and publishing unit of measurement would be useful. Biomass can vary on a seasonal basis, as shown by Levitt *et al.* (1992, 2002), particularly when winter storms uproot whole kelp individuals. This is further evidenced by the increase in beach cast collection during winter months as shown by the case study as Jacobsbaai in Chapter 4 (Figure 4.8).

There is more kelp per kilometer of coastline in the south than in the north (Table 3.5). This supported by the biomass data, showing more biomass/km^2 in the south (Table 3.1).

5.2.2 How do different methods of data acquisition/mapping compare?

Aerial photography is the preferred choice in obtaining good imagery for the reasons outlined in Chapter 1 & 2; which are the control of image acquisition timing, repeat fly-overs and choice of film (CIR for surface kelp and colour for better blue/green water penetration for near surface kelp). This, however, should be combined with scuba surveys and other ground truthing of biomass and standing stock.

The variability *within* methods (based on overlapping survey of the same area) has been shown to be low for most areas; with the notable exception of the Agulhas Region surveyed using CIR(2005); see chapter 3 (Table 3.6) which showed a 400% difference in the size of kelp beds. However, the other regions surveyed in 2005 showed a low Dissimilarity Index (approaching 1).

The variability *between* methods in overlap areas was shown to be high. In particular when comparing aerial based techniques (1m resolution) to the broad-brush (30m resolution) nature of Landsat 7 ETM+ data (see chapter 3, Table 3.5). The sea surface conditions at time of image acquisition were not described, and timing may not have coincided with a spring low tide.

If the methods employed in this thesis are compared with those employed by other studies, a similarity is apparent. Jensen, et al. (1977, 1978, 1980) made use of early Landsat 5 TM imagery and infrared aerial photography. The latter was found to be most suitable and provided similar results to contemporary (late 1970's) large scale inventories. Veisze *et al.* (2000) warns of inconsistencies when comparing between methods of data acquisition in a study done in California, USA.

Geographic Information Systems (GIS) and Remote Sensing (RS) tools have been shown to provide useful analysis and spatial computation structure to kelp bed information. South Africa's kelp beds may be monitored using these tools. Based on South Africa's environmental policy and international trends in near shore coastal monitoring, these tools will be used in future surveys and research (Chapter 1).

5.2.3 What are the trends in commercial kelp harvesting?

Commercial harvesting is within MSY limits and the current management strategy has allocated harvesting rights for the next ten years until 2016 (see Table 3.3, Chapter 3). The kelp products industry could grow rapidly provided there was more secondary/tertiary processing and value adding processes (for example, artificial abalone feed). However, expansion of the industry is subject to the availability of Concession Area permits, weather conditions, use of mainly unskilled labour and international markets for the product. The monthly national kelp harvest is summarized in Figure 3.7 (Chapter 3). The observed trend of a winter dip in collection is also seen in the finer scale bed-by-bed harvesting statistics in Jacobsbaai (Figure 4.9, Chapter 4). Additionally, the increase in winter month beach cast collection is seen in Figure 4.8 (Chapter 4). The amount of kelp collected has fluctuated, due to demand and availability, over the period 1986 - 2003 (Table 1.1). The average per year over that period is about 1000 tonnes.

The trends that are apparent from the results in chapters 3 & 4 indicate that some Concession Areas and kelp beds are harvested less intensely than others. Moreover, a Concession Area is not uniformly harvested. Kelp beds having low biomass and those far away from slipways, extraction points and labour remain unharvested. This observation is supported by anecdotal information supplied by harvesters. The case study (chapter 4) of one seaweed Concession Area shows that there is a seasonal trend of increased harvesting in mid winter and peaking in early summer. There has been a year on year increase in harvested kelp from this study area (seaweed Concession Area 11). There has been a steady increase in the amount of kelp harvested from the Jacobsbaai area from around 1% (1998) to 3.4% (2004) of total standing crop. This harvesting intensity is still within regulated quotas. Troell *et al.* (2006, duplicated in Figure 3.9) show that the Concession Area kelp yield, as a whole is approaching maximum MSY harvesting (greater than 90%). The variation in bed selection for harvesting is seen in Table 4.6 (Chapter 4). The beds near to the Crayfish factory are the most intensely harvested (from 10%-60%). These record yields are probably incorrect, due to the standing crop area calculations from the 1996 aerial survey being an undercount. Comparatively little kelp is harvested in Jacobsbaai and Tooth Rock. Irrespective of the level of harvesting, the Crayfish Factory has sustained this variable harvesting regime.

The demand for kelp by abalone farms is year-round and is met by collecting fresh together with a little beach cast collection. Abalone dietary requirements are supplemented by artificial feed and seaweed (Robertson-Andersson, 2003, unpublished MSc thesis). This is unlikely to change until suitable artificial or alternative feed products are developed and become commercially viable. A number of farms are experimenting with integrated aquaculture of seaweeds and abalone. Increased cultivation of algae to feed the abalone could in future decrease the dependence of abalone farms on fresh cut kelp (Troell *et al.* 2006).

5.2.4 At what scale should management of this resource be done?

Management of kelp resources ideally should have a national context and approach. The present system of having large seaweed Concession Areas is the most manageable route, as it takes into account accessibility and current infrastructure conditions. Additionally, companies should provide fine-scale surveys and information. Alternatives to the current approach would simply be unmanageable, unless vast resources of manpower and infrastructure are developed. Currently, the balance of supply and demand for kelp must be investigated with respect to kelp harvesting quotas, payments and sustainability. However, the boundaries and size of the seaweed Concession Areas could be reviewed in cases where areas are large and underutilized (e.g. Concession Area 5, 14 or 15) or unsustainably small (e.g. Concession Area 12).

Chapter 4 has shown the value in recording kelp bed and bay harvesting information, which in addition to Jacobsbaai Sea Product's survey provides accurate information on their condition, allowing for the appropriate level of management to be implemented. The entire distribution of kelp beds should be monitored, in particular the northern and westerly outmost extents. For example, Cape Agulhas could be an indicator of climate change as it is the southern most point of Africa and the eastward edge of kelp beds. This case study had shown that it is in the best interests of the seaweed concession holders to micromanage the resource that they have 'leased' for a decade. This would allow them to do better business by managing the kelp beds in terms of timing of harvests, intensity and repeat visits.

The development of a self regulating industry with efficient management and administration will negate the need for a top-down law enforcement approach. The need for strict control may be replaced by periodic monitoring such as is the case in Ireland, that has a self regulating *Ascophyllum* industry (Hillman, 2005, see Chapter 1).

5.3. Technical refinements and avenues for future research

Further research may add species specific information. A computational model that assesses the geographic components of the biomass distribution was outside the scope of this project, but offers an avenue for future research.

A weakness in the remote sensing component of the research was the lack of in-situ spectrophotometry readings at time of image acquisition. Menges *et al.* (1998) points out the necessity of this procedure in order to obtain accurate interpretation of the data, through true reflectance values at the time of image acquisition. It is recommended that the above is combined with a suitable ground truthing of surface (water/substrate) reflectance, such as outlined in Clark *et al.* (2002). Nevertheless, the perimeter of the kelp beds were still obtained, but the density of each bed was not investigated. Additionally, some kelp beds in other parts of the world have a significant amount of epiphytes on the kelp fronds that may alter reflectance readings and that may also affect local readings and interpretation. Fyfe (2003) provides the major peaks of reflectance and troughs of absorption for characteristic epiphyte photosynthetic and accessory pigments (575, 590, and 640 nm). A worthwhile research avenue would be to asses the reflectivity (in the lab and field) of kelps and their major epiphytes. In the case of *Ecklonia maxima*, the bulk of the epiphyte load is not on the fronds (Anderson *et al.* 2006), and thus the kelp spectral reading should not be significantly altered.

The ENVI software used in this project allows for the extraction of a selected range of pixel values, by making use of a min/max threshold filter. The resulting image allows for the isolation and potential creation of a binary mask which may be applied over any other image to highlight the features extracted. Histogram stretching allows the selected section of the spectrum to be stretched across the entire range of pixels that have been loaded. Other than using the spectral pixel-based analysis, an object-orientated approach which uses the morphological properties of the kelp beds to derive improved and refined habitat maps may be employed. This refined method was proposed five years ago by Barr & Barnsley (2000) in a paper that was anticipating sub metre satellite imagery. One possibility is to divide the image analysis process into two distinct stages: In the first stage, a multispectral classification algorithm is used to derive an initial set of discrete land-cover parcels (or regions). In the second, information on land use is inferred from an analysis of the morphological properties of these regions and the spatial relations that exist between them. The software (such as e-Cognition) has recently become powerful enough to be used on a project such as this. Therefore, this is the recommended approach for future research on kelp beds in this study's area and in others, such as Namibia.

Edyvane (2003, p73) cautions interpretation and interpolation from the data presented in this study:

> "However, any detailed spatial-temporal (GIS-based) analysis of the historical distribution and current status of *Macrocystis pyrifera* in Tasmania, must recognise the dynamic and gross inter-annual fluctuations of Macrocystis, (which are linked closely to environmental factors and resource availability), and also, should assess and integrate the wide range of quantitative and qualitative, and often disparate, data sources (and their limitations)"

A model approach to the kelp bed ecosystem seems to be the next logical research step. Denny & Hale (2003) provide an integrative approach to the modeling of flexible organisms, appropriately named Cyberkelp. This biomechanical model integrates a variety of forms: conceptual models; physical models; and mathematical models. Koutsias & Kaertiers (2003) applied Landsat TM data for the mapping of land vegetation. The spectral classes were derived by considering as key elements of the classification scheme the main species that prevail in the overstory layer, as well as meaningful mixtures of them, discriminated by their degree of density as indicated from vegetation indices. Similar methods and decision criteria were applied in this project.

5. 4. Conclusions and recommendations

The biomass of *Ecklonia* maxima beds as able to change considerably. Levitt *et al.* (2002) reported fluctuation of as much as 300%, and large storms can visibly thin out kelp beds (R.J. Anderson, pers comm.). Furthermore, between Cape Point and Cape Agulhas, warm water (<20^{0}C) can sometimes persist in certain localities in summer, leading to visible loss of canopy biomass within 2-3 weeks (R.J. Anderson, pers. comm.). All of these factors lead to large biomass and density changes, but changes in the extent and surface area of kelp beds are seldom noticeable. Regular surface quadrats (a quick assessment method) along kelp bed transect lines in representative areas should be done in order to track any changes. Perhaps future research would create a kelp biomass index based on environmental variables such as wave direction, swell high, sediment, bathymetry and maximum light penetration depth.

Repeated visits to the sites sampled and ongoing monitoring of the resource is a bases of acceptable levels of sustainable management.

> "An essential step in ensuring marine biodiversity conservation in South Africa is the assessment of its current status, and regular updates thereafter so that problem areas are identified and addressed." Griffiths et al (2000).

Further research should be undertaken with Infrared aerial photography in order to build a time series. However, this study found that ground truthing done by kayak is an accurate method of mapping the exact location of bed and area of kelp exposed and near the surface at a particular tidal height.

The datasets presented in this thesis could be integrated within an Environmental Decision Support System (EDSS, as described in Poch *et al.* 2004) or existing legal and planning frameworks, for example, the City of Cape Town's 2002 Coastal Zone Strategy. Additionally, other biotic databases and model could be used in conjunction with this database, for example Shiran-Klotz's (2003, unpublished MSc thesis) Abalone Ranching Model (ARM) which shows the impact of mining activities on kelp bed areas that impact on suitable abalone habitat).

The most important benefit of this project has been the consolidation, coordination, and integration of spatially based information into a database that is accessible to other users. With GIS and related technologies (e.g. ENVI), vast arrays of disjointed and unrelated data may rapidly be combined to address numerous institutional issues quickly. The adoption of standard inventory methods, and GPS field mapping techniques, accelerates the data acquisition. Subsurface monitoring of individual kelp beds (ie. SCUBA-based) can measure indices of kelp survival, growth and reproduction. Rothman (2006, unpublished MSc thesis) provides such data for South African kelps. Table 5.1 provides a possible long term monitoring program for kelps in Southern Africa. The suggestions are based on ideal economic conditions, as surveying and monitoring is expensive. Consecutive visits could be determined by available resources (money and manpower).

Table 5.1 Proposed long-term kelp monitoring program of kelp is South Africa.

Variable	Criteria	Method	Frequency
Kelp Abundance	Kelp canopy area	Aerial photography (CIR/colour)	10 years
Kelp Density	Canopy biomass	Remove & weigh or kelp primary blade count	Annual/3years
Climatic Variability	Sea Surface Temperature	AVHRR imagery	continuous
	Down welling radiance	In situ recorders	continuous
	Sediment	In situ recorders	continuous
Kelp plant size	Kelp morphometrics	SCUBA	annual
Community ecology	Kelp epiphytes	SCUBA	annual
Harvesting intensity	Harvesting records	Administrative	monthly

Future data acquisition should take advances in satellite technologies into account. The Satellite Applications Centre (SAC), a component of the CSIR provides data satellite imagery at negligible cost and can act as a data broker for future research. Should any accuracy measurements be done in the future, Zhang *et al.* (2004) provides a good mathematical approach with sub-sampling techniques that would be suited to the datasets created in his project. Larson *et al.* (2004) claims to be the first to combine landscape, habitat, and population viability models in a single analysis provides benefits beyond those of the individual modeling stages. This thesis provides the habitat component for future studies wishing to integrate the datasets presented here with population studies and ecological information to provide a predictive tool. A proposed goal for future research is to produce a single, long-term monitoring method that would allow for time-series analyses to be done on the distribution and biomass of kelp beds. This would have to be based on a combination of infrared photography and a simple, rapid method for biomass assessment such as floating surface quadrats to count the number of kelp heads at the surface at low tide.

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APPENDIX

Contents

APPENDIX 1. Glossary of Terms

Absorption - The process by which radiant energy is absorbed by an object.

Albedo - Ratio of the amount of energy reflected by a surface to the amount of energy received.

Attribute - A descriptive characteristic of a feature. An attribute object holds the non-locational or non-spatial information about the feature.

Azimuth - Geographic orientation of a line given as an angle measured in degrees clockwise from North.

Classification - Process of assigning individual pixels of an image to categories, generally on the basis of spectral reflectance characteristics.

Colour infrared (CIR)- A false colour film different from ordinary colour film in that the three sensitized layers are sensitive to green, red and infrared radiation instead of blue, green and red.

CSIR - The Council for Scientific and Industrial Research (CSIR) is one of the largest R&D, technology and innovation institutions in Africa

CD:S&M - The Chief Directorate of Surveys and Mapping (CD:S&M) is responsible for the official, definitive, national topographic mapping and control network system of South Africa.

Datum - A mathematical surface from which heights or positions are referenced.

ETM - Enhanced Thematic Mapper (TM) - A high-resolution scanner system on board the LANDSAT-6 and later satellites.

Generalization - A process which may involve the selection, displacement, simplification, exaggeration or aggregation of features from their true position for the sake of cartographic clarity.

Geodetic datum - A datum defines the basis of a coordinate system. A local or regional geodetic datum is normally referred to an origin whose coordinates are defined. The datum is associated with a specific reference ellipsoid which best fits the surface (geoid) of the area of interest. A global geodetic datum (eg. WGS84) is now related to the centre of the earth's mass, and its associated spheroid is a best fit to the known size and shape of the whole earth. The position of a point common to two different surveys executed on different geodetic datums will be assigned two different sets of geographical coordinates.

Geographical coordinates - A position given in spherical coordinates commonly known as latitude and longitude.

Geographic Information System (GIS) - A spatial database and the associated resources which can be manipulated using a set of spatial commands.

Inventory – "the collection of information. In the context of natural resources, inventory requires measurement of objects and features, but no interpretation regarding their importance or value ... Inventory data are typically derived from field surveys, and minimal professional judgement is required other than interpretation of inventory data descriptions and definitions." *Mason & Knight (2001, p 16)*

Layer - The features in a theme are subdivided into one or more layers on the basis of the spatial objects used to represent the features. Linear networks, polygons and point features are placed in separate layers.

M&CM – Marine and Coastal Management. A division of the DEA&T.

MPA - Marine Protected Area is a specific area of marine environment reserved and managed in perpetuity.

Node - A point that is a junction of two or more chains or which is the end point of a chain. Connectivity of chains is indicated by the sharing of nodes at their intersections.

Node/chain structure - The structuring of linear features in a layer so that they consist of chains broken by nodes at intersections or at the point where an attribute of the feature changes.

Pixel - A contraction of picture elements.

Planimeter Area - A mechanical or electronic device that calculates the area of a map feature.

Point - A geometric representation defined by a single (x,y) coordinate pair or an (x,y,z) triplet, where the z-coordinate is the height value.

Polygon - A continuous area defined by a set of bounding chains. There is only one external polygon and there may be one or more internal, non-nested inner boundaries.

Positional accuracy - Statistical estimate of the degree to which coordinates and elevations of features agree with their real world values.

Radiance - The amount of electromagnetic radiation leaving or arriving at a point on a surface.

Reflectance - Spectral reflectance is the reflectance measured within a specific wavelength interval.

Resolution - In satellite imagery it refers to the smallest object that can be discerned. Resolution may also be expressed in terms of spectral resolution.

SAC - Satellite Application Centre (SAC), an arm of the CSIR (Council for Scientific and Industrial Research.

Thematic Mapper (TM) - A high-resolution scanner system on board the LANDSAT-4 and LANDSAT-5 satellites.

Theme - The information contained in GIS database that can be divided into themes which contain logically related geographic information.

Topological integrity - The measure of how well spatial data conform to the sophisticated data structure required for GIS, especially with respect to connectivity and adjacency.

Vector Data - Vector data uses points and straight lines (vectors) to describe features on, or characteristics of, the earth's surface. Vector data can also include polygons, which are areas enclosed by a number of vectors. To record additional information, data attributes can be attached to individual vector features.

Vertex - The connecting point of two line segments.

WGS84 - World Geodetic System 1984. A geocentric datum.

APPENDIX 2. Marine Protected Areas along the South African Coast

Langebaan Lagoon Marine Protected Area
Langebaan Lagoon is divided into three zones. Recreational fishing is allowed in the northern-most zone (Zone C), north of a line joining Beacons LB4, in Kraal Bay, and LB3, at Oesterwal.

Sixteen Mile Beach Marine Protected Area
No fishing from the shore is allowed in the area between Plankies and Rooipan se Klippe (near Yzerfontein).

Malgas Island, Jutten Island and Marcus Island Marine Protected Areas
No fishing is allowed along the shores of these islands.

Castle Rock Marine Protected Area
No fishing is allowed in the area between Bakoven Rock (south of Miller's Point at beacon VB1) and Bobbejaanklip (south of Partridge Point at beacon VB2), extending one nautical mile seawards from the high-water mark.

Helderberg Marine Protected Area
No fishing is allowed between the mouth of the Eerste River and the mouth of the Lourens River in False Bay, extending 500m seawards from the high-water mark.

Betty's Bay Marine Protected Area
Only shore angling (and no other type of fishing) is allowed between beacon B1 at Stoney Point and beacon B4, to the east of Jock-se-baai, extending two nautical miles seawards from the high-water mark.

De Hoop Marine Protected Area
No fishing is allowed between beacon DH1 at Still Bay Point and beacon DH2 between Rys Point and Skipskop, extending three nautical miles seawards from the high-water mark.

Goukamma Marine Protected Area
Only shore angling (and no other type of fishing) is allowed between Portion 1 of the farm Walker's Point at Buffels Bay and the western boundary of the Goukamma Nature Reserve, extending two nautical miles seawards from the high-water mark.

Robberg Marine Protected Area
No fishing is allowed in a rectangular area surrounding the Robberg Peninsula between the latitudes 34°04'.916S and 34°07'.633S and the longitudes 023°22'.300E and 023°25'.967E, although shore angling is allowed.

Tsitsikamma National Park (includes the Tsitsikamma Marine Protected Area)
No fishing is allowed between Groot River at Oubos to Groot River at Nature's Valley, extending three nautical miles sea-wards from the high-water mark.

Sardinia Bay Marine Protected Area
No fishing is allowed between beacon PECR1 near Schoenmakerskop and beacon PECR2 near Bushy Park, extending one nautical mile seawards from the high-water mark.

Dwesa-Cwebe Marine Protected Area
No fishing is allowed between the western bank of the mouth of the Suku River (in the District of Elliotdale) and Human's Rock (in the district of Willowvale), including the tidal portion of the Mbashe River, extending six nautical miles seawards of the high-water mark.

Hluleka Marine Protected Area
No fishing is allowed adjacent to the Hluleka Nature Reserve (in the Ngqeleni District), extending six nautical miles seawards from the high-water mark.

Mkambati Marine Protected Area
No fishing is allowed between the eastern bank of the mouth of the Mtentu River and the western bank

of the mouth of the Msikaba River, including the tidal portions of these two rivers.

Trafalgar Marine Protected Area
Only shore angling and fishing for pelagic bony fish (and no other type of fishing) is allowed between beacon N1 south of Centre Rocks and beacon N2 opposite the southern boundary of the Mpenjati Resort, extending 500 m seawards from the high-water mark.

The Greater St Lucia Wetland Park (includes St Lucia and Maputaland Marine Protected Areas)

St Lucia Marine Protected Area extends from beacon N3 north of Ngoboseleni Stream to beacon N4 south of Cap Vidal, and extends three nautical miles seawards from the high-water mark. No fishing is allowed in the **Sanctuary Zone** between beacon N5 at Red Cliffs and beacon N6 at Leven Point, extending three nautical miles due east from the high-water mark. In the **Restricted Zones** which lie to the north of beacon N5 at Red Cliffs and to the south of beacon N6 at Leven Point, respectively, shore anglers may catch fish, and skiboat anglers and spearfishers may catch pelagic bony fish.

Maputaland Marine Protected Area extends from beacon N7 at the Moçambique border to beacon N3 north of Ngoboseleni Stream, extending three nautical miles seawards from the high-water mark.

No fishing is allowed in the **Sanctuary Zone** between the beacon N8 at Boteler Point and beacon N9 500m south of Dog Point, extending three nautical miles due east from the high-water mark.

No fishing is allowed in the **Sanctuary Zone** between the beacon N7 at the Moçambique border and the beacon N13, extending three nautical miles due east from the high-water mark, except that shore angling is allowed north of beacon N27, which lies 2 km south of the mouth of the Kosi Lakes.

In the **Restricted Zones** between beacon N13 and beacon N8 and between beacon N9 and beacon N3 shore anglers may catch fish, and skiboat anglers and spearfishers may catch pelagic bony fish.

CLOSED AREAS

St Helena Bay
No rock lobster may be caught between Stompneus Point and beacons SHBE/DR at Wilde Varkens Valley (near Doctor's Reef), extending six nautical miles seawards from the high-water mark.

No rock lobster may be caught between Shell Bay Point and Stompneus Point, extending three nautical miles seawards from the high-water mark.

Saldanha Bay

No rock lobster may be caught between North Head and South Head (the entire Saldanha Bay).

Table Bay
No rock lobster may be caught between Melkbos Point (beacon MB1) and Die Josie (near Chapman's Peak - beacon MB2), extending 12 nautical miles seawards from the high-water mark.

Cape of Good Hope
No fishing is allowed between Schuster Bay (Scarborough) and Cape Point lighthouse, extending 500 m seawards from the high-water mark, except that shore angling and the catching of rock lobster and abalone is allowed between Hoek van Bobbejaan to the Cape Point lighthouse.

Fish Hoek
Only shore angling is allowed (and no other type of fishing) between the start of Jager's Walk at Fish Hoek to Elsebaai at Glencairn Beach, extending 500 m seawards from the high-water mark.

St James
No fishing is allowed between St James Station and Kalk Bay Station, extending 500 m seawards from the high-water mark.

Muizenberg
Only shore angling is allowed (and no other type of fishing) between Neptune's Corner at Muizenberg Station to St James Station, extending 500 m seawards from the high-water mark.

Strand
Only shore angling (and no other type of fishing) is allowed between the mouth of the Lourens River, and the eastern breakwater of the harbour at Gordon's Bay, extending 500 m seawards.

Mudge Point
Only shore angling and the catching of rock lobster and abalone is allowed between the western limit of the Hawston harbour and the eastern limit of the Frans Senekal Reserve, extending 100 m seawards from the high-water mark.

Onrus River
Only shore angling (and no other type of fishing) is allowed inside Harderbaai north of a line drawn between the beacons at Van der Riet Hoek (OR1) and Marine Drive Point (OR2) respectively.

Hermanus
Only shore angling (and no other type of fishing) is allowed between the beacons at Kraal Rock (HR1), Walker Bay, and Rietfontein (HR2), Hermanus, extending 500 m seawards from the high-water mark

Dyer Island
Only shore angling (and no other type of fishing) is allowed at Dyer Island, in an area extending two nautical miles seawards from the high-water mark.

East London
Only fishing from the shore is allowed in the following three areas near East London:
(i) between Nahoon Point and Gonubie Point, extending three nautical miles seawards from the high-water mark,
(ii) between Christmas Rock and Gxulu River mouth extending three nautical miles seawards from the high-water mark, and
(iii) between Nyara River mouth and Great Kei River mouth, extending three nautical miles seawards from the high-water mark.

Durban
Fishing for invertebrates is not allowed in the area between the line drawn 145° from the south breakwater of Durban Harbour and another line drawn 145° from the mouth of the Umgeni river, extending three nautical miles from the high-water mark.

Appendix 3. Current Seaweed Concession Areas (excluding reserves) of South Africa.

1. Kei River (32°40′28″S , 28°23′00″E) to Cape Seal (34°01′12″S , 23°24′48″E)
2. Cape Seal (34°01′12″S , 23°24′48″E) to Cape St Blaize (34°10′16″S , 22°05′30″E)
3. Cape St Blaize (34°10′16″S , 22°05′30″E) to the eastern bank of the Breede River (34°24′00″S , 20°50′00″E)
4. Western Bank of the Breede River (34°24′40″S , 20°50′00″E) to Cape Agulhas (34°49′40″S , 20°00′40″E)
5. Cape Agulhas (34°49′40″S , 20°00′40″E) to the eastern bank of the Uilenkraal River (34°36′24″S , 19°24′36″E)
6. Western Bank of the Uilenkraal River (34°36′24″S , 19°24′36″E) to the eastern bank of the Mossel River (34°24′30″S , 19°16′24″E)
7. Western Bank of the Mossel River (34°24′30″S , 19°16′24″E) to the eastern bank of the Palmiet River (34°20′36″S , 18°59′56″E)
8. Western bank of the Palmiet River (34°20′36″S , 18°59′56″E) to Swartklip (34°04′29″S , 18°41′12″E)
9. Simons Town municipal border at Rocklands Point (34°13′00″S , 18°28′00″E) to the RSC boundary at Klein Koeelbaai near Bakoven (33°57′38″S , 18°22′20″E)
10. CCC/RSC boundary south of Blouberg (33°48′48″S, 18°28′12″E) to South Head, Saldanha (33°06′18″S, 17°57′18″E)
11. North Head (Schooner Rock), Saldanha (33°03′05″S, 17°54′36″E) to the southern bank of the Berg River (32°46′12″S , 18°08′42″E)
12. North Bank of the Berg River (32°46′06″S, 18°08′48″E) to the southern border of Lambert's Bay (32°06′00″S, 18°18′12″E)
13. Groothoek Bay (31°54′36″S, 18°16′22″E) to the southern bank of the Olifant's River (31°42′36″S, 18°11′15″E)
14. Northern bank of the Olifant's River (31°42′04″S, 18°11′15″E) to the southern bank of the Groen River (30°51′00″S, 17°34′36″E)
15. Security fence at Mitchell's Bay near the mouth of the Spoeg River (30°27′54″S, 17°21′22″E) to the angling club slipway at Kleinsee (29°42′48″S, 17°03′24″E)
16. Northern border of the farm Oubeep south of McDougallsbaai (29°19′45″S, 16°54′38″E) to the border of the proclaimed State Alluvial Diggings just north of Port Nolloth (29°13′56″S, 16°51′15″E)
17. South Head (33°06′18″S, 17°57′18″E) to the North Head (Schooner Rock) of Saldanha Bay including Saldanha Bay but excluding Langebaan (33°03′05″S, 17°54′36″E)
18. From the slipway at the angling club at Kleinsee (29°42′48″S, 17°03′24″E) to the northern border of the farm Oubeep, south of McDougallsbay. (29°19′45″S, 16°54′38″E)
19. From the border of the proclaimed State Alluvial Diggings just north of Port Nolloth. (29°13′56″S , 16°51′15″E) to the southern bank of the Orange River. (28°38′18″S, 16°27′42″E)
20. Kei River (32°40′28″S , 28°23′00″E) to Qora River. (32°27′00″S, 28°40′24″E)
21. Qora River (32°27′00″S , 28°40′24″E) to Mbashe River. (32°14′54″S, 28°54′00″E)
22. Mbashe River. (32°14′54″S, 28°54′00″E) to Mnenu River. (31°48′24″S, 29°19′46″E)
23. Mnenu River. (31°48′24″S, 29°19′46″E) to Mtamvuna River. (31°04′50″S, 30°11′42″E)

Appendix 4. Africa Albers Equal Area Conic Projection Information

Projection: Africa_Albers_Equal_Area_Conic
  Alias: Kelp_Project_RAND_ALBERS
  Abbreviation:
  Remarks:
Projection: Albers
Parameters:
  False_Easting: 0.000000
  False_Northing: 0.000000
  Central_Meridian: 25.000000
  Standard_Parallel_1: 20.000000
  Standard_Parallel_2: -23.000000
  Latitude_Of_Origin: 0.000000
Linear Unit: Meter (1.000000)
Geographic Coordinate System:
  Name: GCS_WGS_1984
  Alias:
  Abbreviation:
  Remarks:
  Angular Unit: Degree (0.0174532925199433299)
  Prime Meridian: Greenwich (0.000000000000000000)
  Datum: D_WGS_1984
    Spheroid: WGS_1984
      Semimajor Axis: 6378137.000000000000000000
      Semiminor Axis: 6356752.314245179300000000
      Inverse Flattening: 298.257223563000030000

Appendix 5. Visual Basic code used in spatial data creation.

For calculating the area of the kelp beds in the base unit of the projection (Albers Equal Area Conic):

```
>Area
>Dim dblArea as double
>Dim pArea as IArea
>Set pArea = [shape]
>dblArea = pArea.area

>Length
>Dim dblLength as double
>Dim pCurve as ICurve
>Set pCurve = [shape]
>dblLength = pCurve.Length
```

The following code was obtained from Ianko Tchoukanski and used to get the start and end point of lines:

```
'polyline_Get_X_ToPoint.cal

On Error Resume Next
Dim pMxDoc As IMxDocument
Dim pMap As IMap
Dim pCurve As ICurve
Dim pToPoint As IPoint
Dim dXTo As Double
Dim bSrefFromMap As Boolean
'======================
'Adjust the parameter below
'bSrefFromMap = True ==> the coordinates will be calculated in the projection of the Map
'bSrefFromMap = False ==> the coordinates will be calculated in the projection of the data
bSrefFromMap = True
'======================
If (Not IsNull([Shape])) Then
  Set pCurve = [Shape]
  If (Not pCurve.IsEmpty) Then
    If (bSrefFromMap) Then
      Set pMxDoc = ThisDocument
      Set pMap = pMxDoc.FocusMap
      pCurve.Project pMap.SpatialReference
    End If
    Set pToPoint = pCurve.ToPoint
    dXTo = pToPoint.X
'polyline_Get_X_FromPoint.cal
On Error Resume Next
Dim pMxDoc As IMxDocument
Dim pMap As IMap
Dim pCurve As ICurve
Dim pFromPoint As IPoint
Dim dXFrom As Double
Dim bSrefFromMap As Boolean
'======================
'Adjust the parameter below
'bSrefFromMap = True ==> the coordinates will be calculated in the projection of the Map
'bSrefFromMap = False ==> the coordinates will be calculated in the projection of the data
bSrefFromMap = True
'======================
If (Not IsNull([Shape])) Then
  Set pCurve = [Shape]
  If (Not pCurve.IsEmpty) Then
    If (bSrefFromMap) Then
      Set pMxDoc = ThisDocument
```

```
      Set pMap = pMxDoc.FocusMap
      pCurve.Project pMap.SpatialReference
    End If
    Set pFromPoint = pCurve.FromPoint
    dXFrom = pFromPoint.X
  End If
End If
```

APPENDIX 6. Image header information for Landsat 5 image.

PRODUCT =99038783-01
WRS =175/08400
ACQUISITION DATE =19910629
SATELLITE =L5 INSTRUMENT =TM10
PRODUCT TYPE =ORBIT ORIENTED
PRODUCT SIZE =FULL SCENE
TYPE OF GEODETIC PROCESSING =SYSTEMATIC
RESAMPLING =D6 RAD
GAINS/BIASES =

    00.00398/-0.0100
    00.00964/-0.0232
    00.00540/-0.0078
    00.01043/-0.0193
    00.00235/-0.0080
    00.00000/0.00000
    00.00154/-0.0040

TAPE SPANNING FLAG=1/1
START LINE #= 1 LINES PER VOL=40096
ORIENTATION = -8.53
PROJECTION =UTM USGS
PROJECTION # = 1 USGS MAP ZONE = 34 USGS PROJECTION PARAMETERS =

    0.184133384345779D+02 -0.346204262563385D+02 0.000000000000000D+00
    0.000000000000000D+00 0.000000000000000D+00 0.000000000000000D+00
    0.000000000000000D+00 0.000000000000000D+00 0.000000000000000D+00
    0.000000000000000D+00 0.000000000000000D+00 0.000000000000000D+00
    0.000000000000000D+00 0.000000000000000D+00 0.000000000000000D+00

EARTH ELLIPSOID =CLARKE 1880 SEMI-MAJOR AXIS =6378249.145 SEMI-MINOR AXIS =6356514.967
PIXEL SIZE =30.00
PIXELS PER LINE= 6920
LINES PER IMAGE= 5728

    UL 0173916.0303E 334313.3616S 189958.549 6264097.089
    UR 0193603.1152E 340008.3680S 370787.134 6236983.526
    LR 0191136.0365E 353100.9753S 336168.317 6068413.361
    LL 0171231.3473E 351333.3949S 154894.706 6095593.651

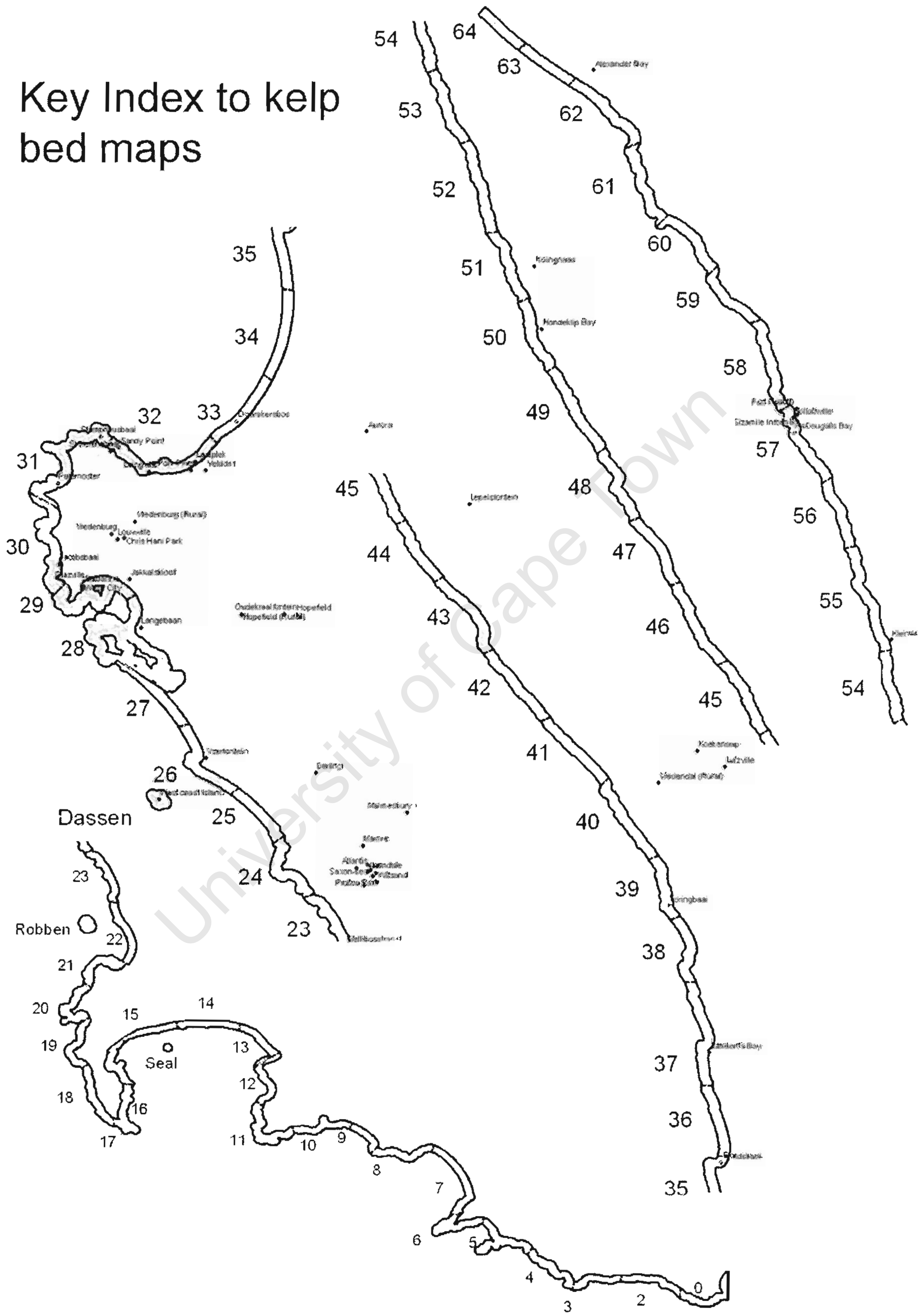
BANDS PRESENT =1234567
BLOCKING FACTOR = 1
RECORD LENGTH = 6920
SUN ELEVATION =20
SUN AZIMUTH = 41
CENTER 0182448.0184E 343713.5345S
262539.114 6165135.595 3386 2865
OFFSET=-265 REVB

Appendix 7. Metadata information summary of CIR 2005 photography.

Note: The reason for the non-overlap of kelp beds and water in the analysis is due to coastline dataset inaccuracies and (in fewer instances) misidentification of non-kelp pixels as being kelp.

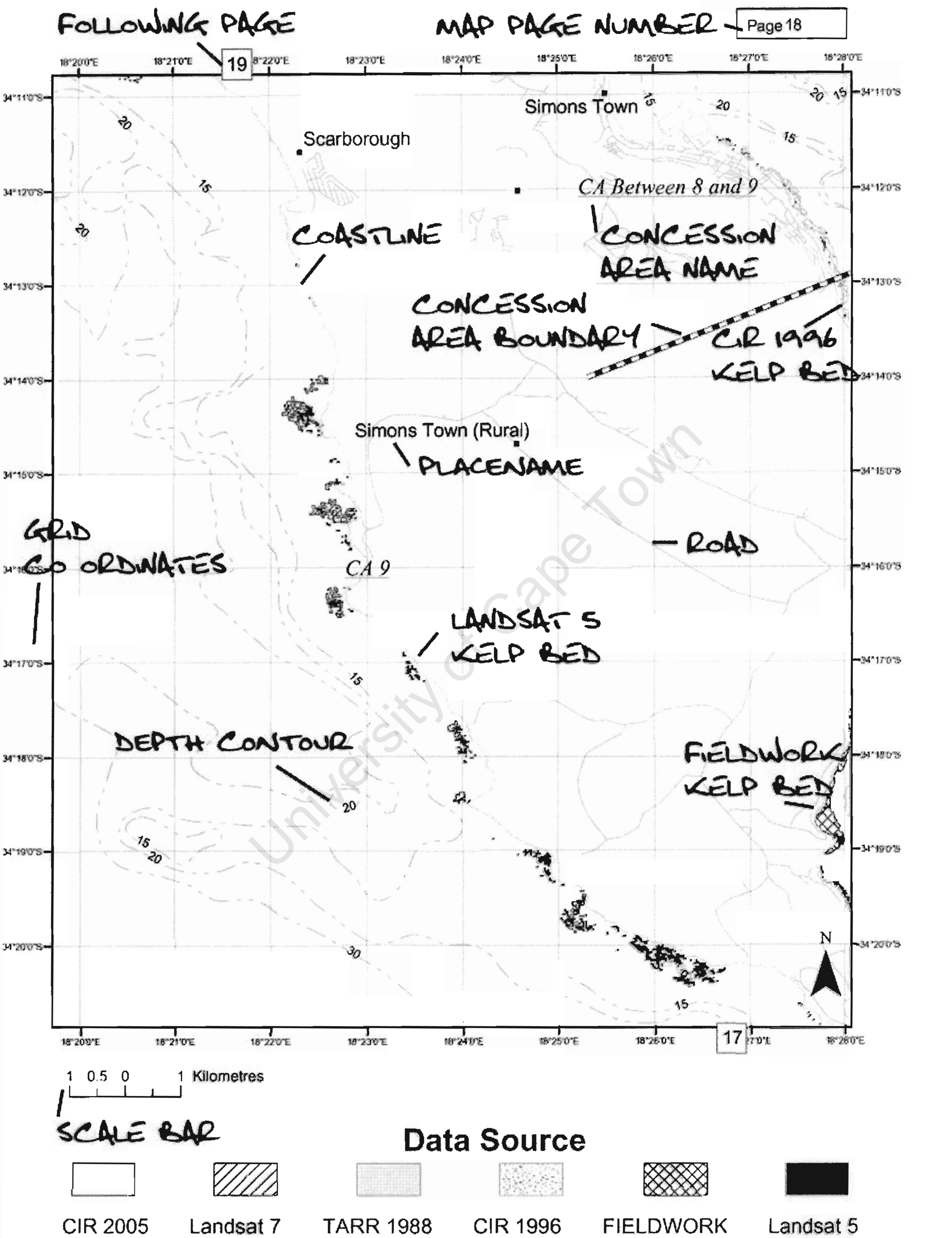
Metadata ID Tag	Typical Value or Range
Strip #	1-7 (The * is for images not used in the final mosaic)
Photo #	1-159
Unrectified Image Name	e.g. "CIR_image-00112.jpg"
Photo Reference	1-587
Day	Mon, Tue or Fri
Month	March
Date	11, 28, 29
Year	2005
Time	08:29:02 AM - 09:29:29 AM
Lon	17.2200583 E - 20.07028 E
Lat	34.8439233 S - 30.181685 S
Height Flown	836.7 - 1529.8 metres
Track (deg)	1.1 – 359.9
GPS Time	06:34:28 AM - 09:50:43 AM
Angle of the sun measured from horizon up	21.729148 - 54.97979 degrees
Angle of the sun measured from north	24.057588 - 80.889643 degrees
Differential	2
Pdop	0.9 – 1.5
#SV's	7 – 10
Strip #	e.g. "2s"
Geo-Rectified Image Name	e.g. "CIR_image-00114_rect"
Scale/Ground Pixel size	0.75, 1 metre
Bands	Infra red, Red, Green
Frequencies of the electromagnetic spectrum	Green 500-610 nm Red 610-710 nm NIR 750-850 nm
Geographic extent of photo	Included in .ers header file
H/V Accuracies	+-5m
Sensor Information	DuncanTech Ms3100 3CCD Sensor With 8mm lens CCDs (1312 X 1040 pixels)
Medium of Photo	Digital (3band configuration)
Aerial Photography done by	Geospace International Pty Ltd
Contact Person	Philip Minnaar
Tel #	+27 12 348 4586
Ground Control/Truthing	GPS data and Tie points in bundle block

Appendix 8. Kelp Inventory Map Index

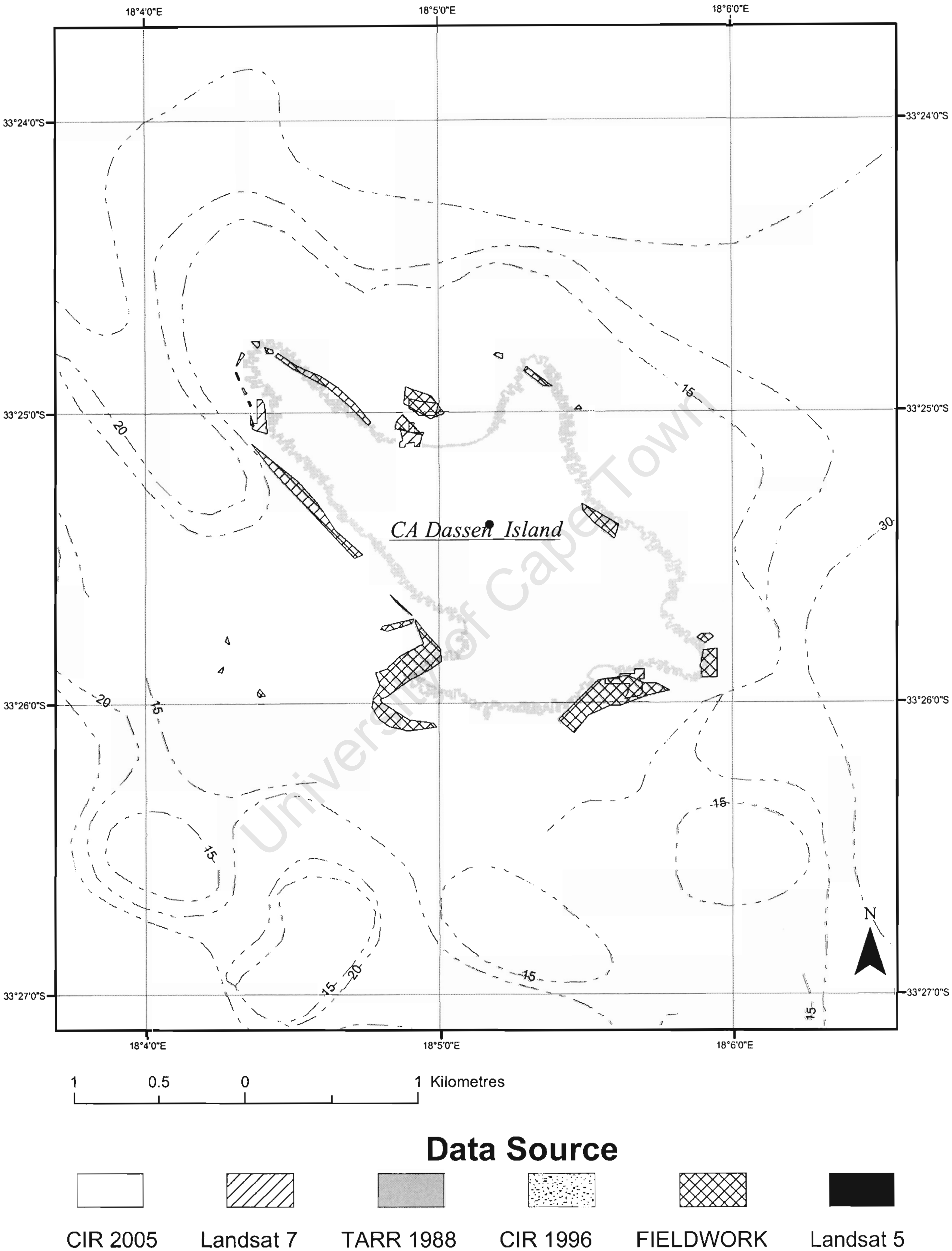


Appendix 8 Map index page of data sources and corresponding map page numbers.

Landsat5	Landsat7	Tarr	Fieldwork	CIR1996	CIR2005
Seal	4	3	17	16	2
6	5	4	19	17	3
7	6	5	Dassen	19	4
8	7	6		29	35
9	8	7		30	36
10	9	8		31	37
11	10	9		32	38
12	11	10		43	39
13	16	11		44	40
15	17			45	41
16	18			46	42
17	19			47	43
18	21			48	44
19	23			50	
20	28			51	
21	30			52	
	31			53	
	32			54	
	35			55	
	36			56	
	39			57	
	54			58	
	55			59	
	Dassen			60	
	Robben			61	
				62	

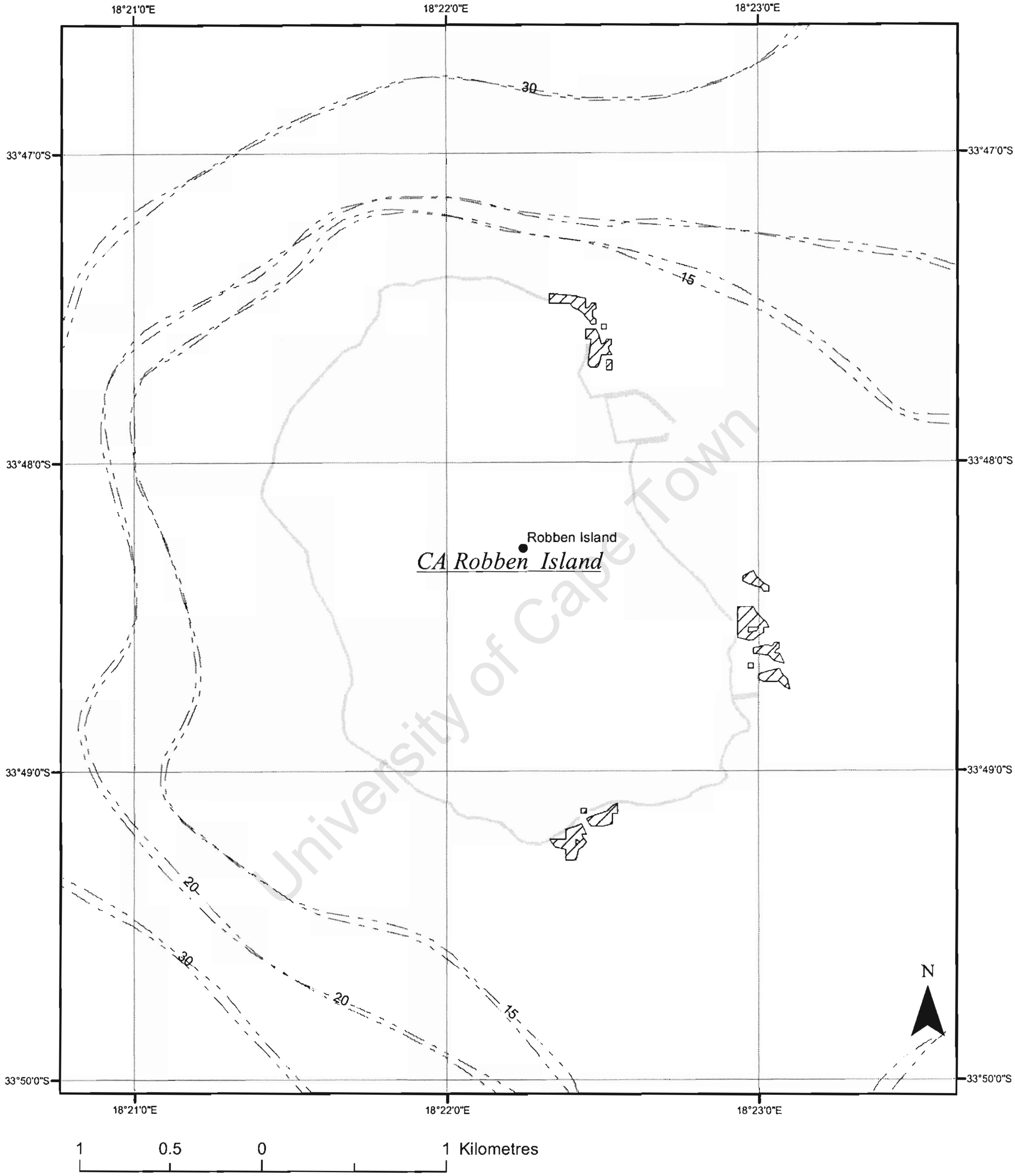

FOLLOWING PAGE
MAP PAGE NUMBER
Page 18
19
18°20'0"E
18°21'0"E
18°22'0"E
18°23'0"E
18°24'0"E
18°25'0"E
18°26'0"E
18°27'0"E
18°28'0"E
34°11'0"S
34°12'0"S
34°13'0"S
34°14'0"S
34°15'0"S
34°16'0"S
34°17'0"S
34°18'0"S
34°19'0"S
34°20'0"S
Simons Town
Scarborough
CA Between 8 and 9
COASTLINE
CONCESSION AREA NAME
CONCESSION AREA BOUNDARY
CIR 1996 KELP BED
Simons Town (Rural)
PLACENAME
GRID CO ORDINATES
ROAD
CA 9
LANDSAT 5 KELP BED
DEPTH CONTOUR
FIELDWORK KELP BED
15
20
30
N
17
1 0.5 0 1 Kilometres
SCALE BAR
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

Page Dassen



18°4'0"E
18°5'0"E
18°6'0"E
33°24'0"S
33°25'0"S
33°26'0"S
33°27'0"S
CA Dassen_Island
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

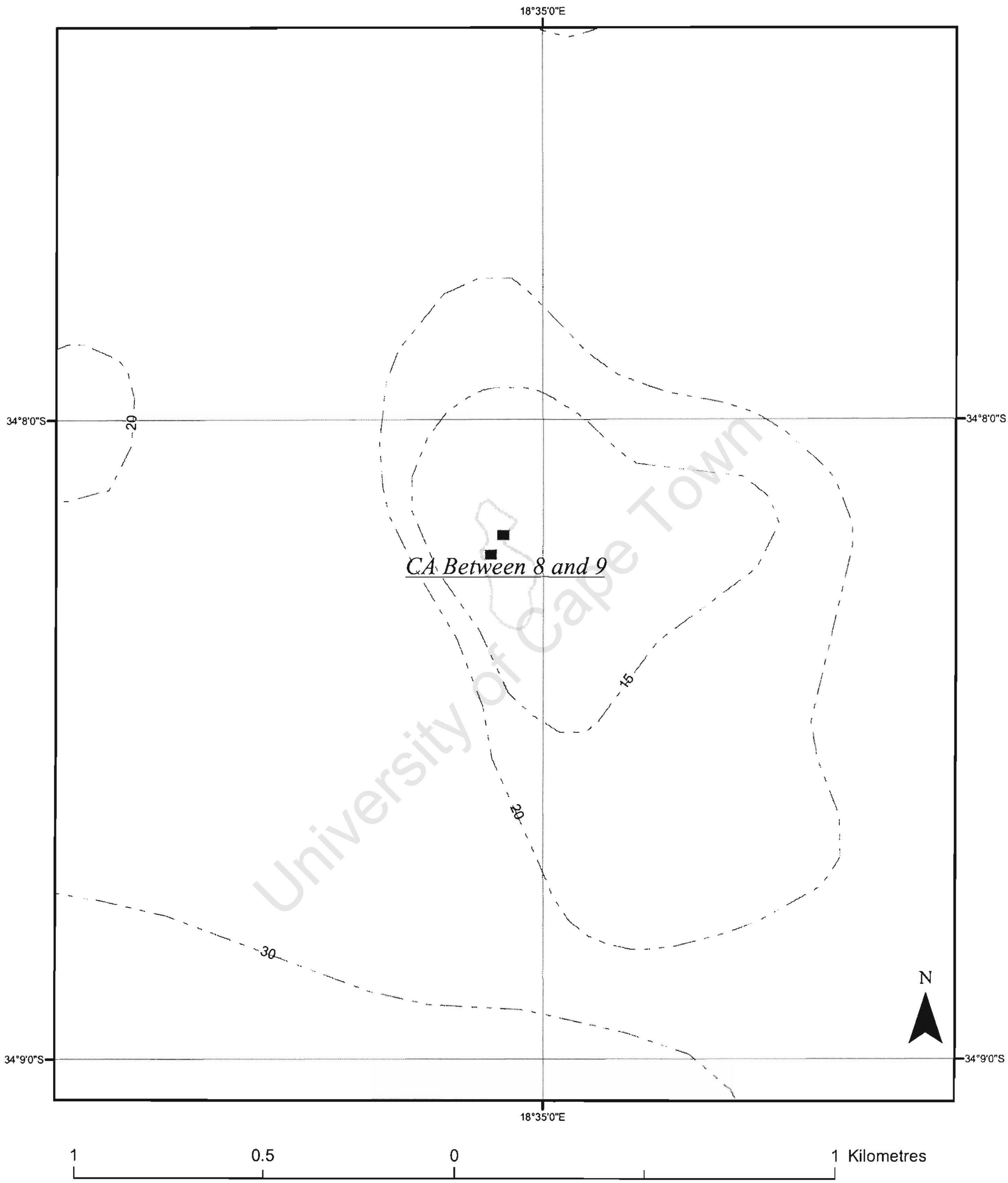
Page Robben



Data Source

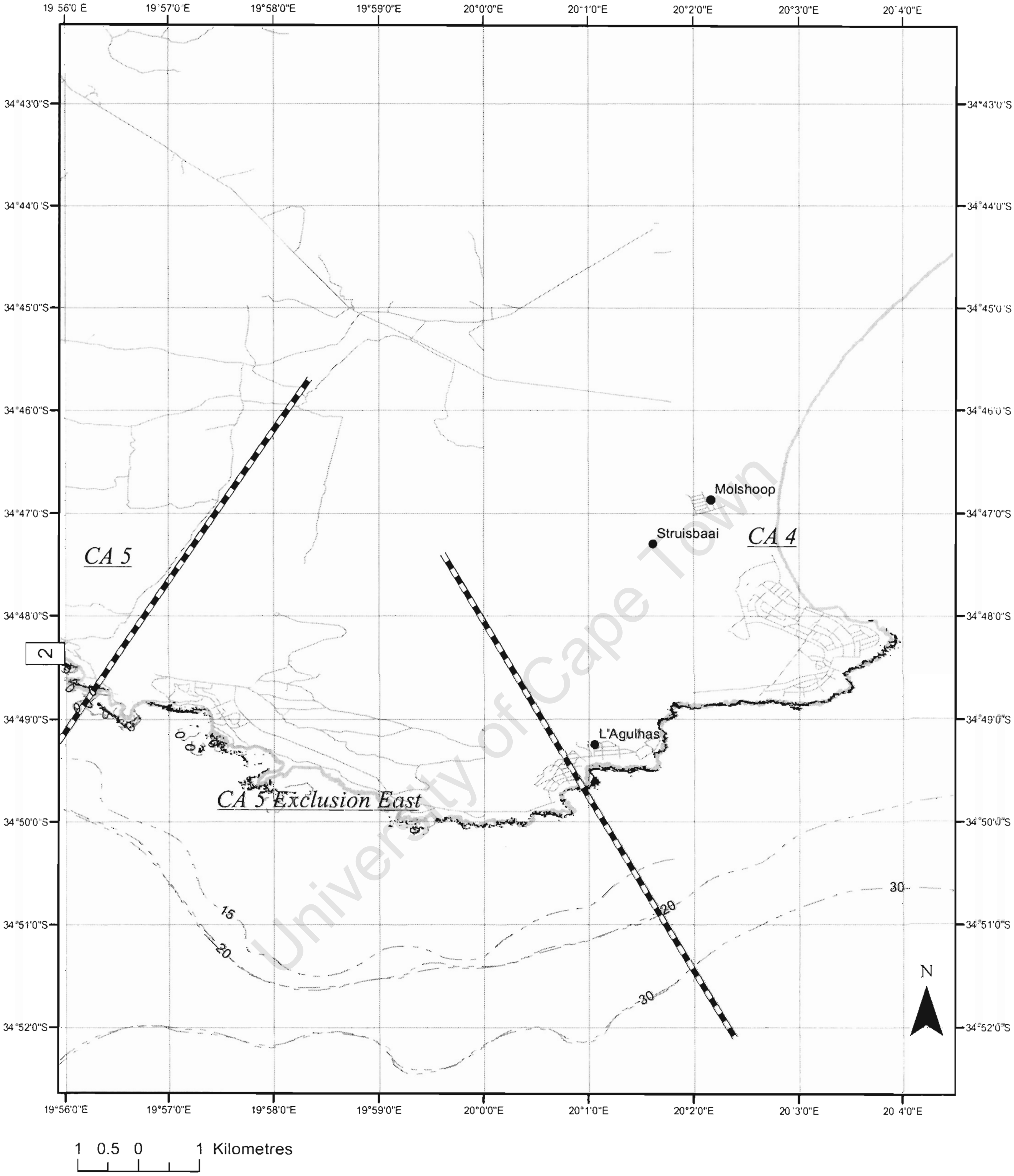
CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5

Page Seal



Data Source

CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5



Data Source

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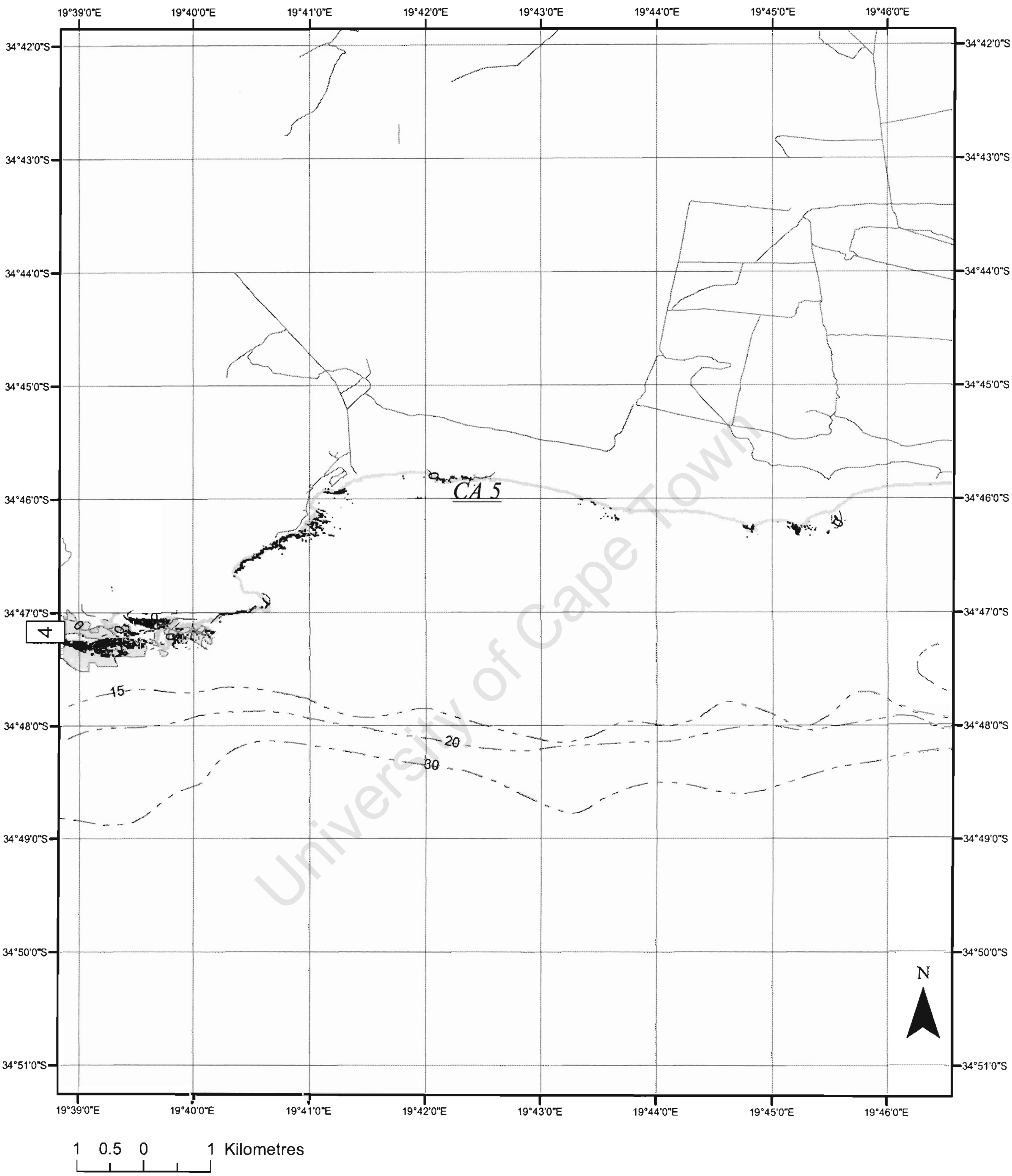

Data Source

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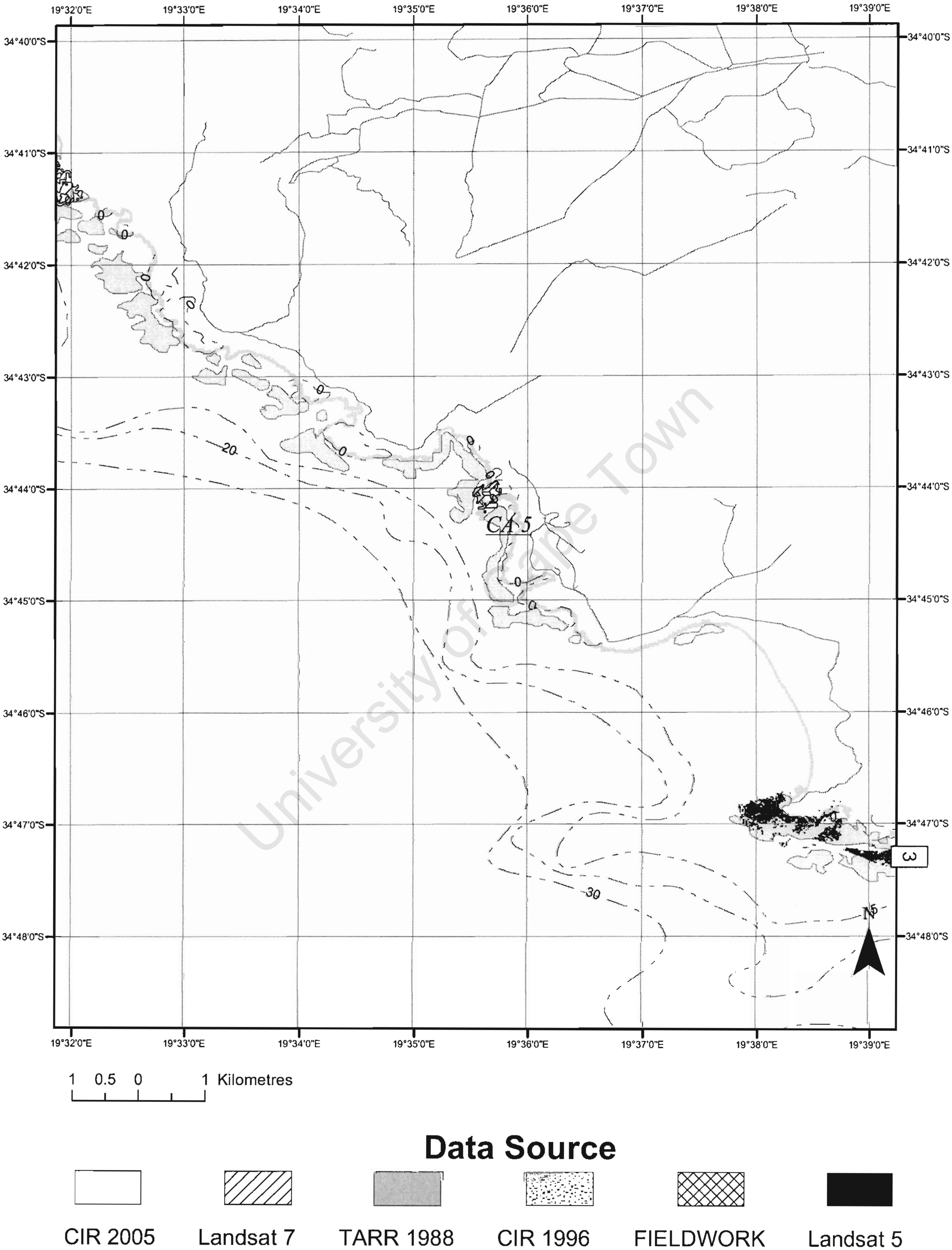
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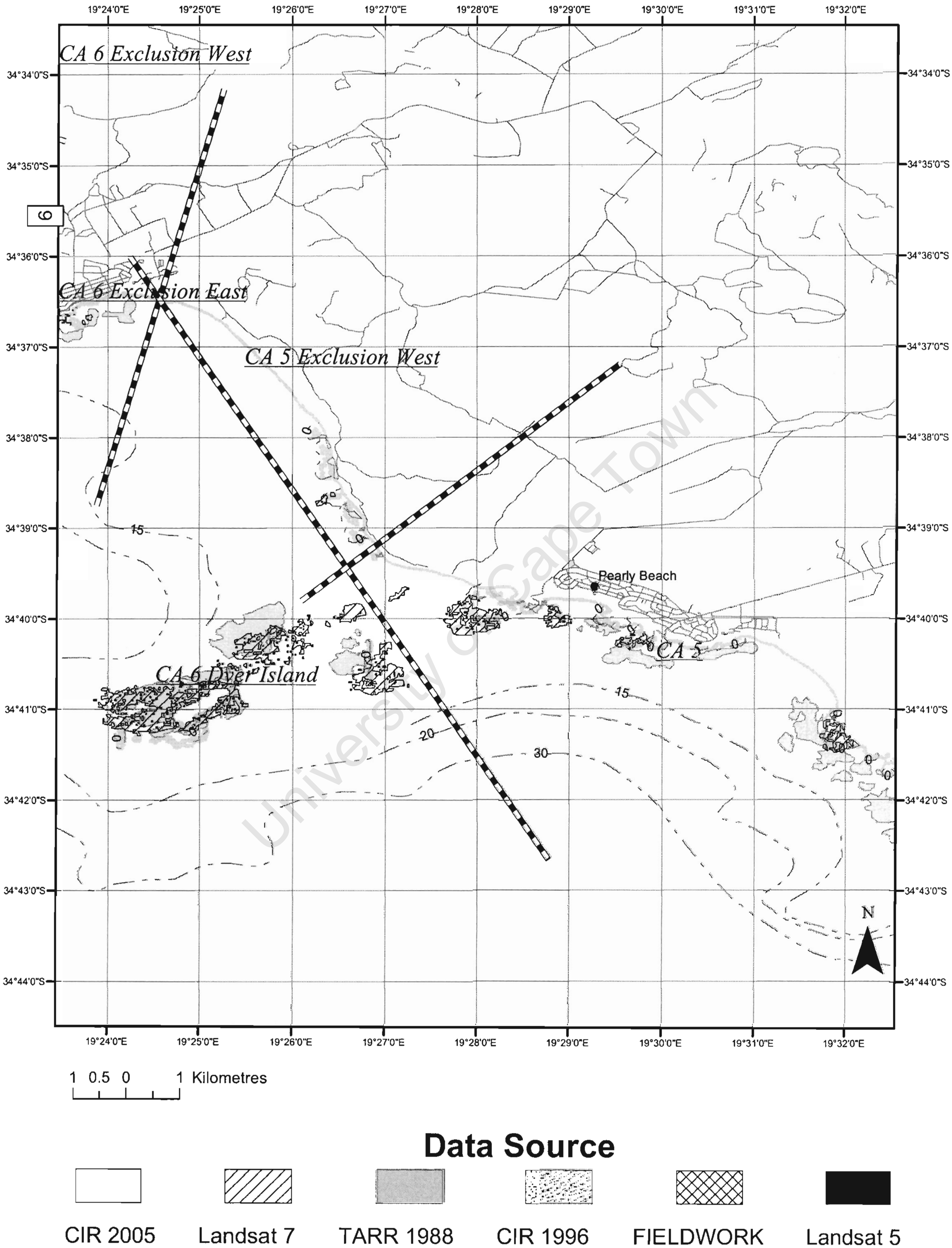
19°35'0"E
19°36'0"E
19°37'0"E
19°38'0"E
19°39'0"E
34°40'0"S
34°41'0"S
34°42'0"S
34°43'0"S
34°44'0"S
34°45'0"S
34°46'0"S
34°47'0"S
34°48'0"S
CA 5
0
20
30
3
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

Page 5

6



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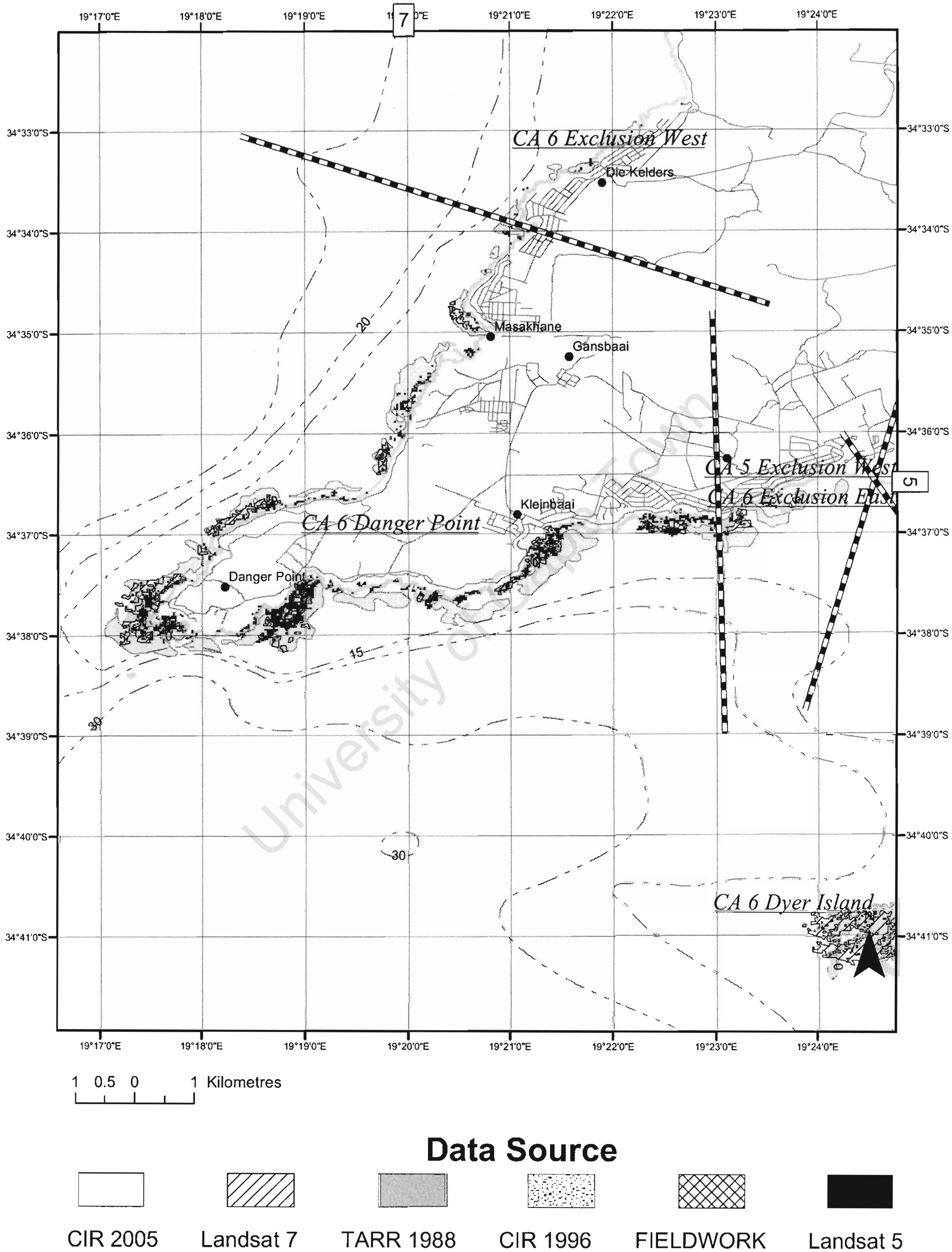
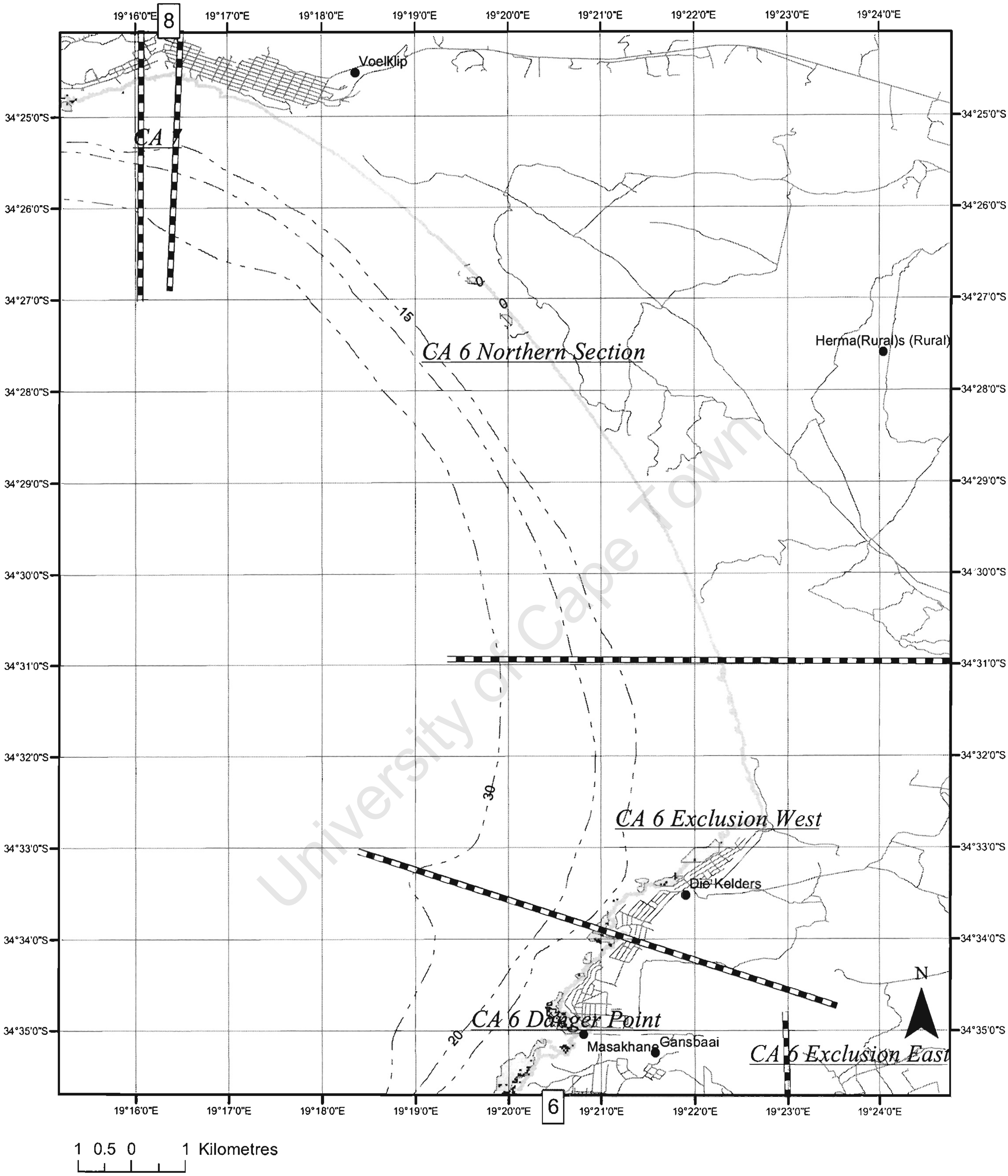
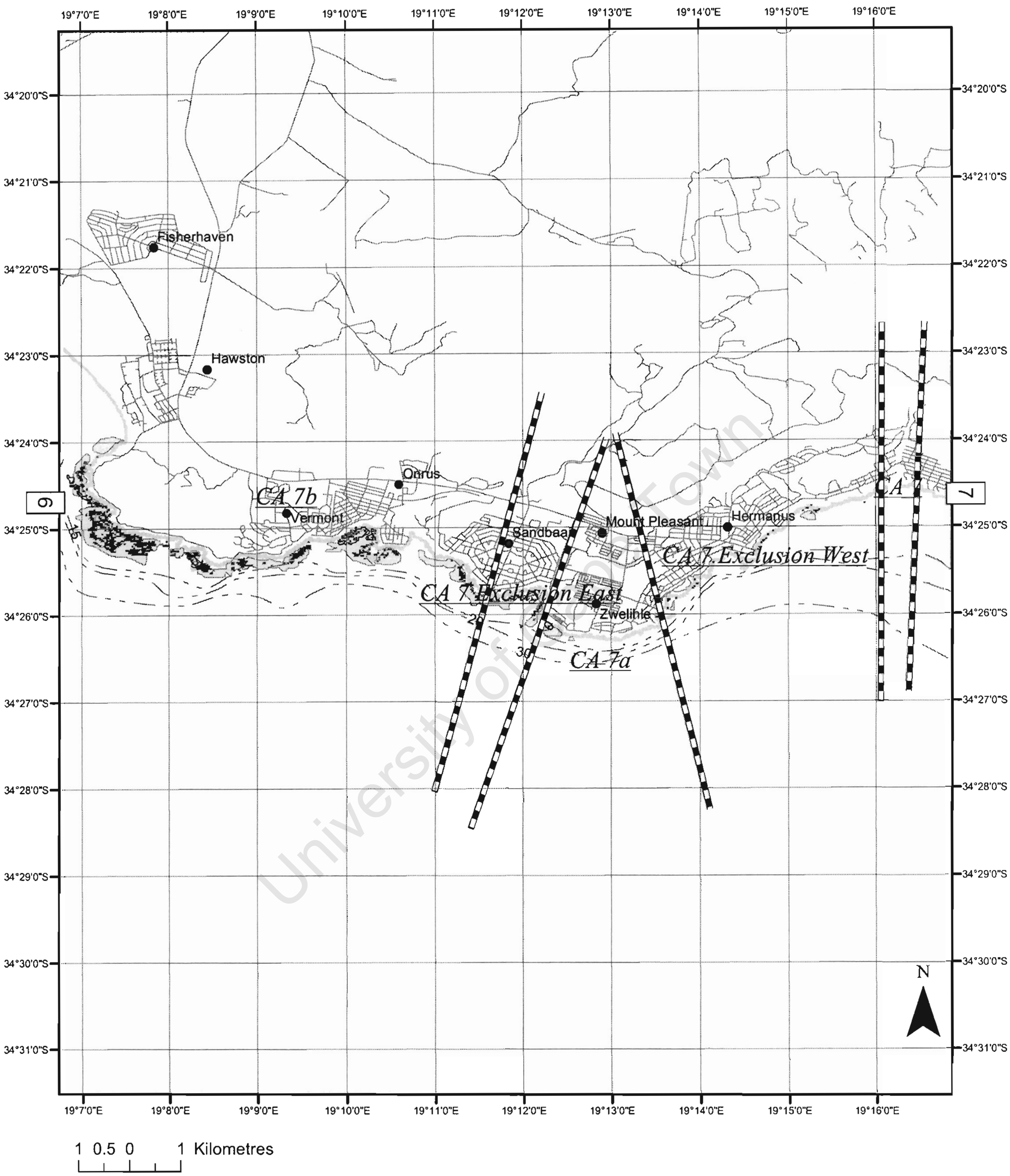
19°27'0"E
19°28'0"E
19°29'0"E
19°30'0"E
19°31'0"E
19°32'0"E
34°34'0"S
34°35'0"S
34°36'0"S
34°37'0"S
34°38'0"S
34°39'0"S
34°40'0"S
34°41'0"S
34°42'0"S
34°43'0"S
34°44'0"S
CA 6 Exclusion West
CA 6 Exclusion East
CA 5 Exclusion West
CA 6 Dyer Island
CA 5
Pearly Beach
15
20
30
0
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


7
5
19°17'0"E
19°18'0"E
19°19'0"E
19°21'0"E
19°22'0"E
19°23'0"E
19°24'0"E
19°20'0"E
34°33'0"S
34°34'0"S
34°35'0"S
34°36'0"S
34°37'0"S
34°38'0"S
34°39'0"S
34°40'0"S
34°41'0"S
CA 6 Exclusion West
Die Kelders
Masakhane
Gansbaai
CA 5 Exclusion West
CA 6 Exclusion East
Kleinbaai
CA 6 Danger Point
Danger Point
CA 6 Dyer Island
20
15
30
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



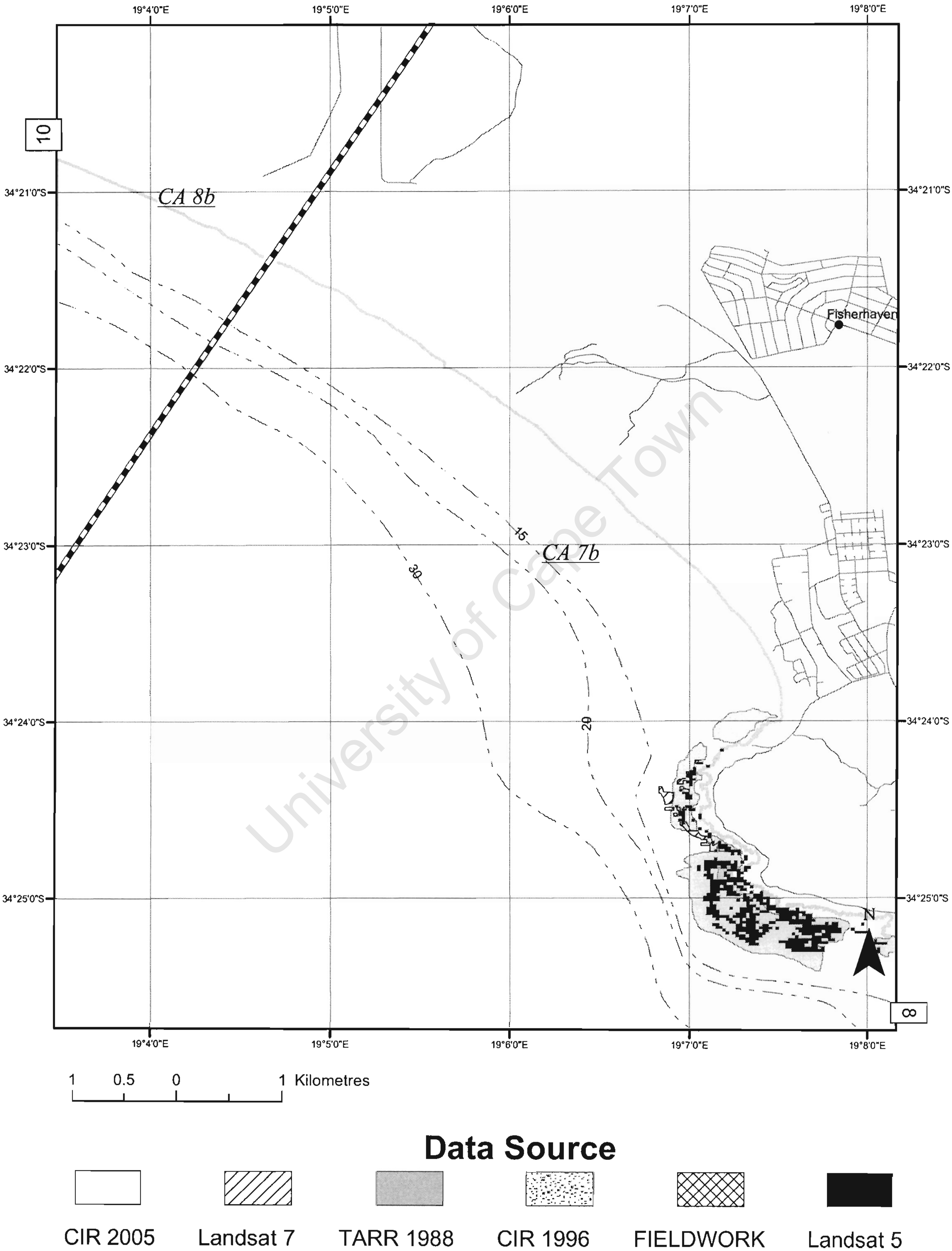
Data Source

CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5



Data Source

CIR 2005	Landsat 7	TARR 1988	CIR 1996	FIELDWORK	Landsat 5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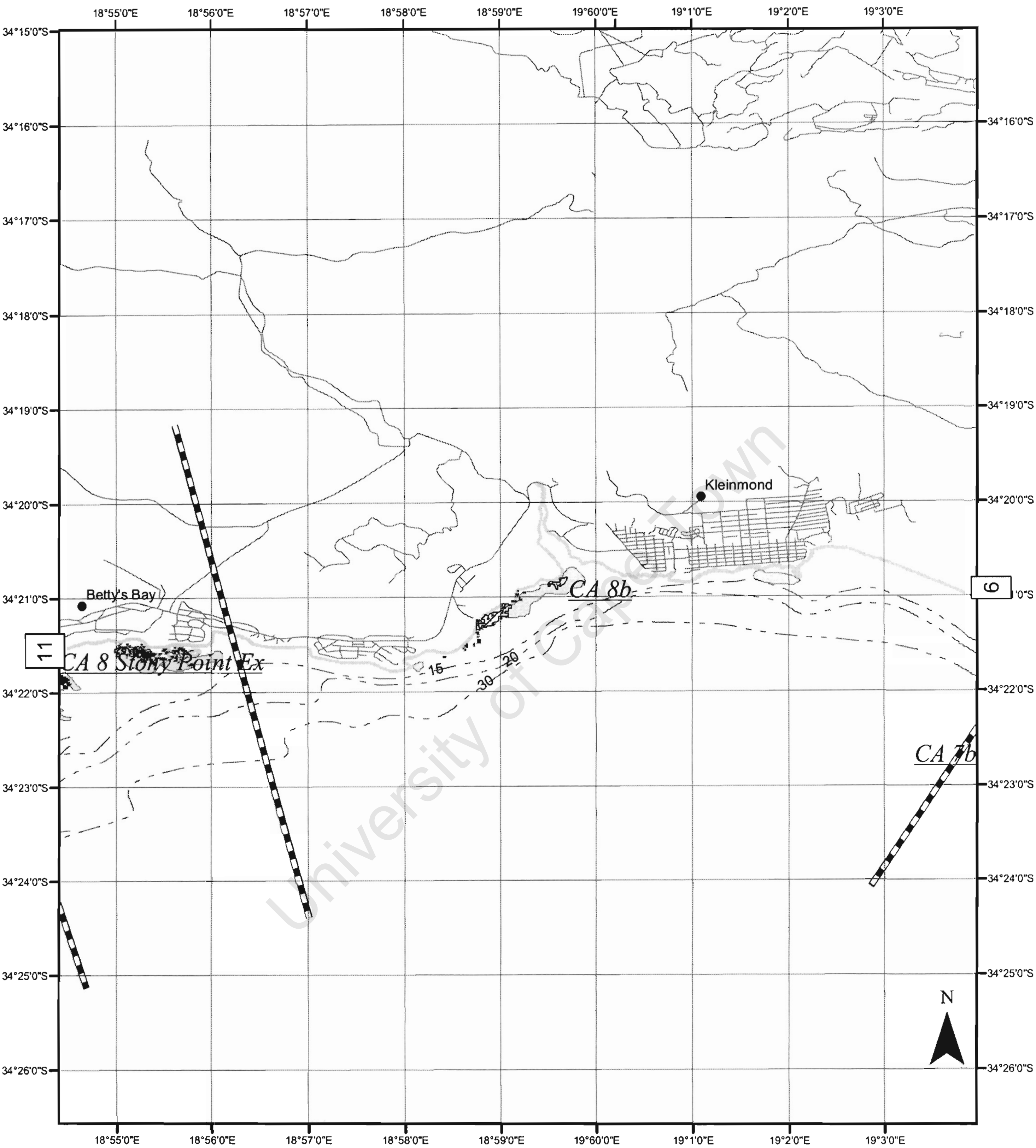
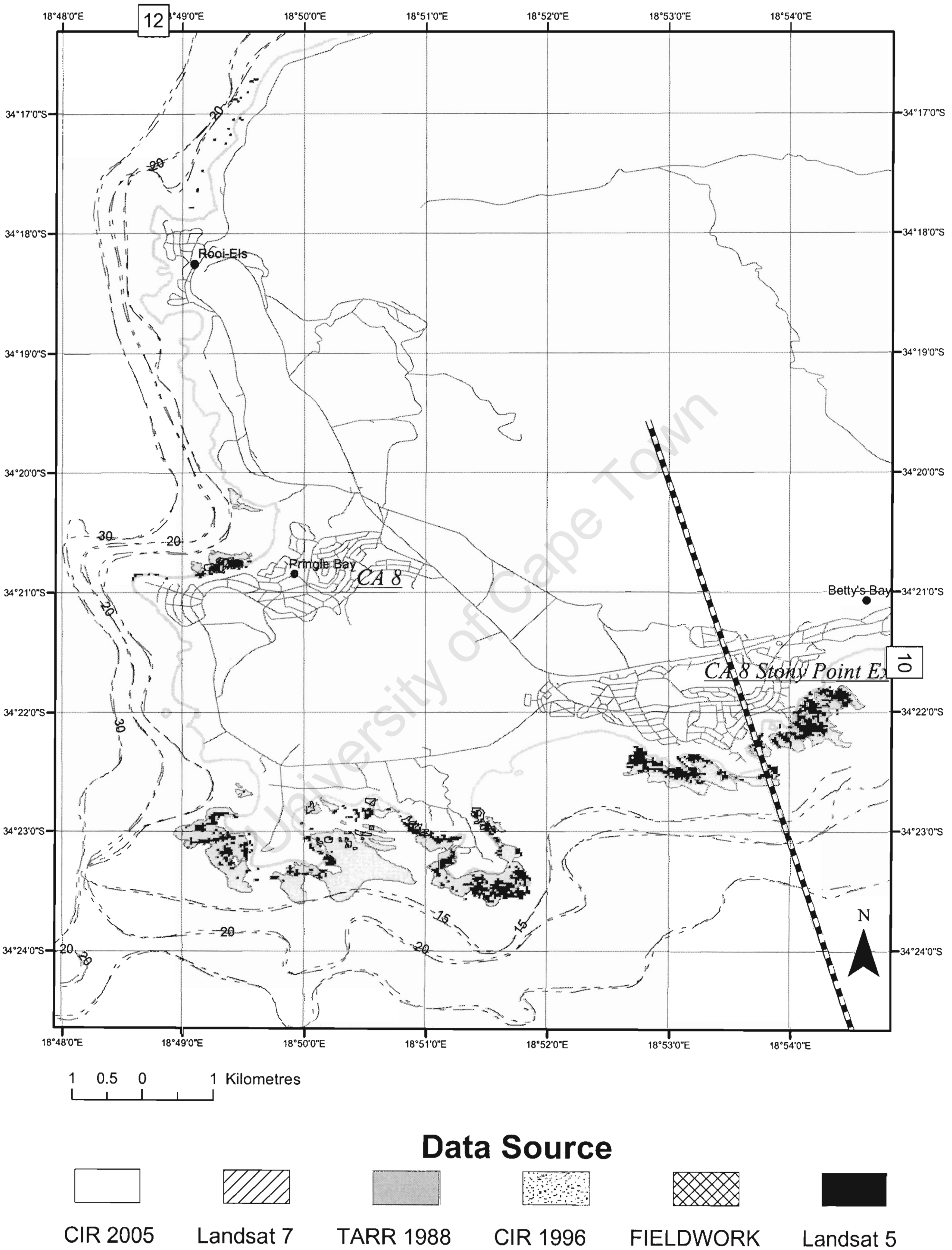
19°5'0"E
19°6'0"E
19°7'0"E
19°8'0"E
10
34°21'0"S
34°22'0"S
34°23'0"S
34°24'0"S
34°25'0"S
CA 8b
CA 7b
Fisherhaven
15
30
20
N
8
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



1 0.5 0 1 Kilometres

Data Source

CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5


12
10
18°48'0"E
18°49'0"E
18°50'0"E
18°51'0"E
18°52'0"E
18°53'0"E
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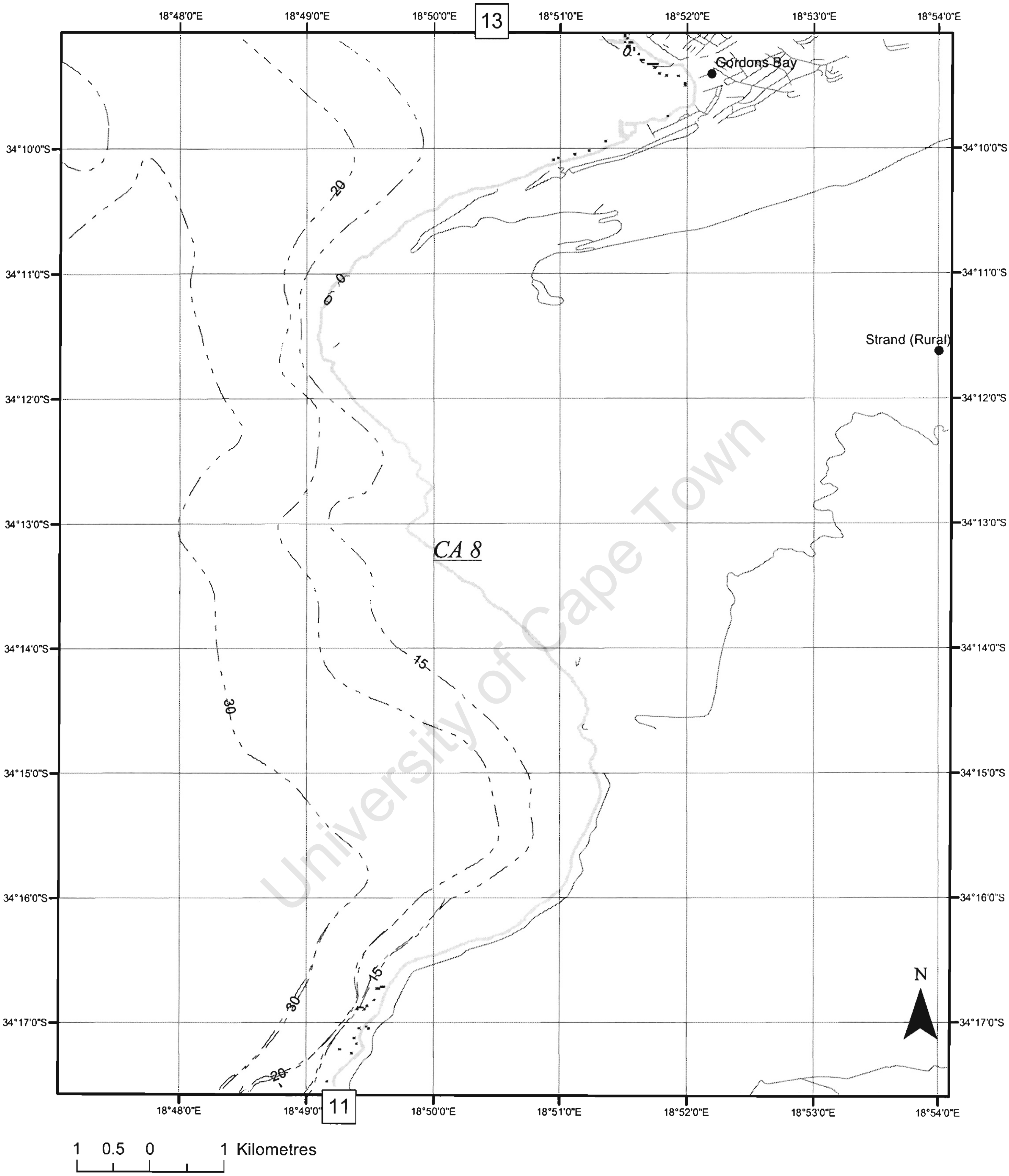
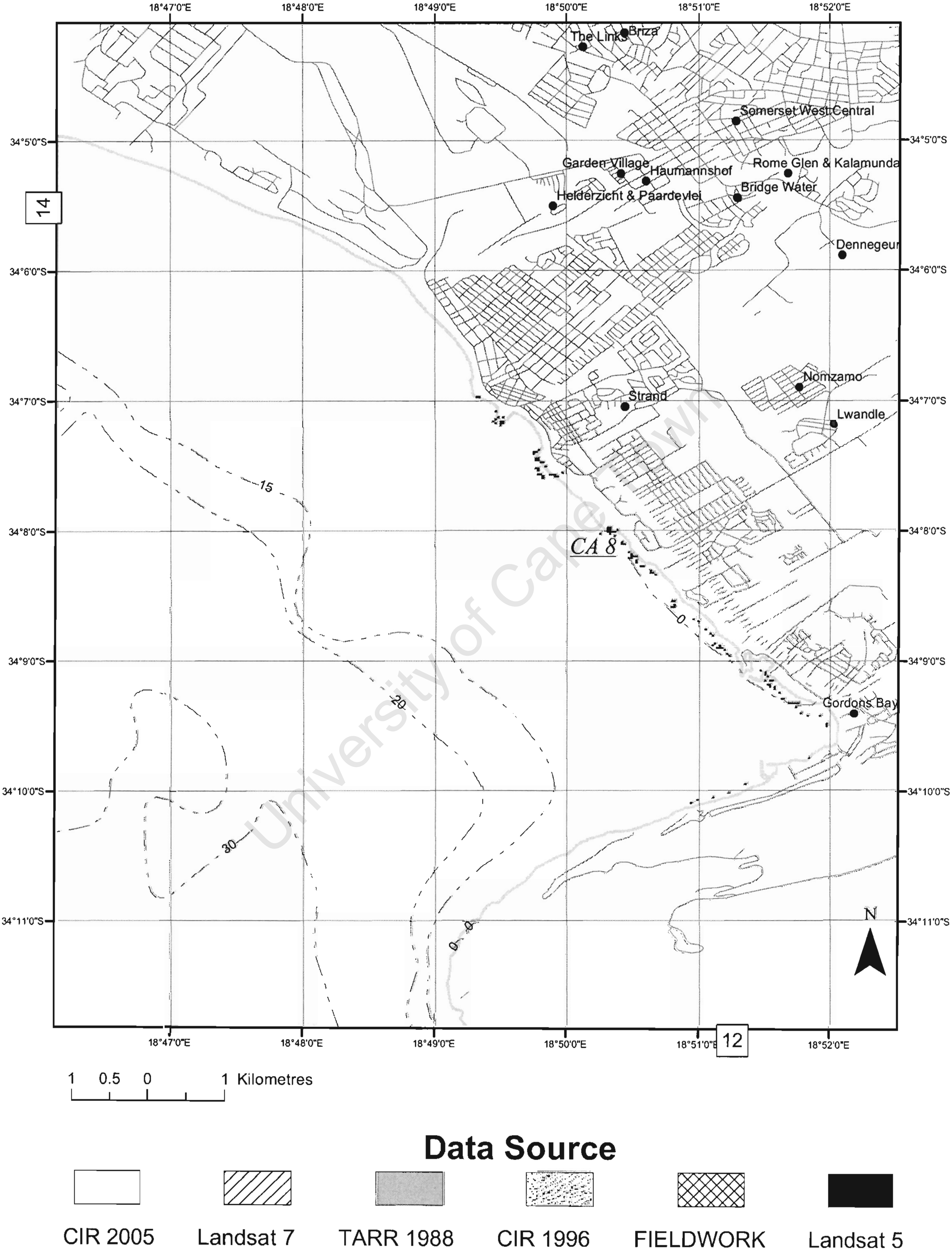
34°18'0"S
34°19'0"S
34°20'0"S
34°21'0"S
34°22'0"S
34°23'0"S
34°24'0"S
Rooi-Els
Pringle Bay
CA 8
Betty's Bay
CA 8 Stony Point Ex
20
30
15
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

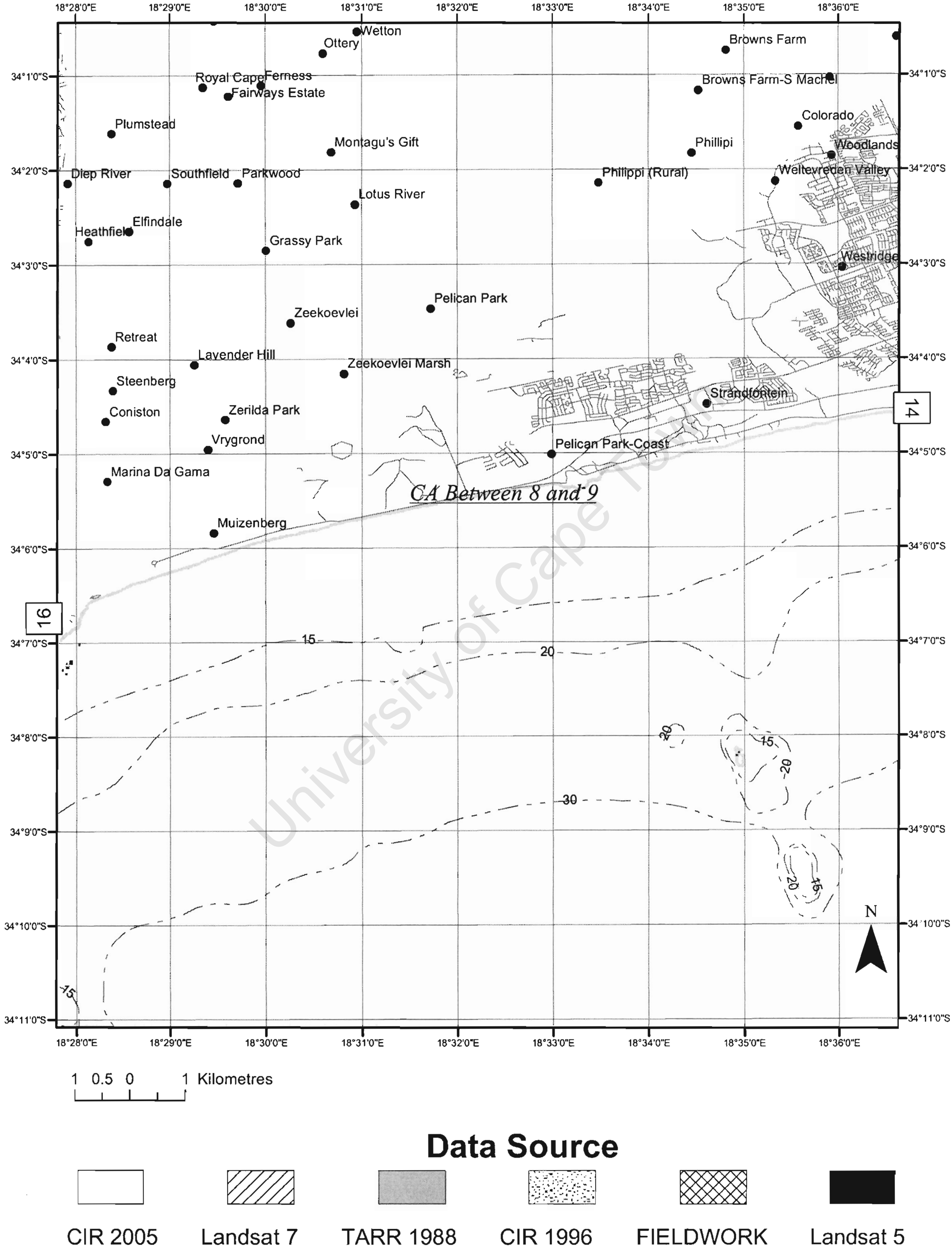


Data Source

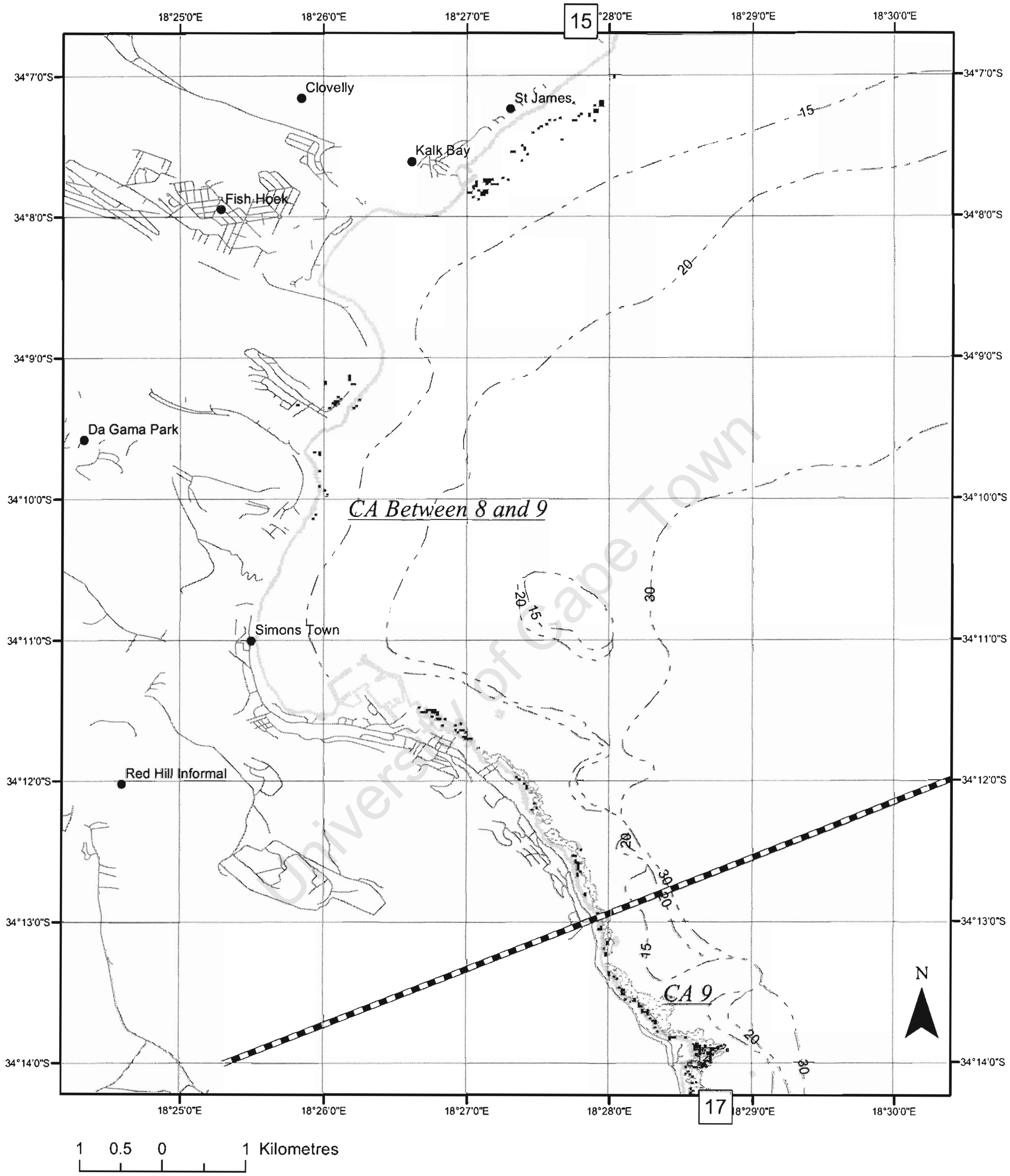
CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5



18°47'0"E
18°48'0"E
18°49'0"E
18°50'0"E
18°51'0"E
18°52'0"E
34°5'0"S
34°6'0"S
34°7'0"S
34°8'0"S
34°9'0"S
34°10'0"S
34°11'0"S
14
12
The Links
Briza
Somerset West Central
Garden Village
Haumannshof
Rome Glen & Kalamunda
Helderzicht & Paardevlei
Bridge Water
Dennegeur
Nomzamo
Strand
Lwandle
Gordons Bay
CA 8
15
20
30
0
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



18°28'0"E
18°29'0"E
18°30'0"E
18°31'0"E
18°32'0"E
18°33'0"E
18°34'0"E
18°35'0"E
18°36'0"E
34°1'0"S
34°2'0"S
34°3'0"S
34°4'0"S
34°5'0"S
34°6'0"S
34°7'0"S
34°8'0"S
34°9'0"S
34°10'0"S
34°11'0"S
Wetton
Ottery
Browns Farm
Royal Cape
Ferness
Fairways Estate
Browns Farm-S Machel
Plumstead
Montagu's Gift
Colorado
Phillipi
Woodlands
Diep River
Southfield
Parkwood
Philippi (Rural)
Weltevreden Valley
Lotus River
Elfindale
Heathfield
Grassy Park
Westridge
Pelican Park
Zeekoevlei
Retreat
Lavender Hill
Zeekoevlei Marsh
Steenberg
Strandfontein
14
Coniston
Zerilda Park
Vrygrond
Pelican Park-Coast
Marina Da Gama
CA Between 8 and 9
Muizenberg
16
15
20
30
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5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18°25'0"E
18°26'0"E
18°27'0"E
18°28'0"E
18°29'0"E
18°30'0"E
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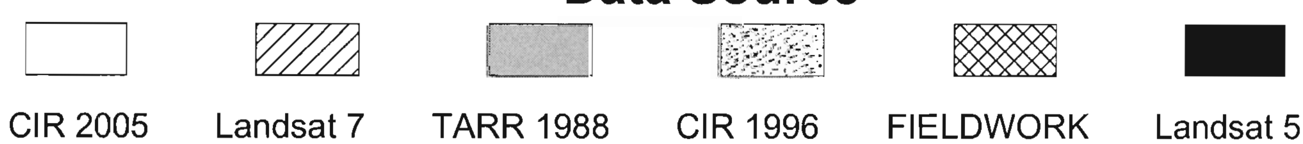
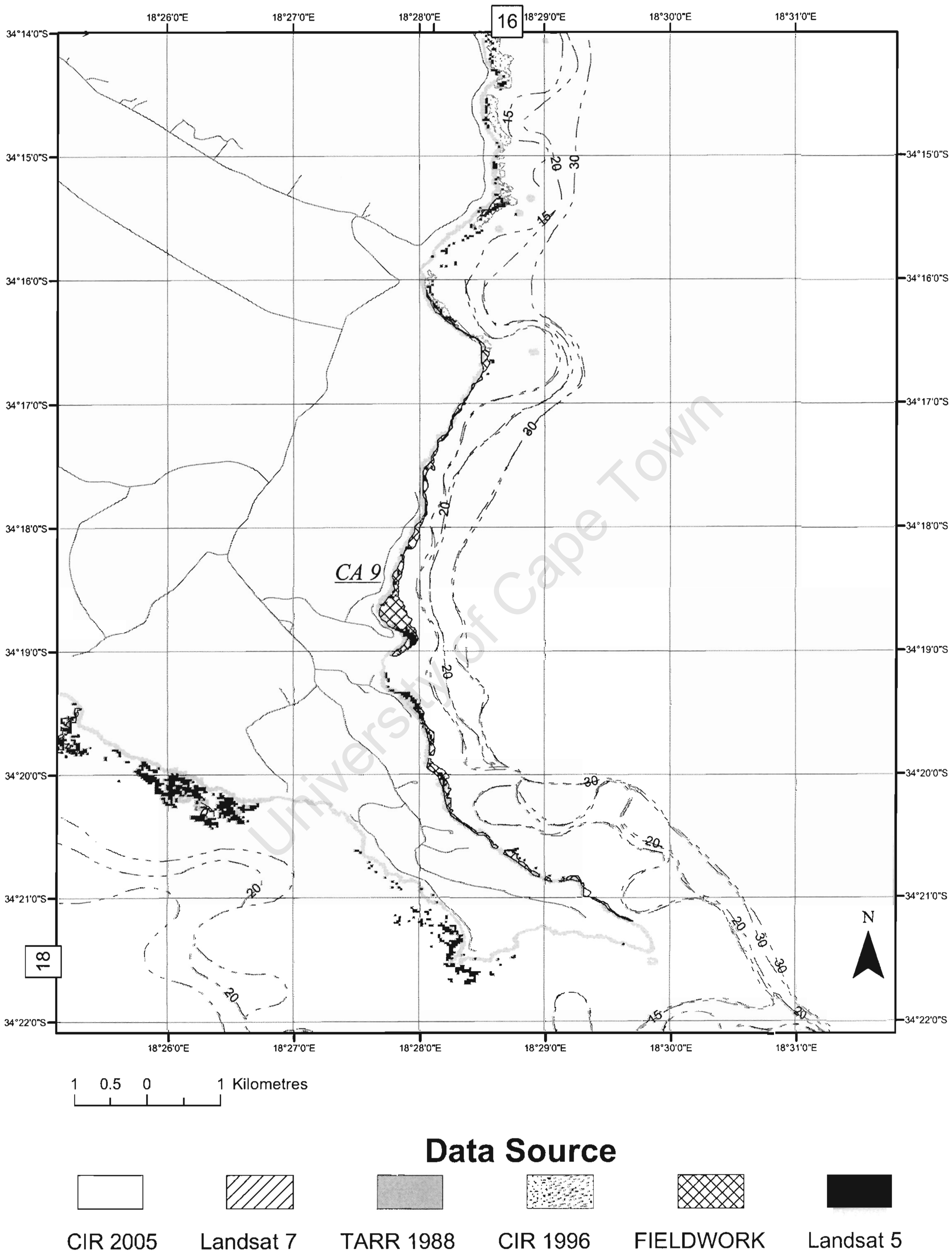
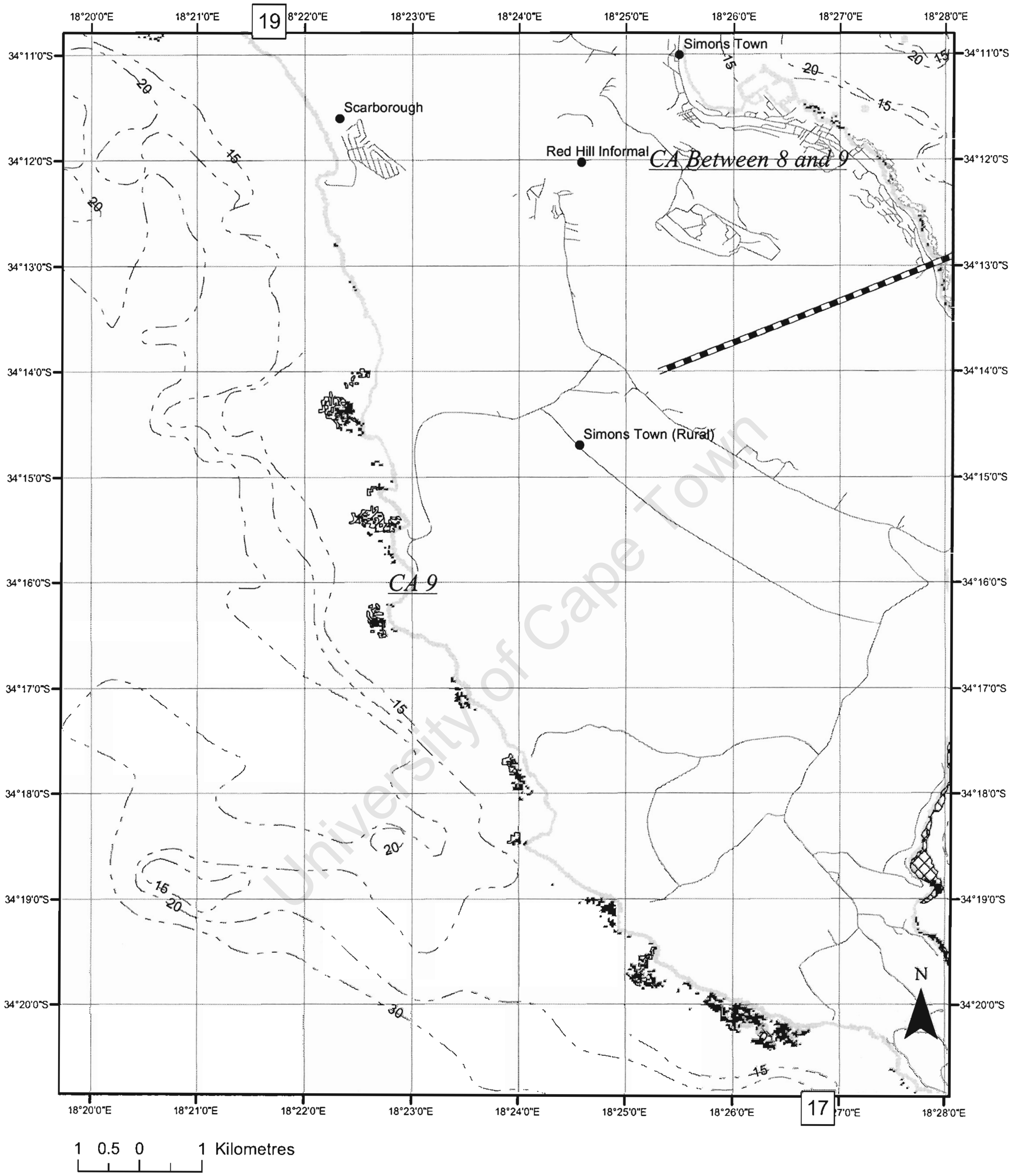
34°8'0"S
34°9'0"S
34°10'0"S
34°11'0"S
34°12'0"S
34°13'0"S
34°14'0"S
Clovelly
St James
Kalk Bay
Fish Hoek
Da Gama Park
Simons Town
Red Hill Informal
CA Between 8 and 9
CA 9
15
20
30
N
17
1 0.5 0 1 Kilometres

Data Source


CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

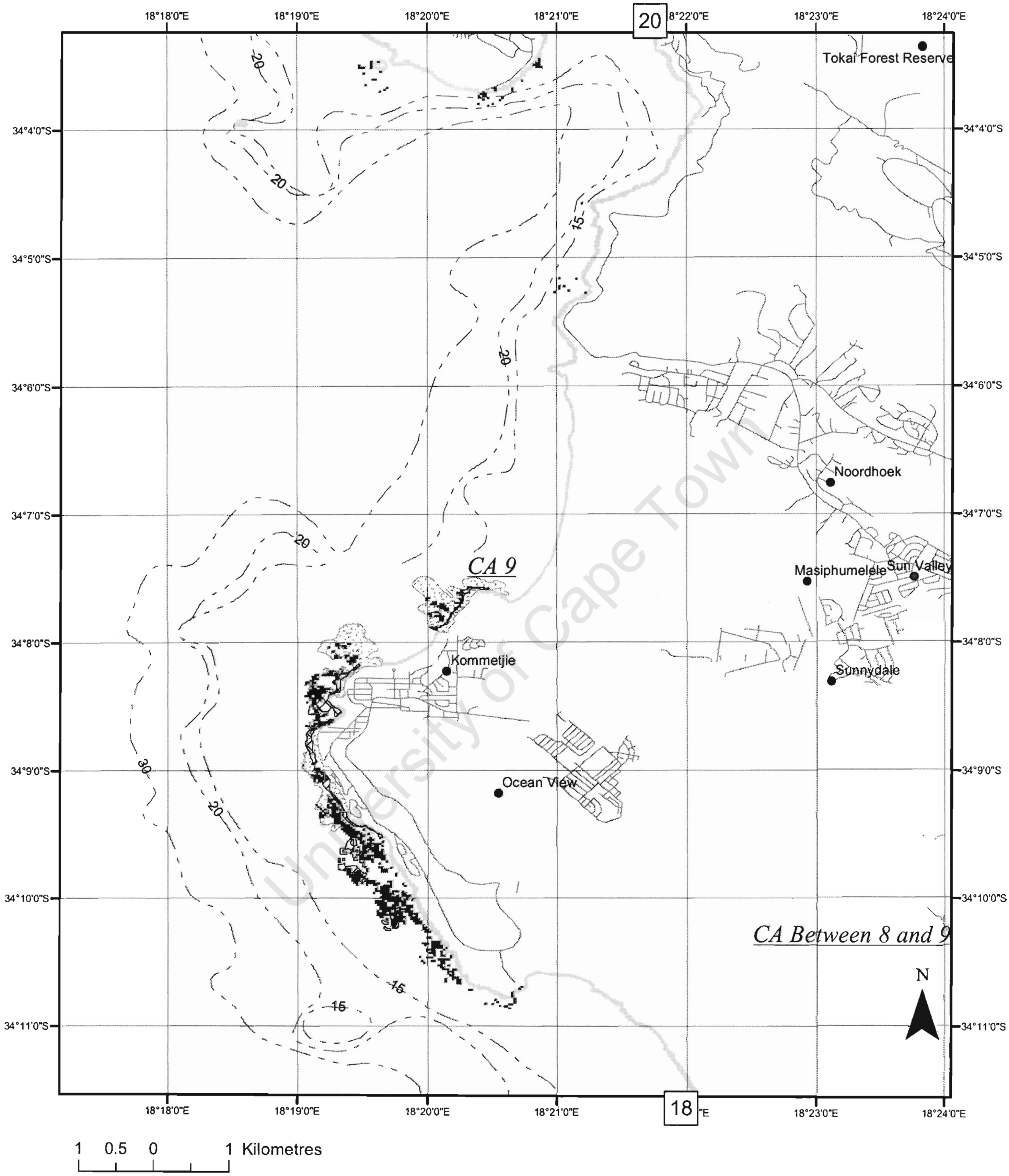


16
18
18°26'0"E
18°27'0"E
18°28'0"E
18°29'0"E
18°30'0"E
18°31'0"E
34°14'0"S
34°15'0"S
34°16'0"S
34°17'0"S
34°18'0"S
34°19'0"S
34°20'0"S
34°21'0"S
34°22'0"S
CA 9
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

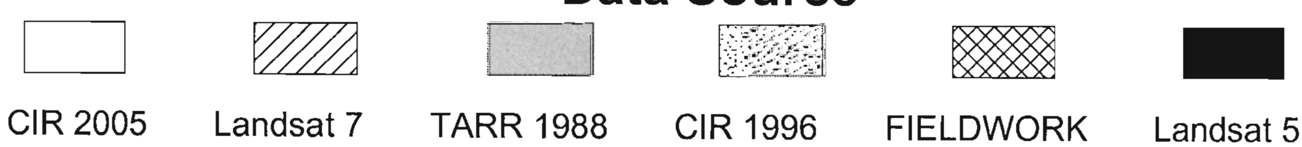


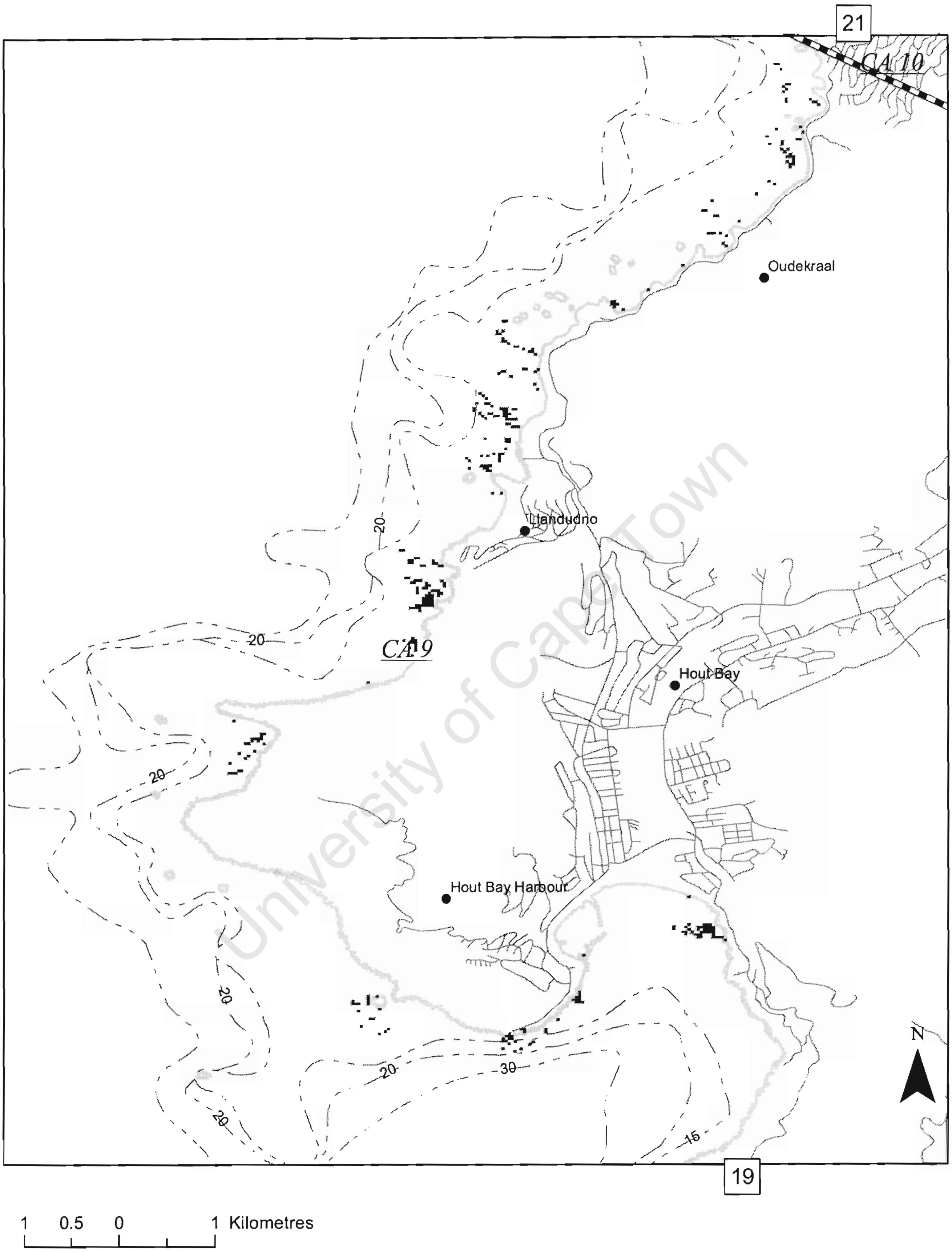
Data Source

CIR 2005	Landsat 7	TARR 1988	CIR 1996	FIELDWORK	Landsat 5


20
18°18'0"E
18°19'0"E
18°20'0"E
18°21'0"E
18°22'0"E
18°23'0"E
18°24'0"E
34°4'0"S
34°5'0"S
34°6'0"S
34°7'0"S
34°8'0"S
34°9'0"S
34°10'0"S
34°11'0"S
Tokai Forest Reserve
Noordhoek
Masiphumelele
Sun Valley
Sunnydale
Kommetjie
Ocean View
CA 9
CA Between 8 and 9
N
20
15
30
18
1 0.5 0 1 Kilometres

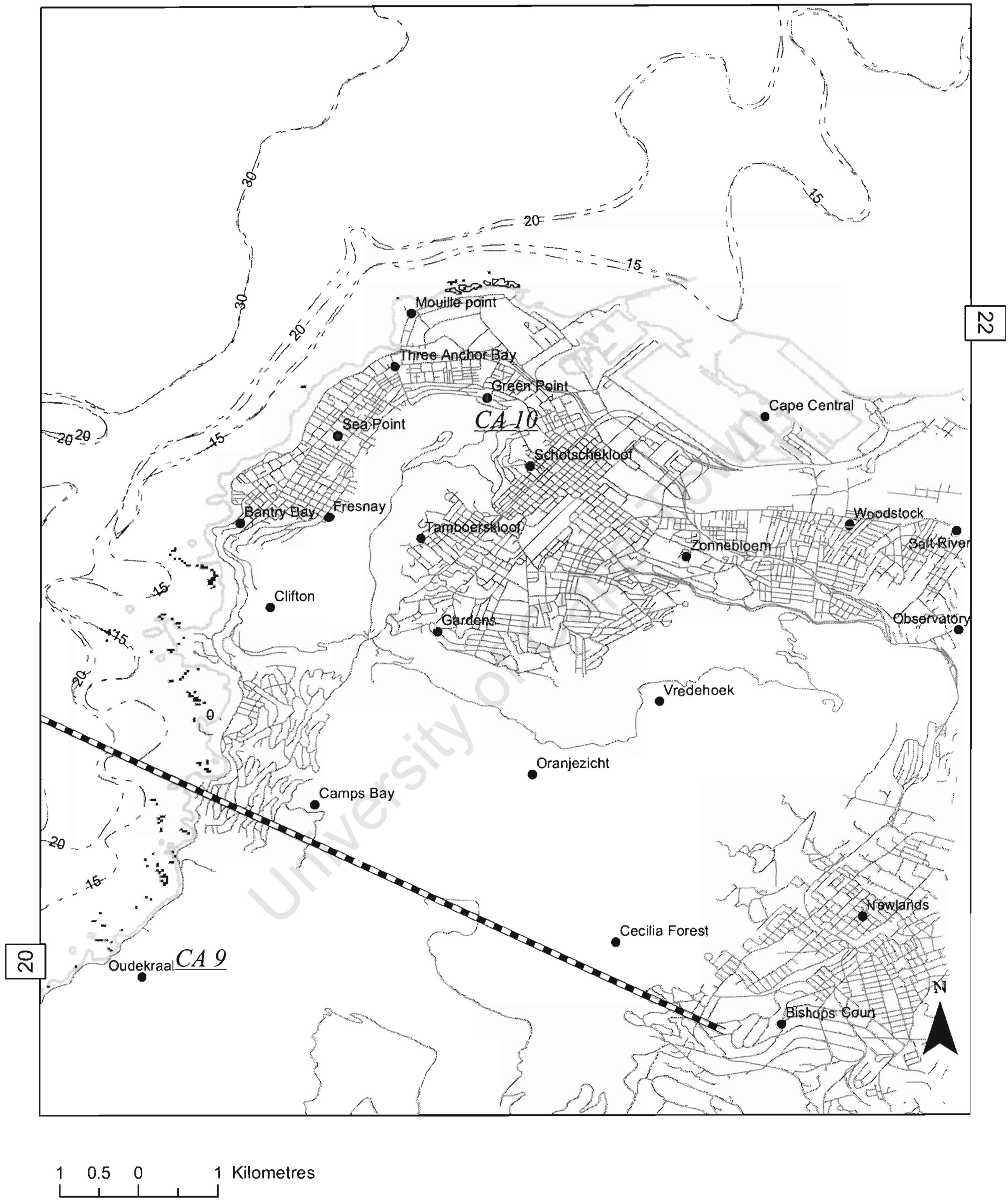
Data Source


CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



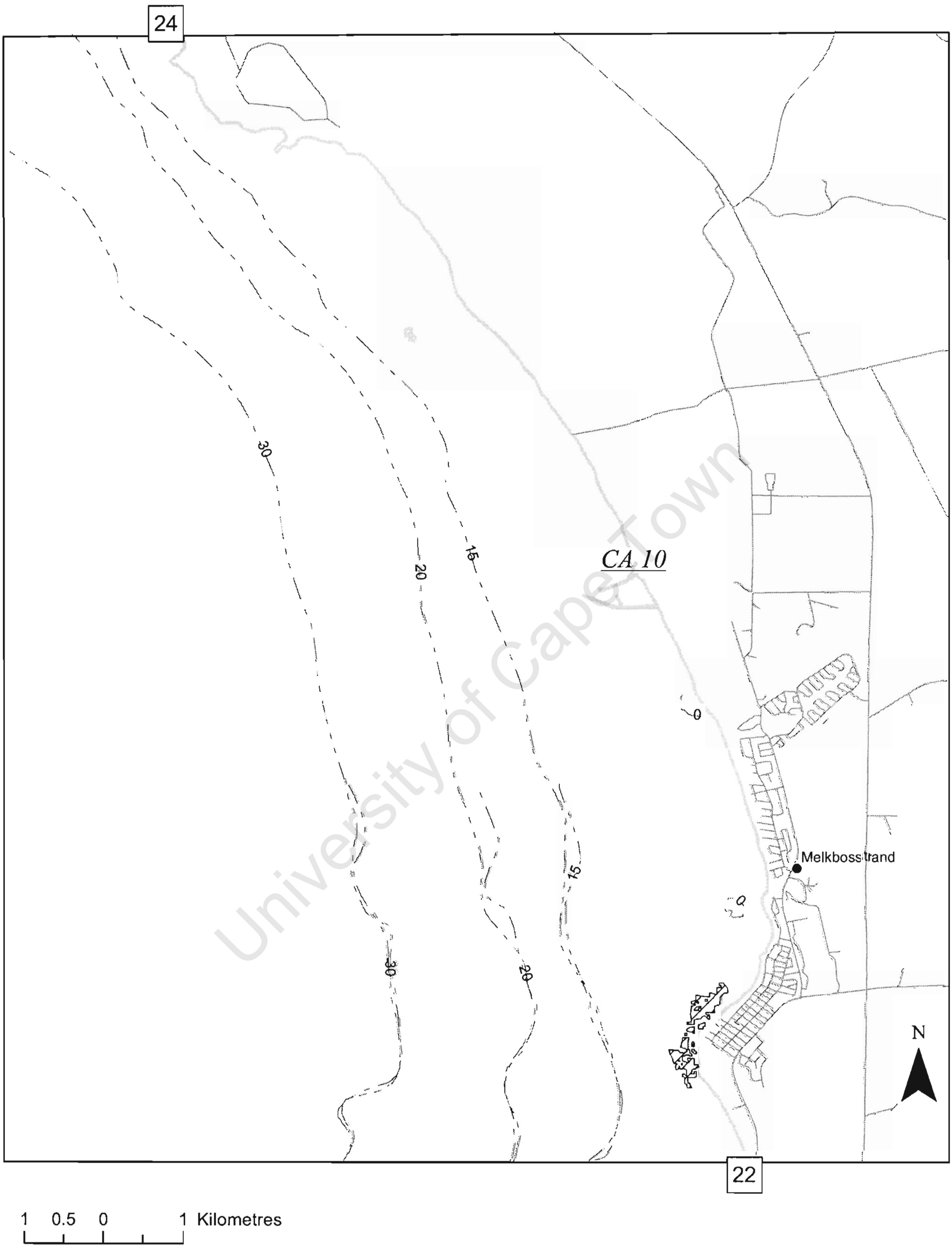
Data Source

CIR 2005	Landsat 7	TARR 1988	CIR 1996	FIELDWORK	Landsat 5



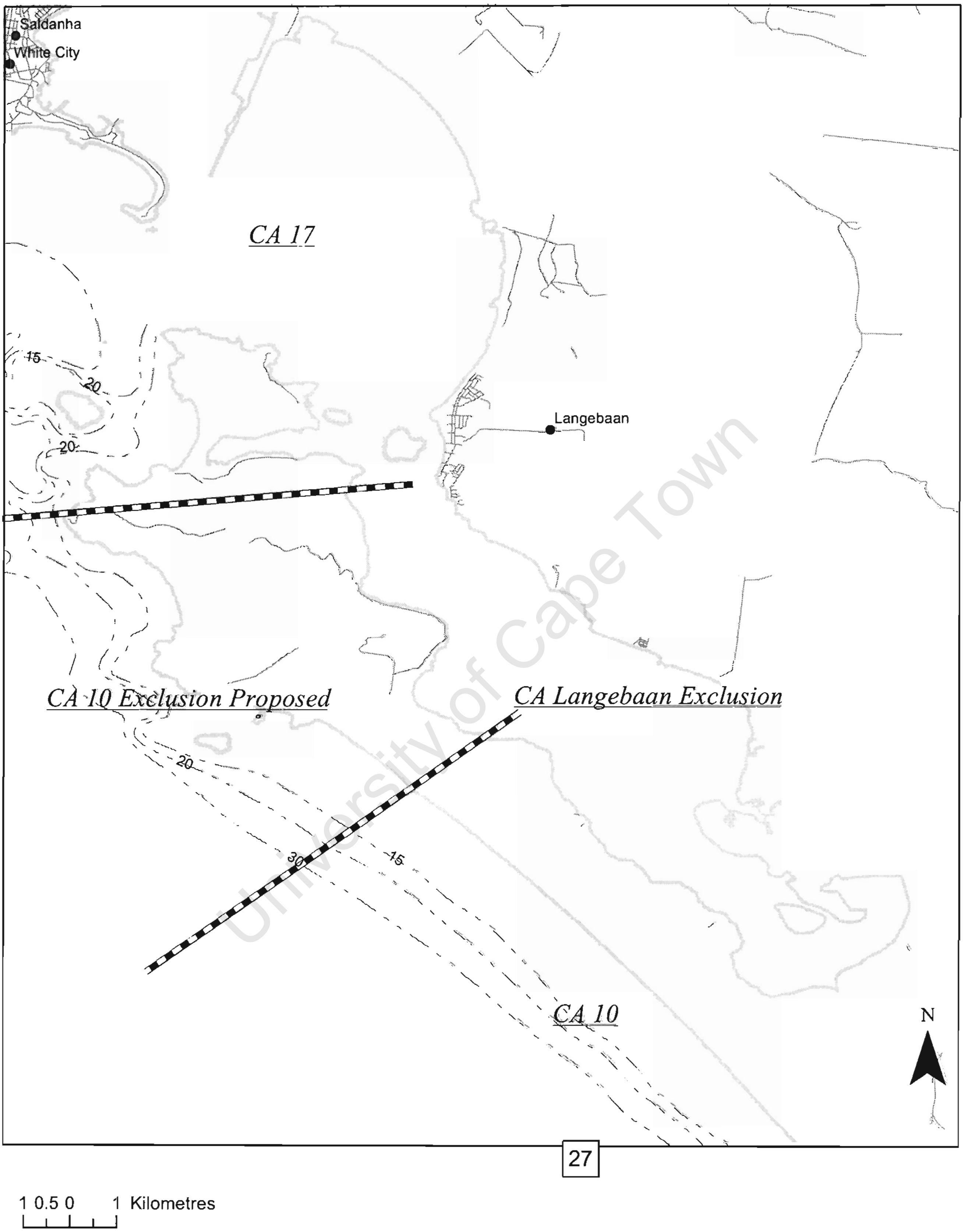
Data Source

CIR 2005	Landsat 7	TARR 1988	CIR 1996	FIELDWORK	Landsat 5

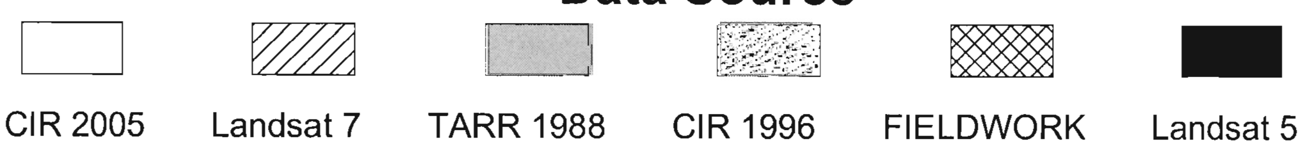


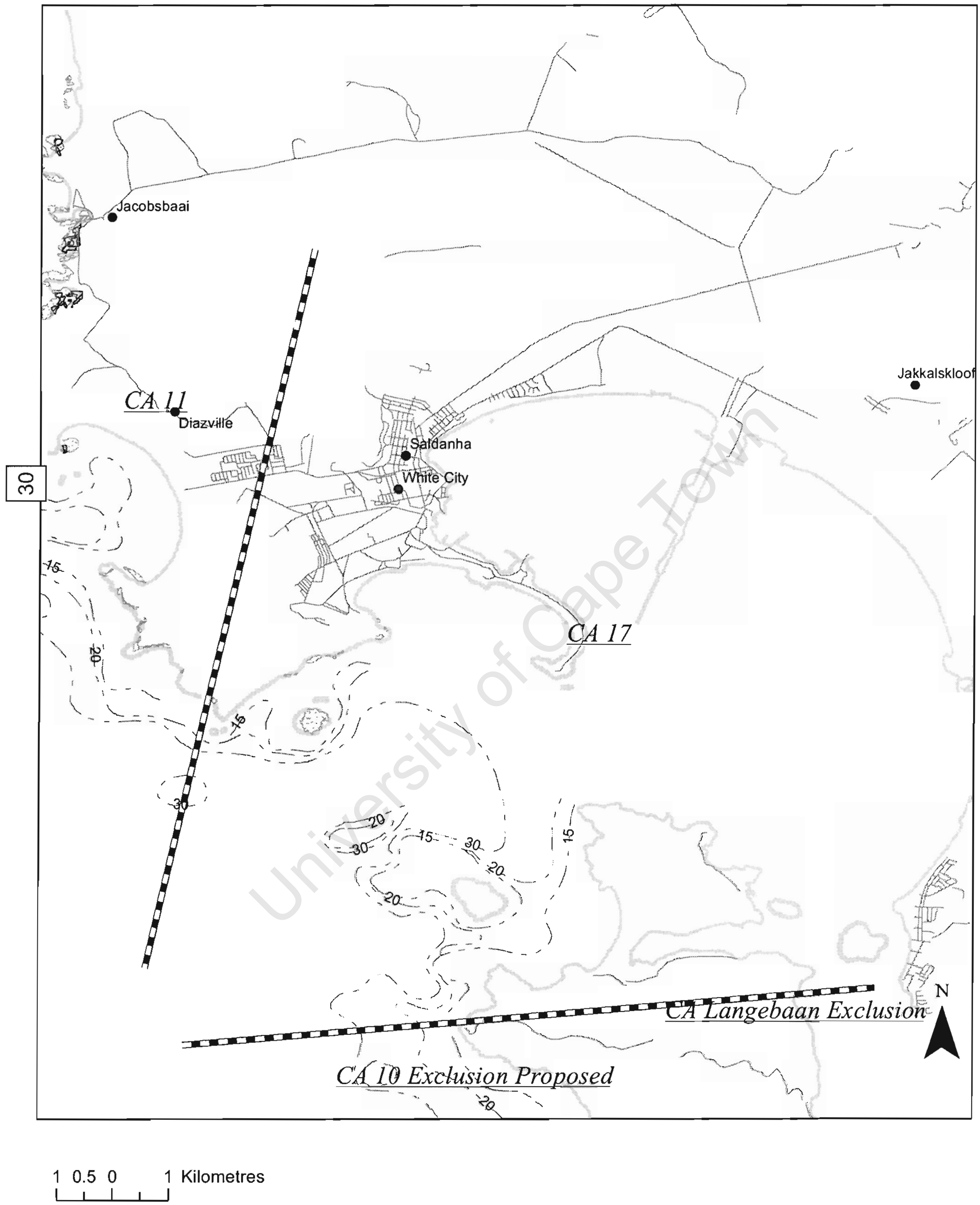
Data Source

CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5


Saldanha
White City
CA 17
15
20
20
Langebaan
CA 10 Exclusion Proposed
CA Langebaan Exclusion
20
30
15
CA 10
N
1 0.5 0 1 Kilometres

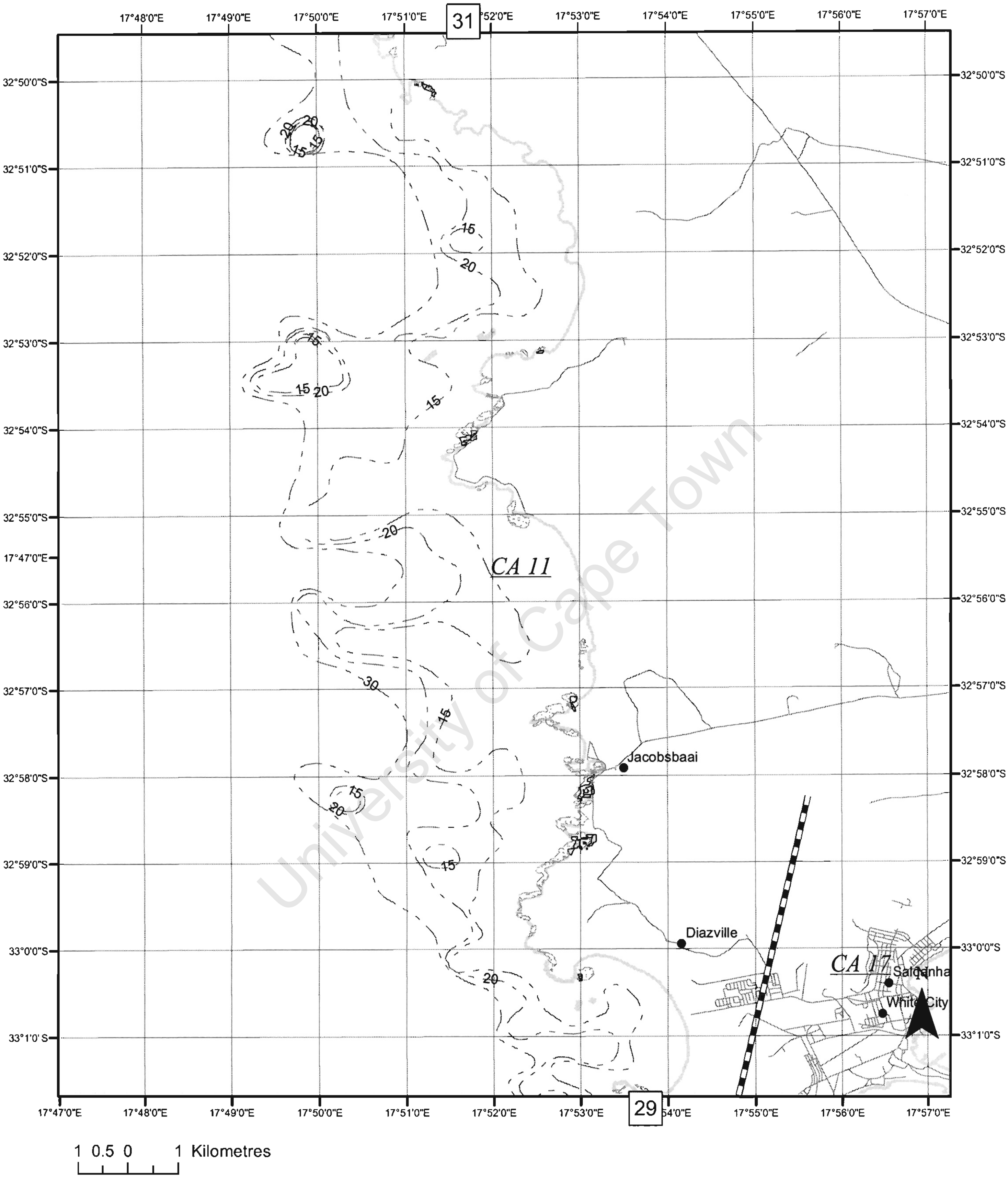
Data Source


CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



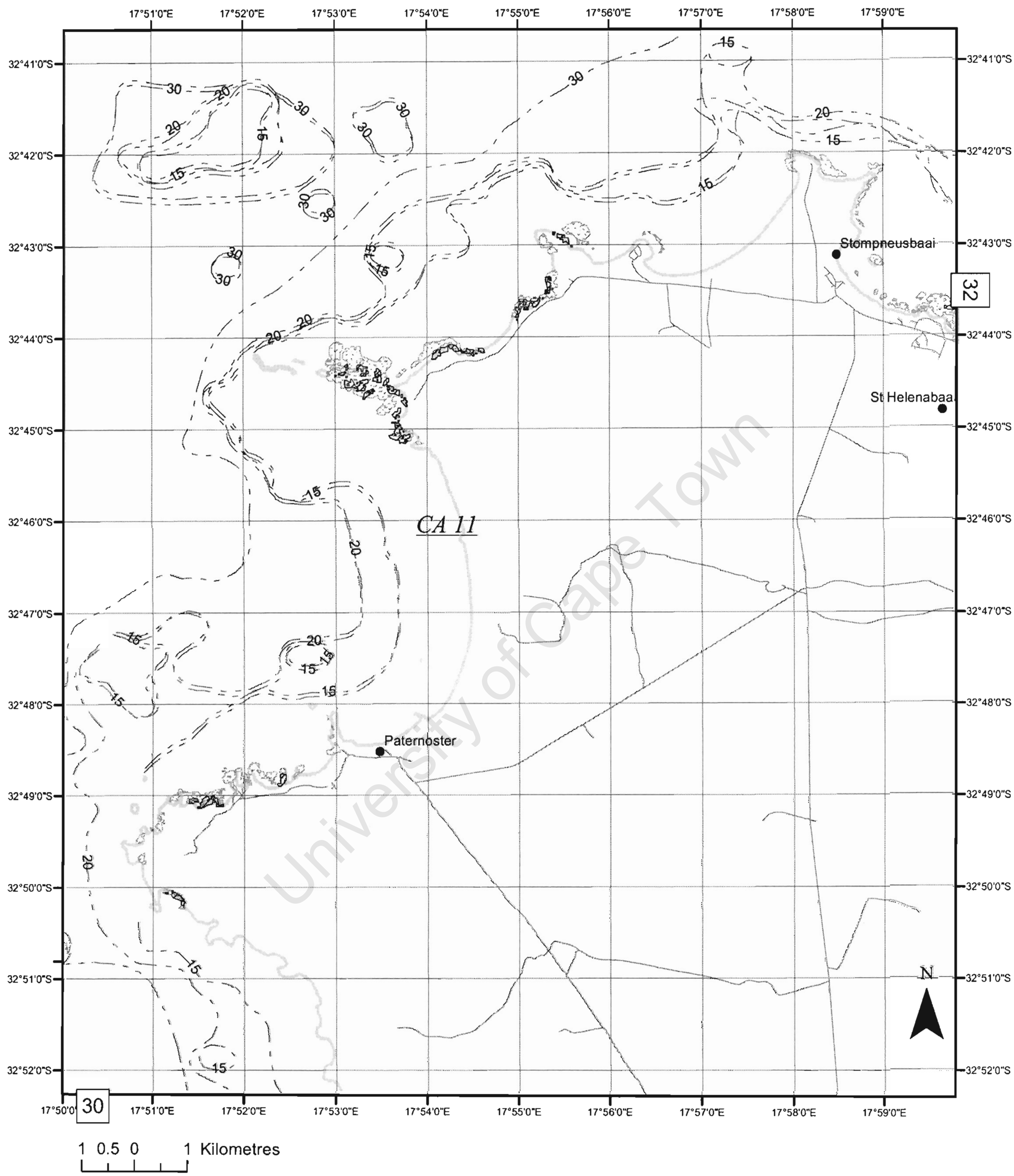
Data Source

CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5



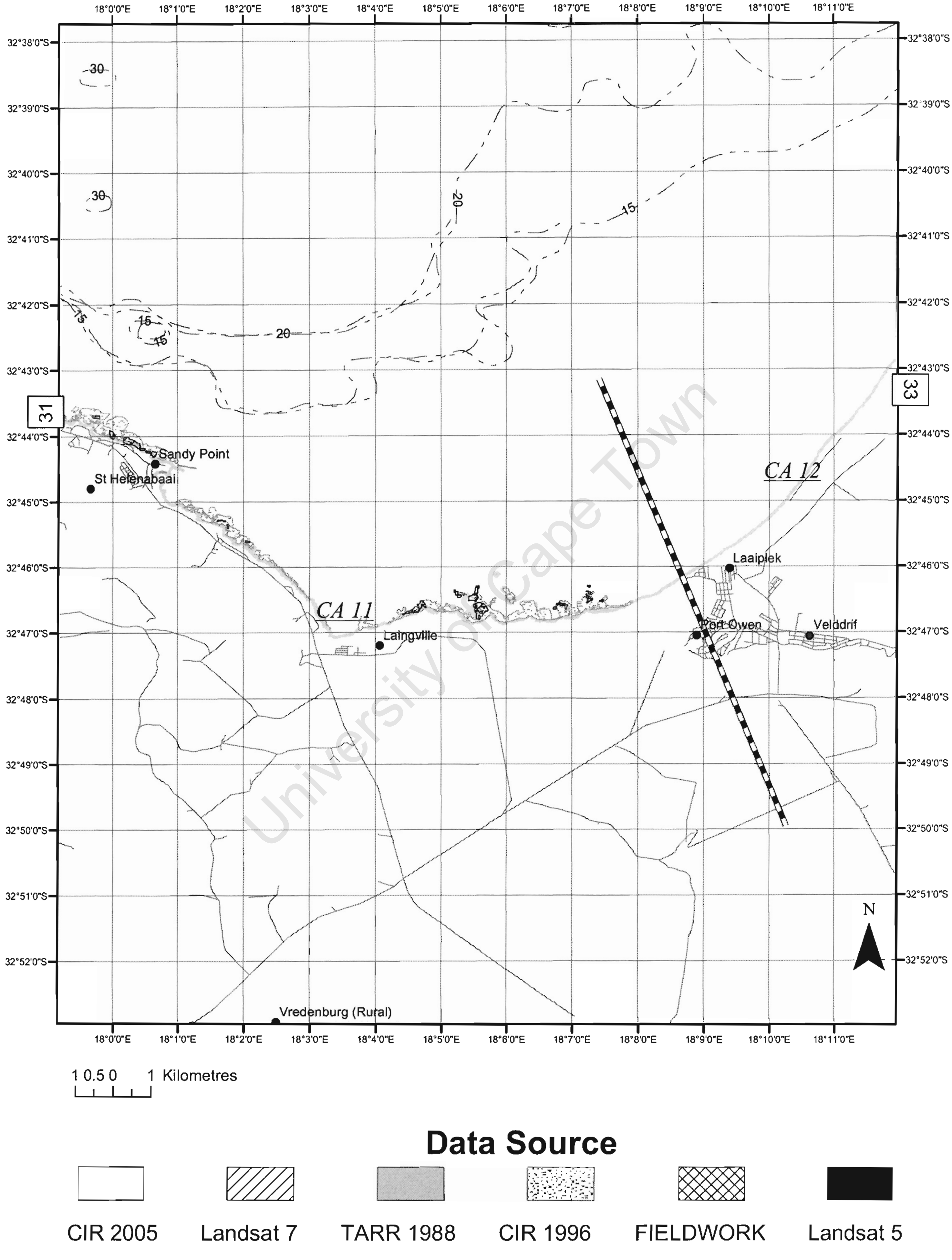
Data Source

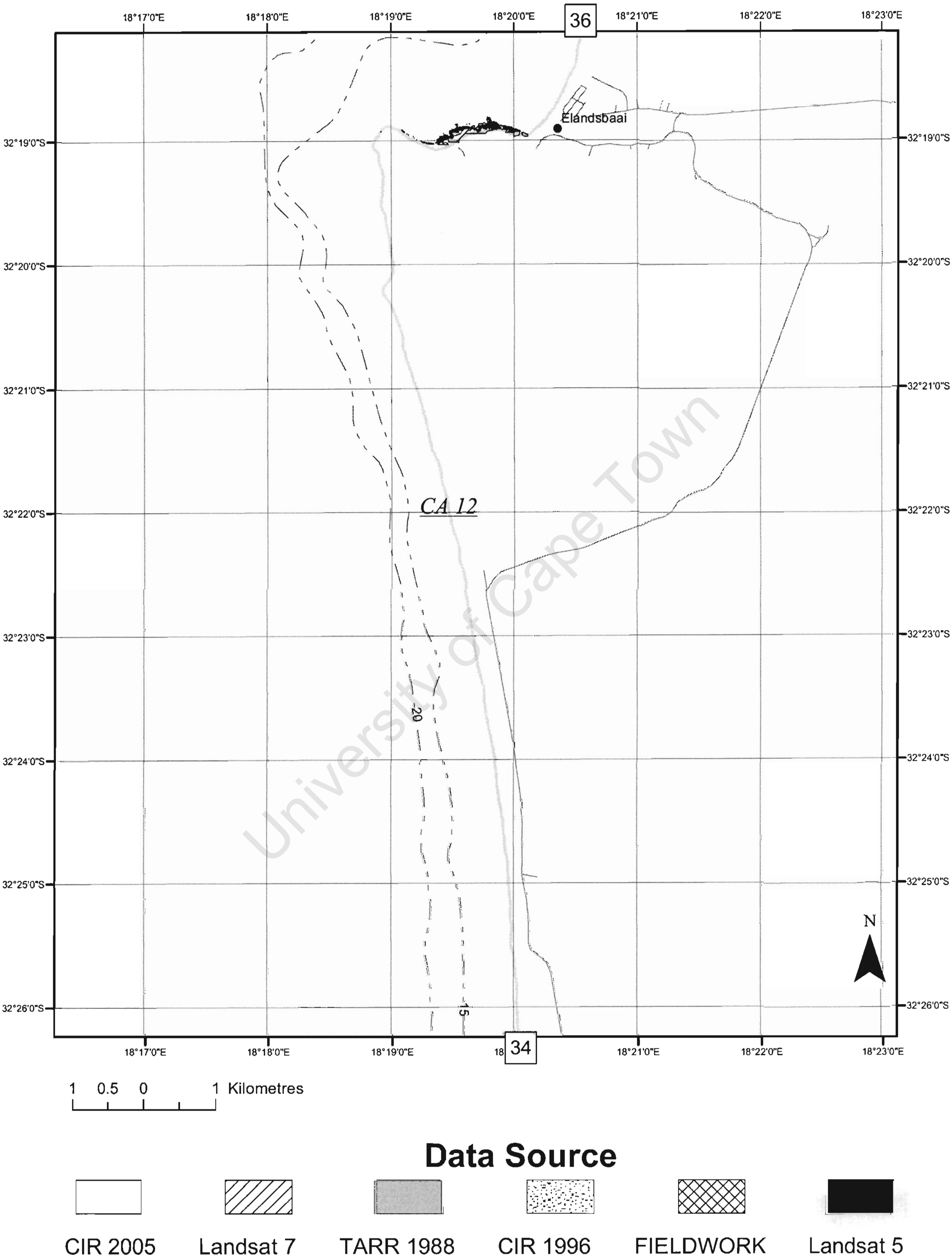
CIR 2005	Landsat 7	TARR 1988	CIR 1996	FIELDWORK	Landsat 5

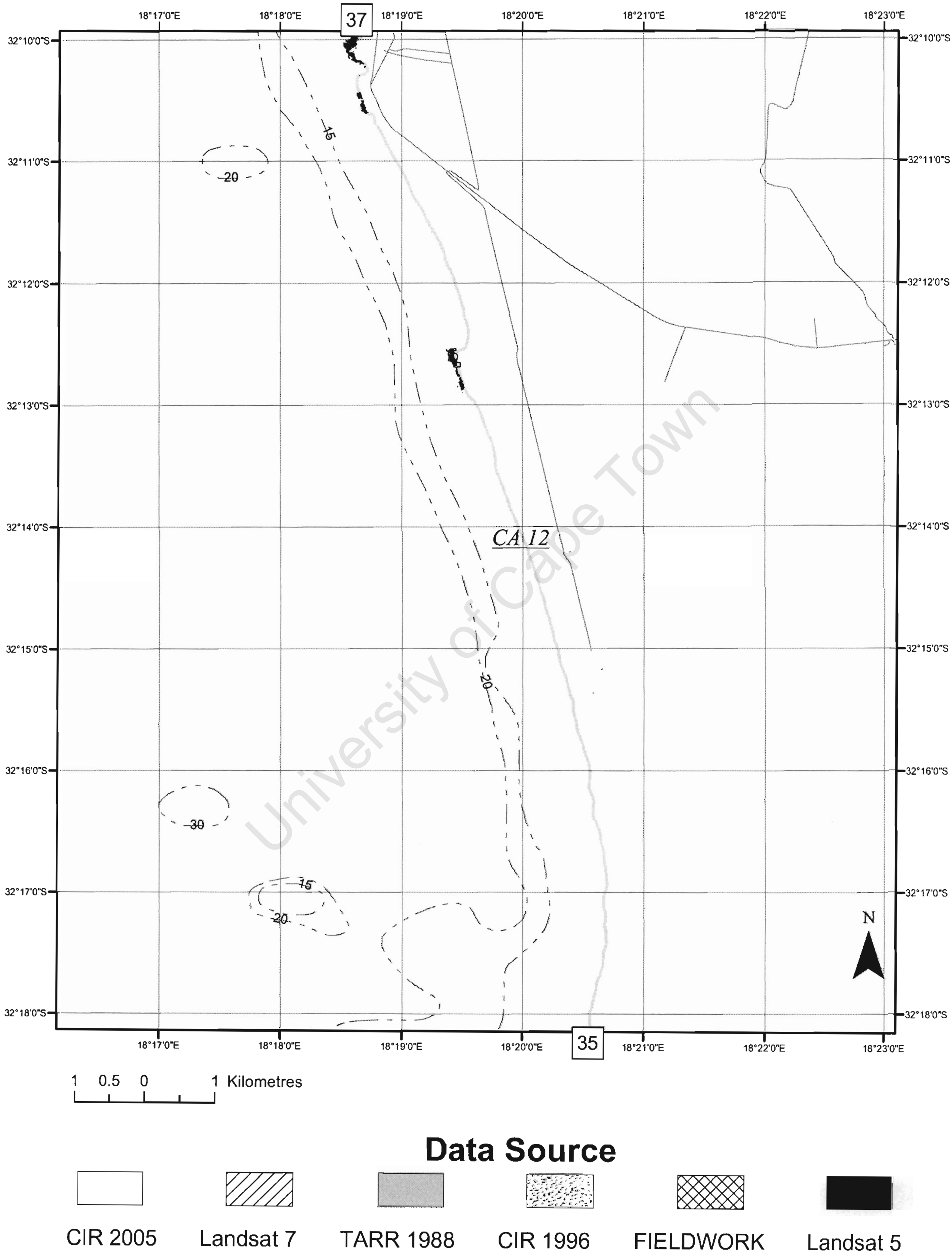


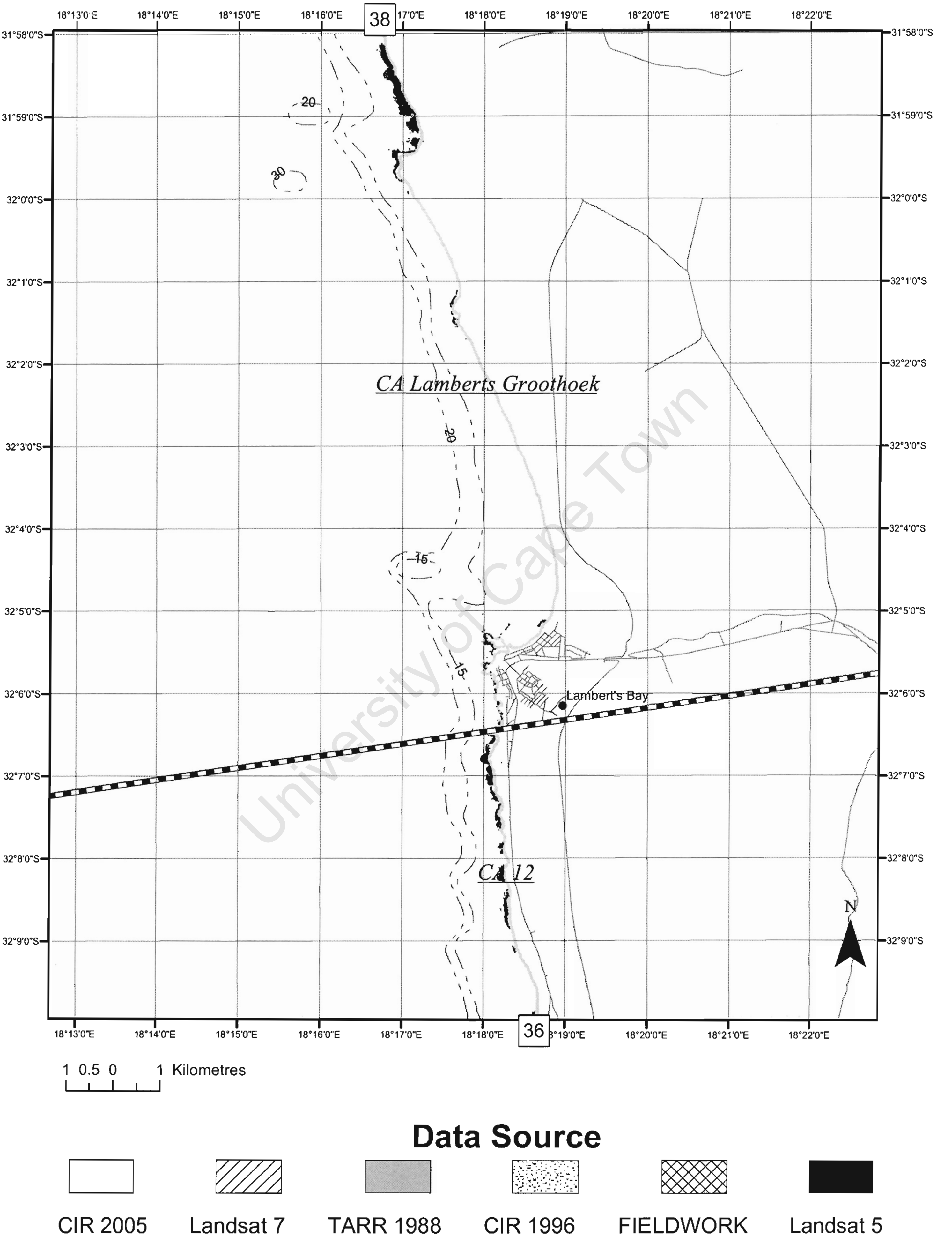
Data Source

CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5

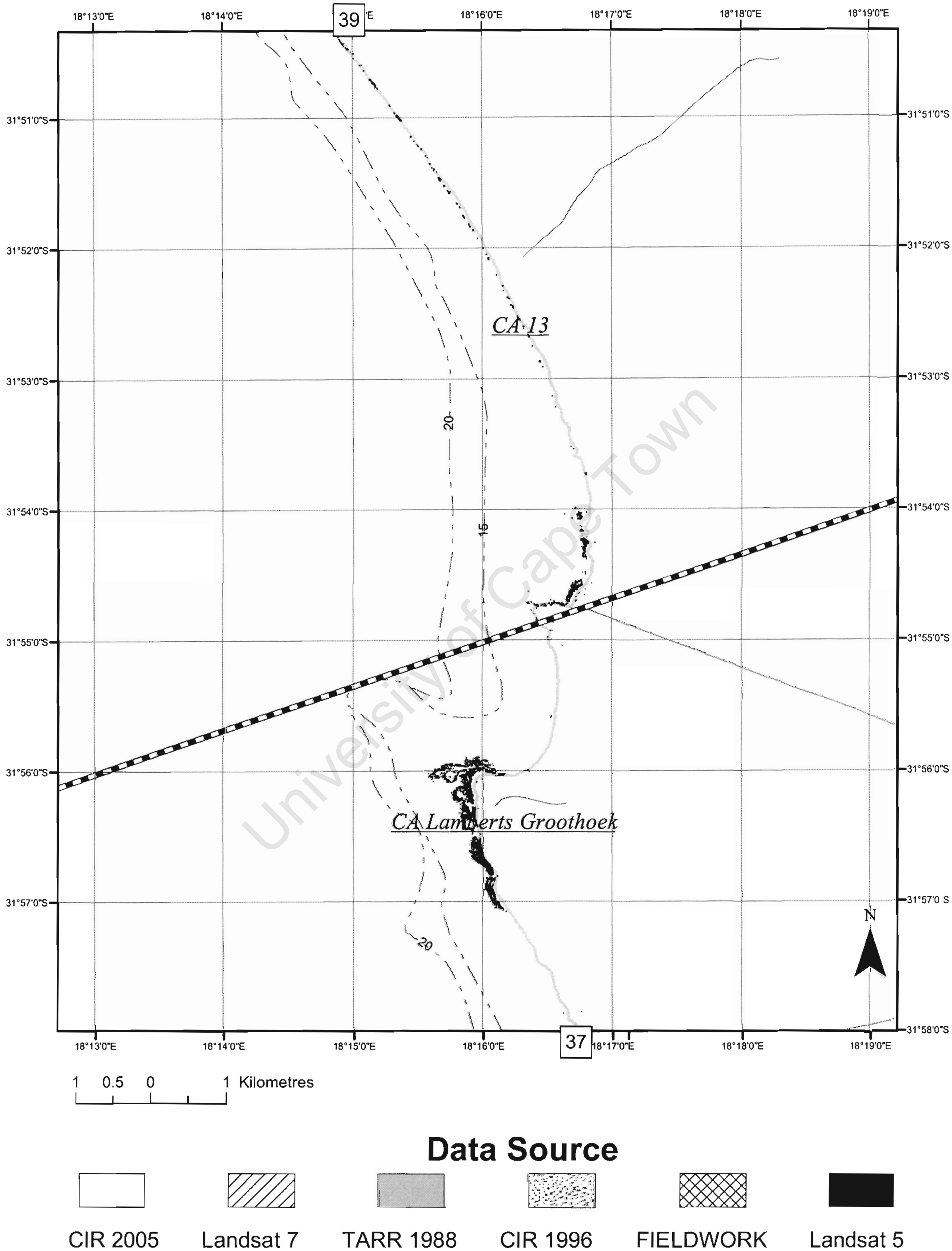

18°0'0"E
18°1'0"E
18°2'0"E
18°3'0"E
18°4'0"E
18°5'0"E
18°6'0"E
18°7'0"E
18°8'0"E
18°9'0"E
18°10'0"E
18°11'0"E
32°38'0"S
32°39'0"S
32°40'0"S
32°41'0"S
32°42'0"S
32°43'0"S
32°44'0"S
32°45'0"S
32°46'0"S
32°47'0"S
32°48'0"S
32°49'0"S
32°50'0"S
32°51'0"S
32°52'0"S
30
20
15
31
33
Sandy Point
St Helenabaai
CA 12
CA 11
Laaiplek
Port Owen
Velddrif
Laingville
Vredenburg (Rural)
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

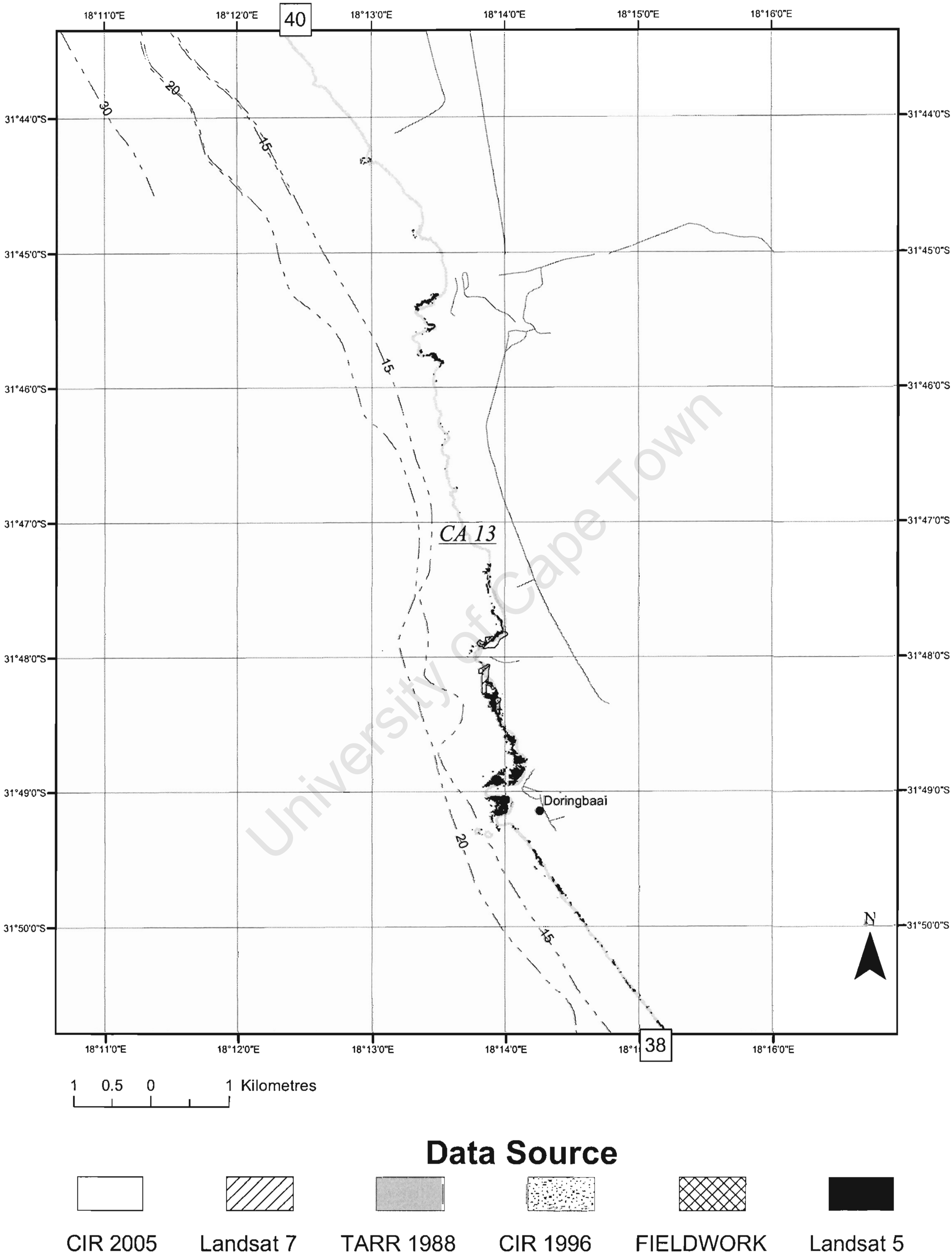

36
18°17'0"E
18°18'0"E
18°19'0"E
18°20'0"E
18°21'0"E
18°22'0"E
18°23'0"E
32°19'0"S
32°20'0"S
32°21'0"S
32°22'0"S
32°23'0"S
32°24'0"S
32°25'0"S
32°26'0"S
Elandsbaai
CA 12
20
15
N
34
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

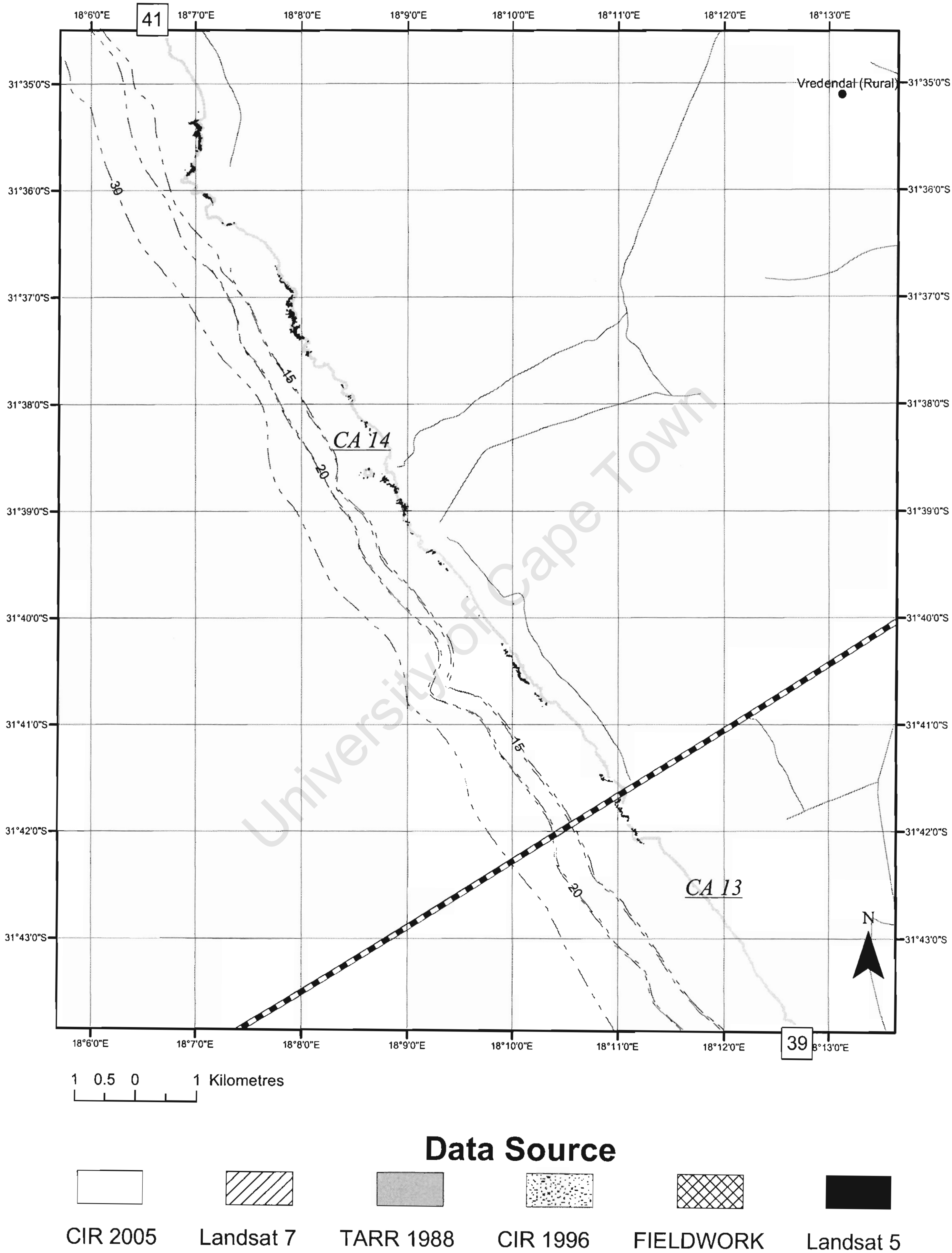

37
18°17'0"E
18°18'0"E
18°19'0"E
18°20'0"E
18°21'0"E
18°22'0"E
18°23'0"E
32°10'0"S
32°11'0"S
32°12'0"S
32°13'0"S
32°14'0"S
32°15'0"S
32°16'0"S
32°17'0"S
32°18'0"S
15
20
30
CA 12
N
35
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

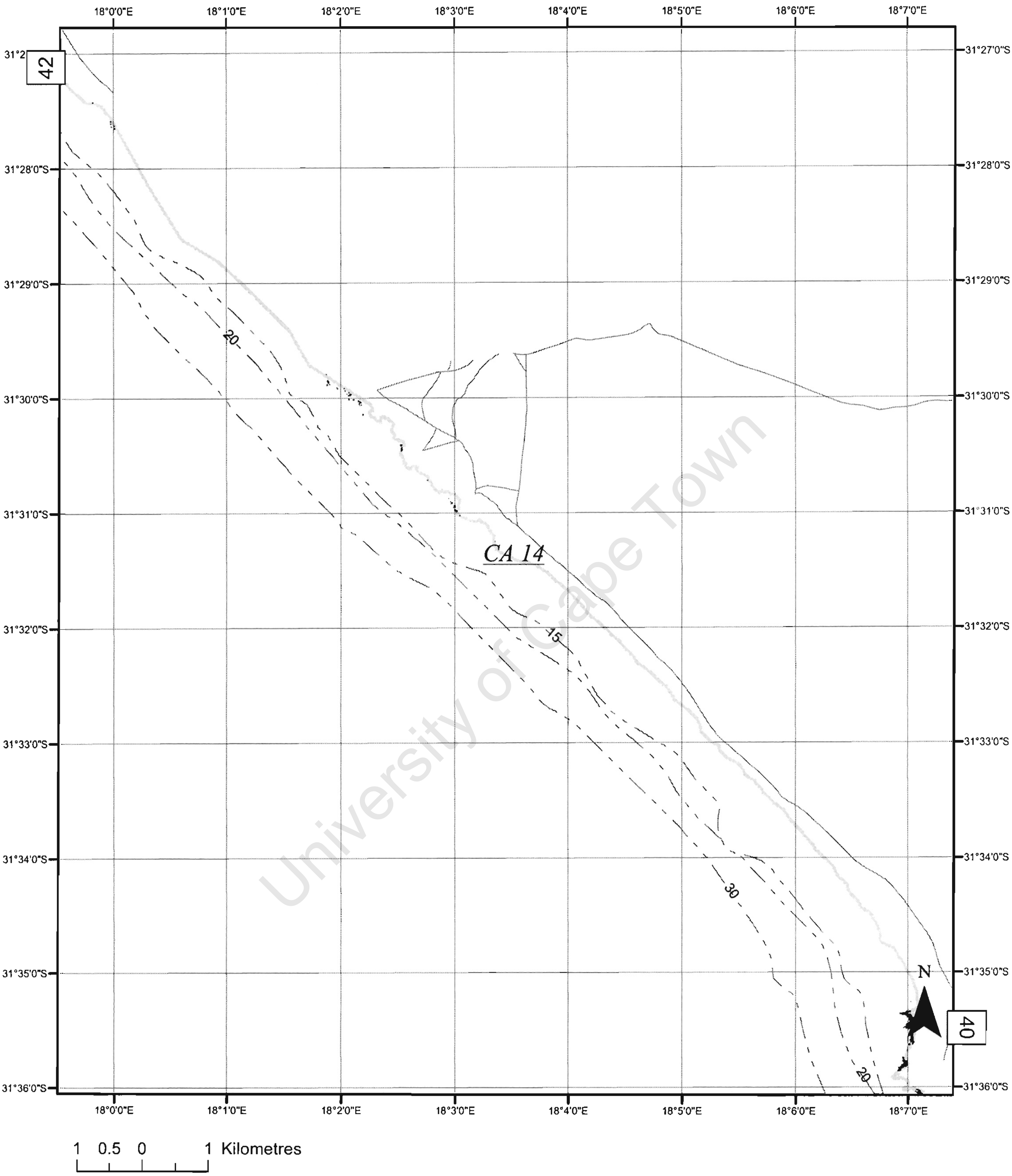


38
36
18°13'0"E
18°14'0"E
18°15'0"E
18°16'0"E
18°17'0"E
18°18'0"E
18°19'0"E
18°20'0"E
18°21'0"E
18°22'0"E
31°58'0"S
31°59'0"S
32°0'0"S
32°1'0"S
32°2'0"S
32°3'0"S
32°4'0"S
32°5'0"S
32°6'0"S
32°7'0"S
32°8'0"S
32°9'0"S
20
30
15
CA Lamberts Groothoek
Lambert's Bay
CA 12
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


39
18°13'0"E
18°14'0"E
18°16'0"E
18°17'0"E
18°18'0"E
18°19'0"E
31°51'0"S
31°52'0"S
31°53'0"S
31°54'0"S
31°55'0"S
31°56'0"S
31°57'0"S
31°58'0"S
CA 13
20
15
CA Lamberts Groothoek
20
N
37
18°15'0"E
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

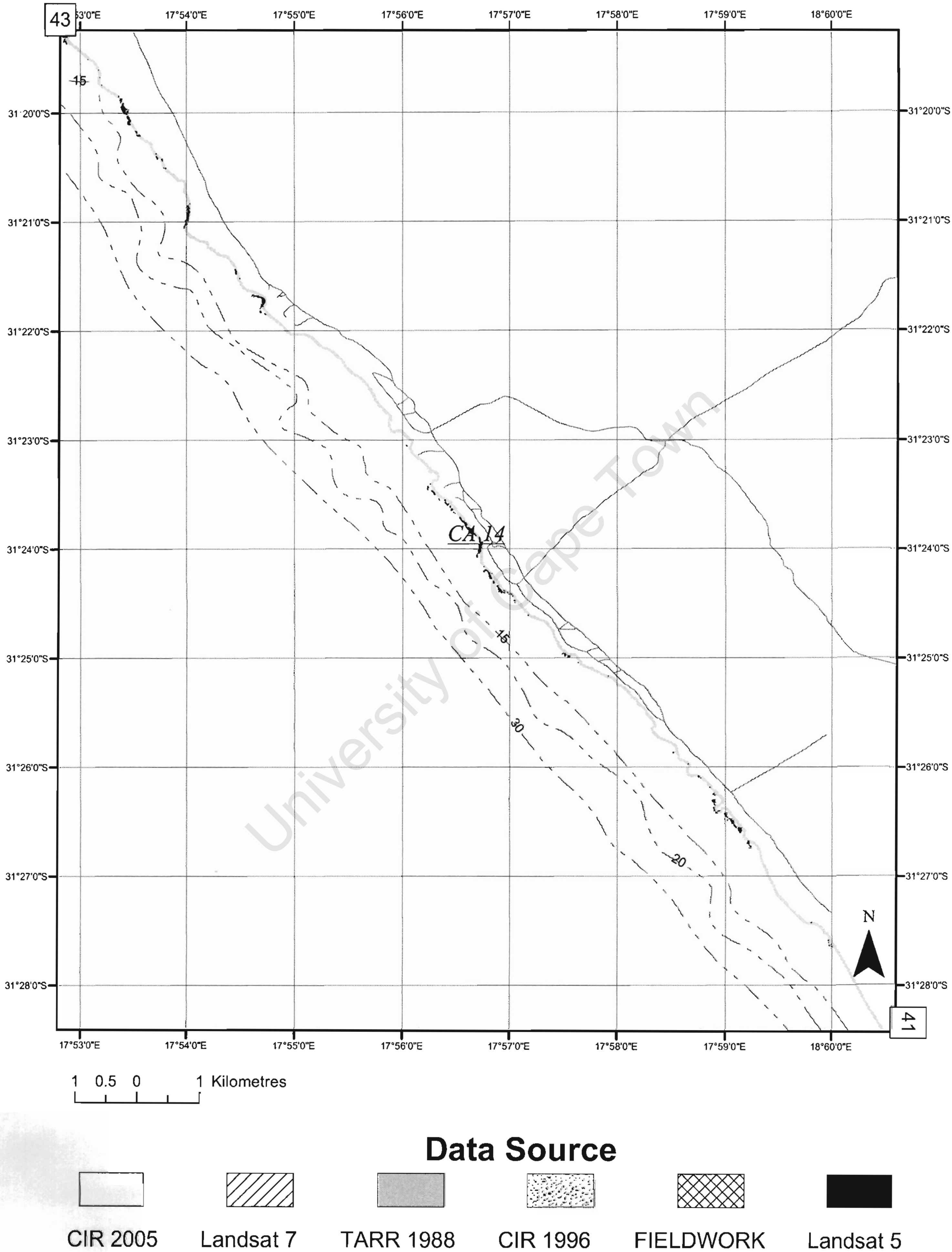

40
18°11'0"E
18°12'0"E
18°13'0"E
18°14'0"E
18°15'0"E
18°16'0"E
31°44'0"S
31°45'0"S
31°46'0"S
31°47'0"S
31°48'0"S
31°49'0"S
31°50'0"S
30
20
15
15
CA 13
Doringbaai
20
15
N
38
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

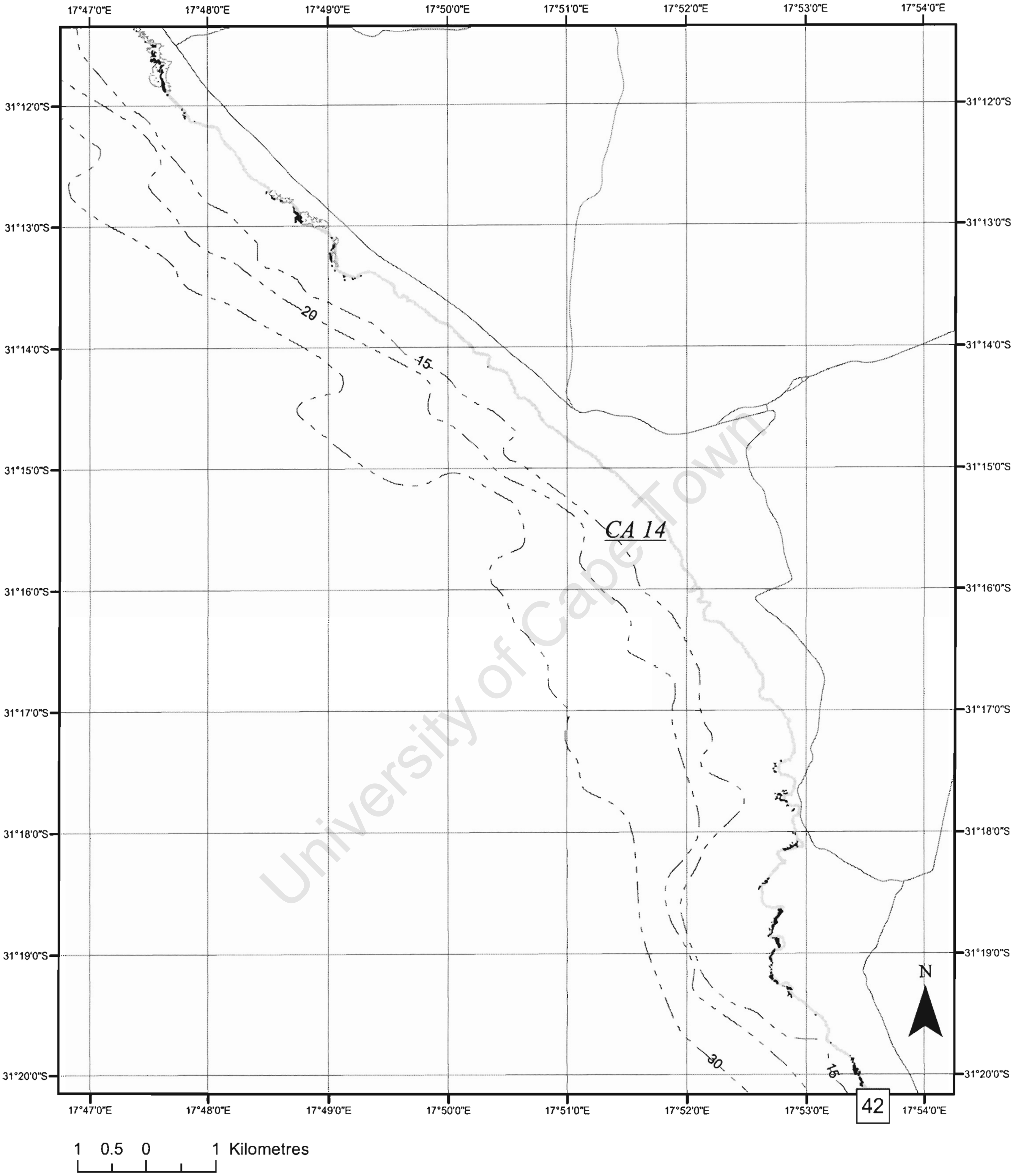

41
18°6'0"E
18°7'0"E
18°8'0"E
18°9'0"E
18°10'0"E
18°11'0"E
18°12'0"E
18°13'0"E
31°35'0"S
31°36'0"S
31°37'0"S
31°38'0"S
31°39'0"S
31°40'0"S
31°41'0"S
31°42'0"S
31°43'0"S
Vredendal (Rural)
30
15
CA 14
20
15
20
CA 13
N
39
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



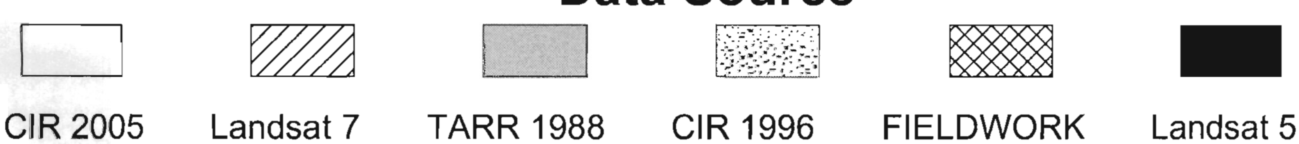
Data Source

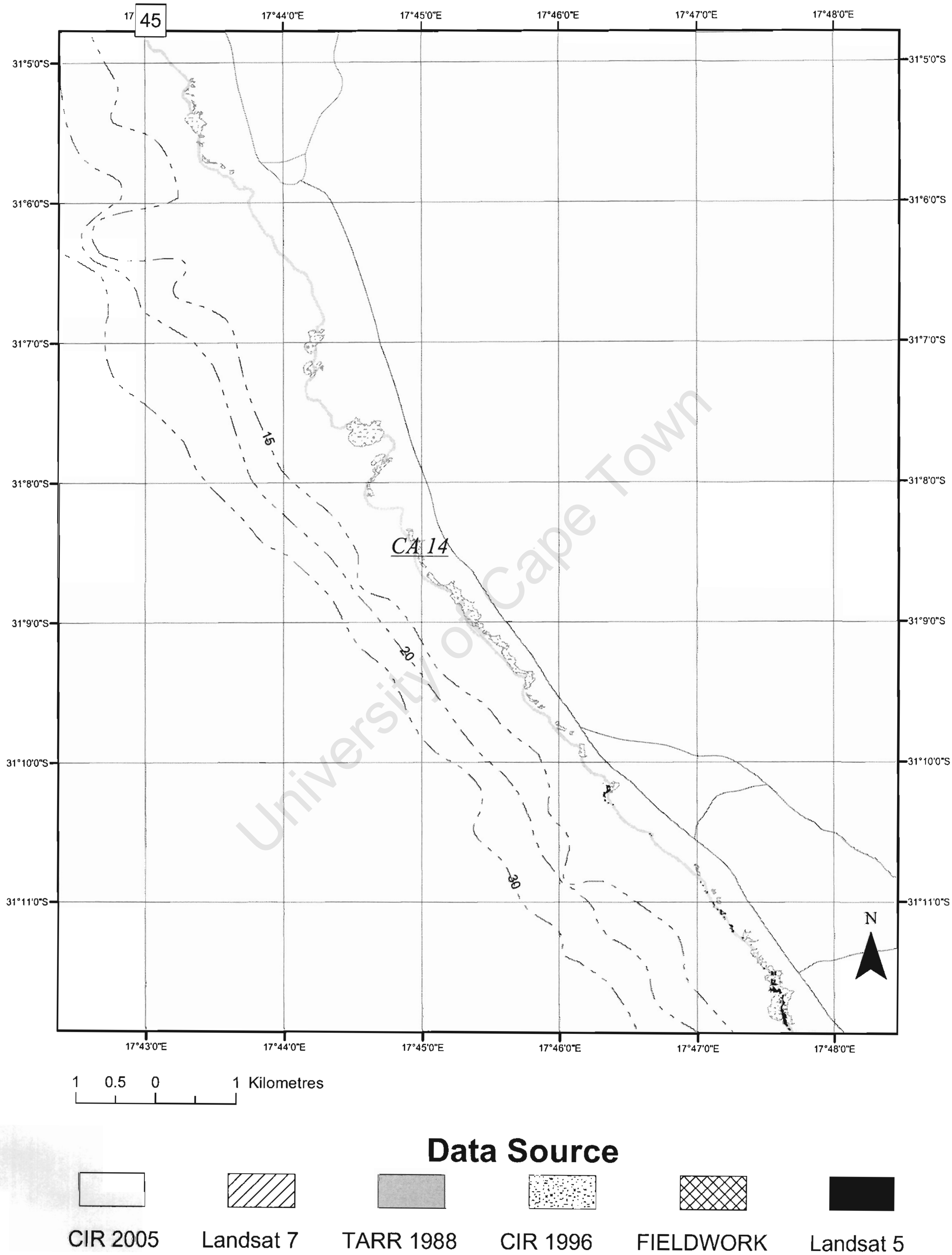
CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5

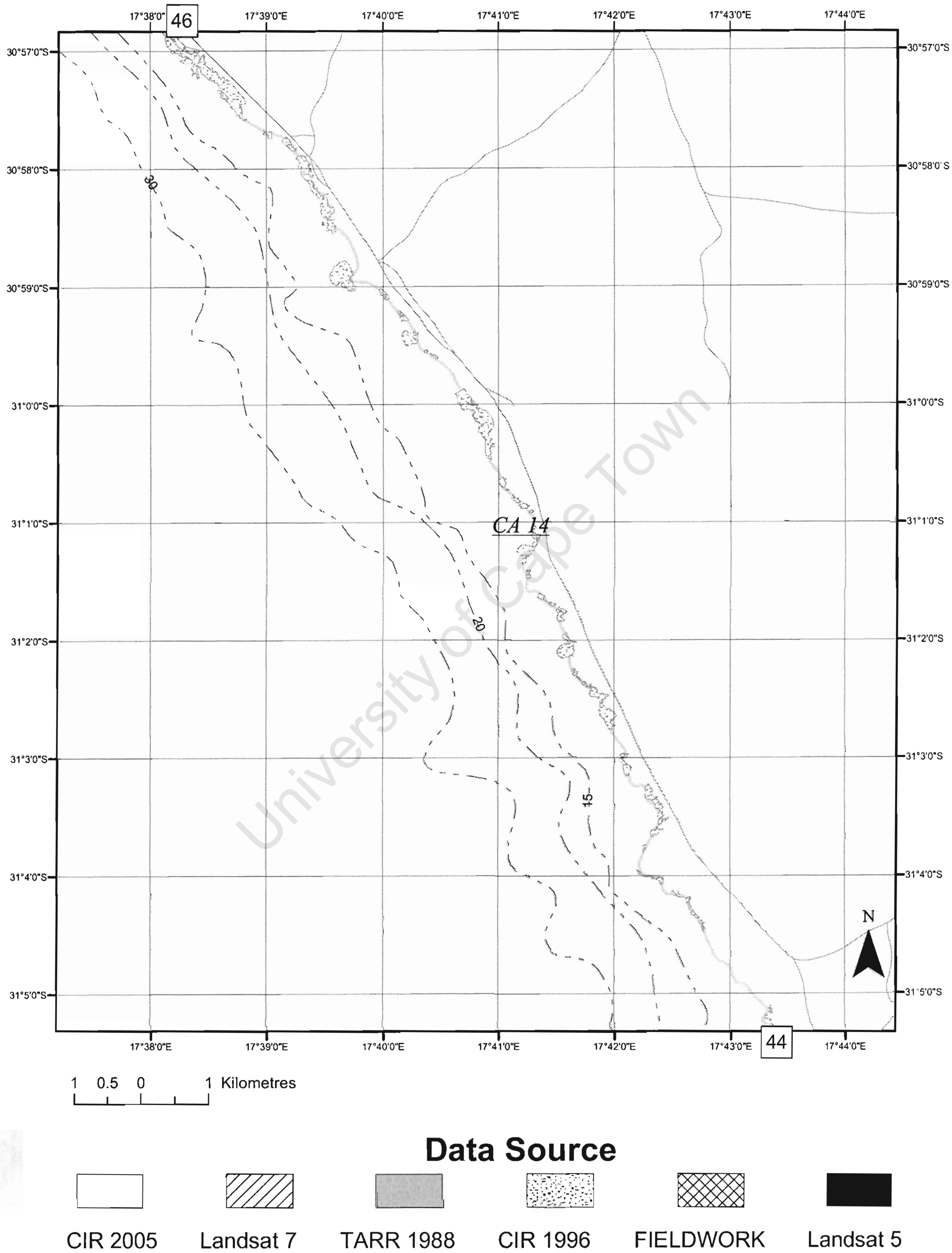

43
17°53'0"E
17°54'0"E
17°55'0"E
17°56'0"E
17°57'0"E
17°58'0"E
17°59'0"E
18°60'0"E
31°20'0"S
31°21'0"S
31°22'0"S
31°23'0"S
31°24'0"S
31°25'0"S
31°26'0"S
31°27'0"S
31°28'0"S
15
CA 14
15
30
20
N
41
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


17°47'0"E
17°48'0"E
17°49'0"E
17°50'0"E
17°51'0"E
17°52'0"E
17°53'0"E
17°54'0"E
31°12'0"S
31°13'0"S
31°14'0"S
31°15'0"S
31°16'0"S
31°17'0"S
31°18'0"S
31°19'0"S
31°20'0"S
20
15
CA 14
30
15
N
42
1 0.5 0 1 Kilometres

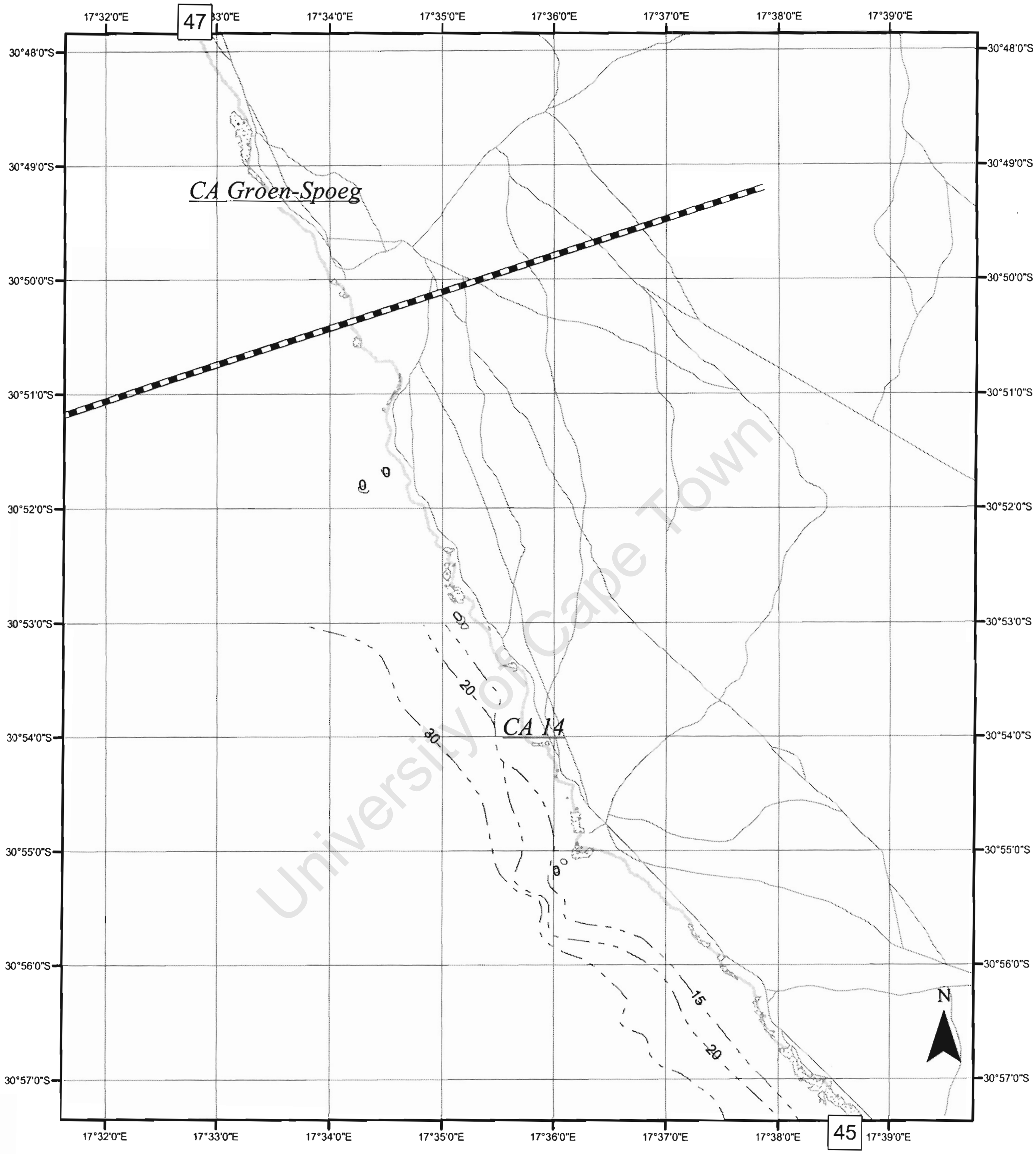
Data Source


CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


45
17°43'0"E
17°44'0"E
17°45'0"E
17°46'0"E
17°47'0"E
17°48'0"E
31°5'0"S
31°6'0"S
31°7'0"S
31°8'0"S
31°9'0"S
31°10'0"S
31°11'0"S
15
20
30
CA 14
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



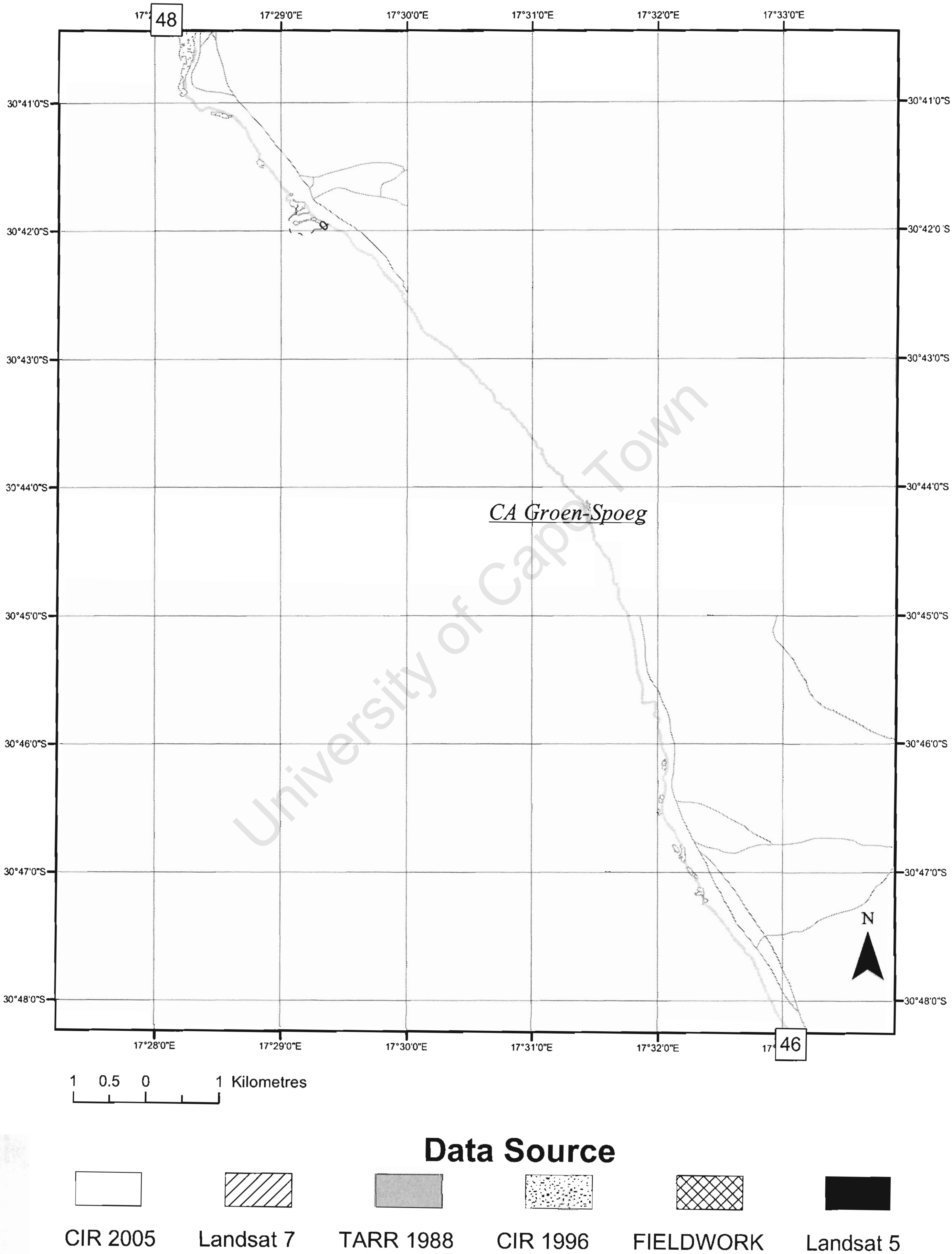
46
44
17°38'0"E
17°39'0"E
17°40'0"E
17°41'0"E
17°42'0"E
17°43'0"E
17°44'0"E
30°57'0"S
30°58'0"S
30°59'0"S
31°0'0"S
31°1'0"S
31°2'0"S
31°3'0"S
31°4'0"S
31°5'0"S
30
20
15
CA 14
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

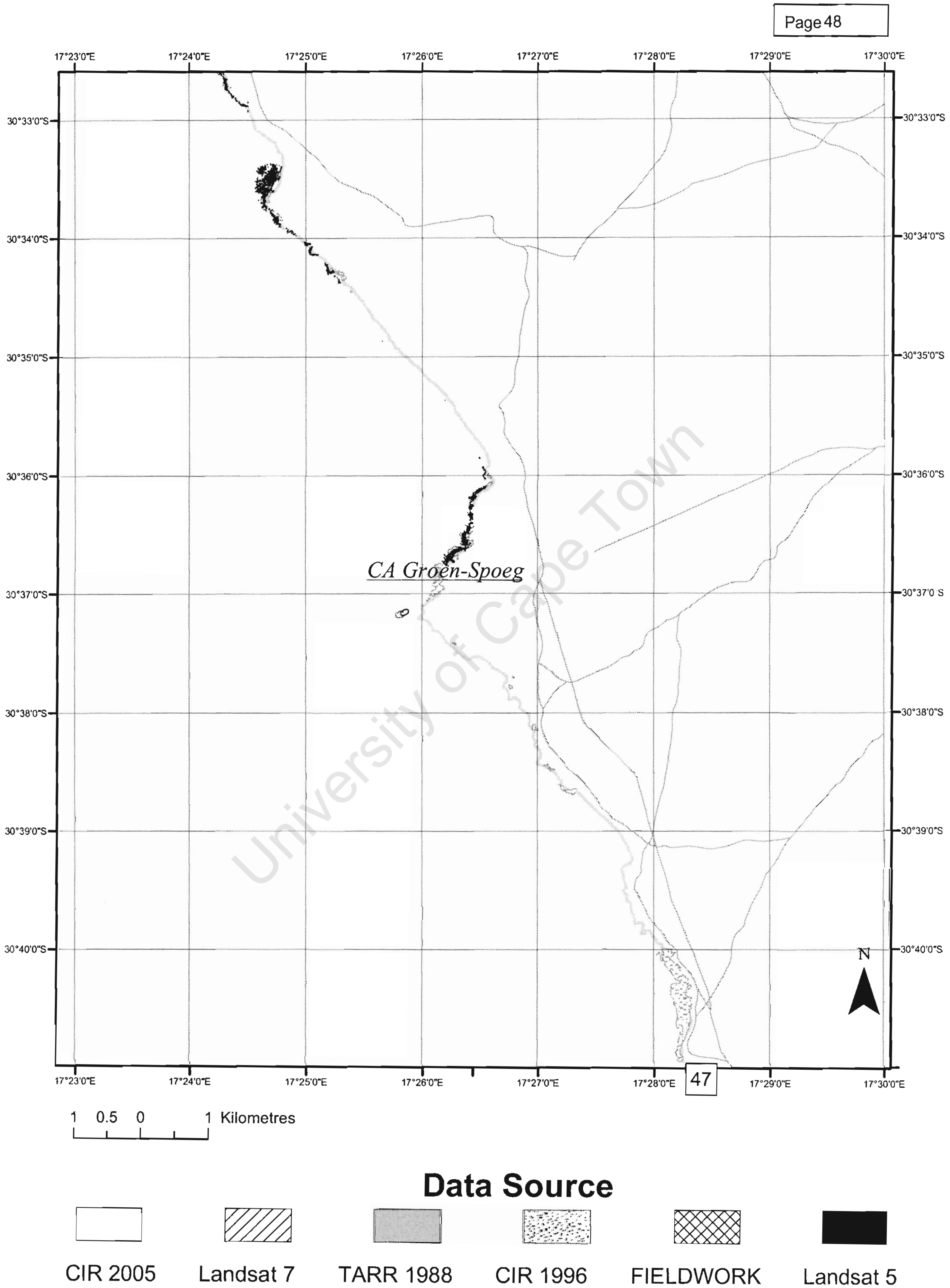


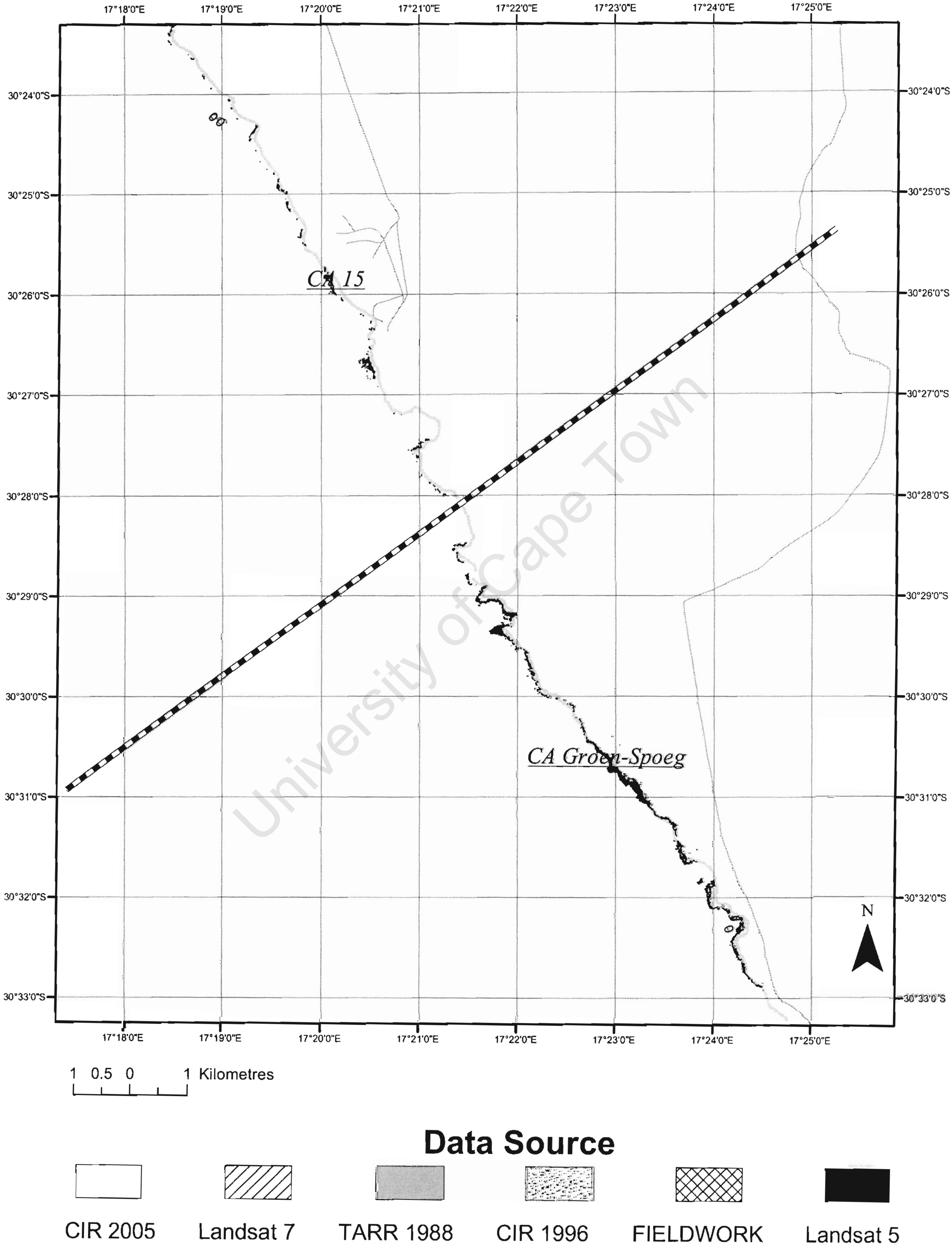
1 0.5 0 1 Kilometres

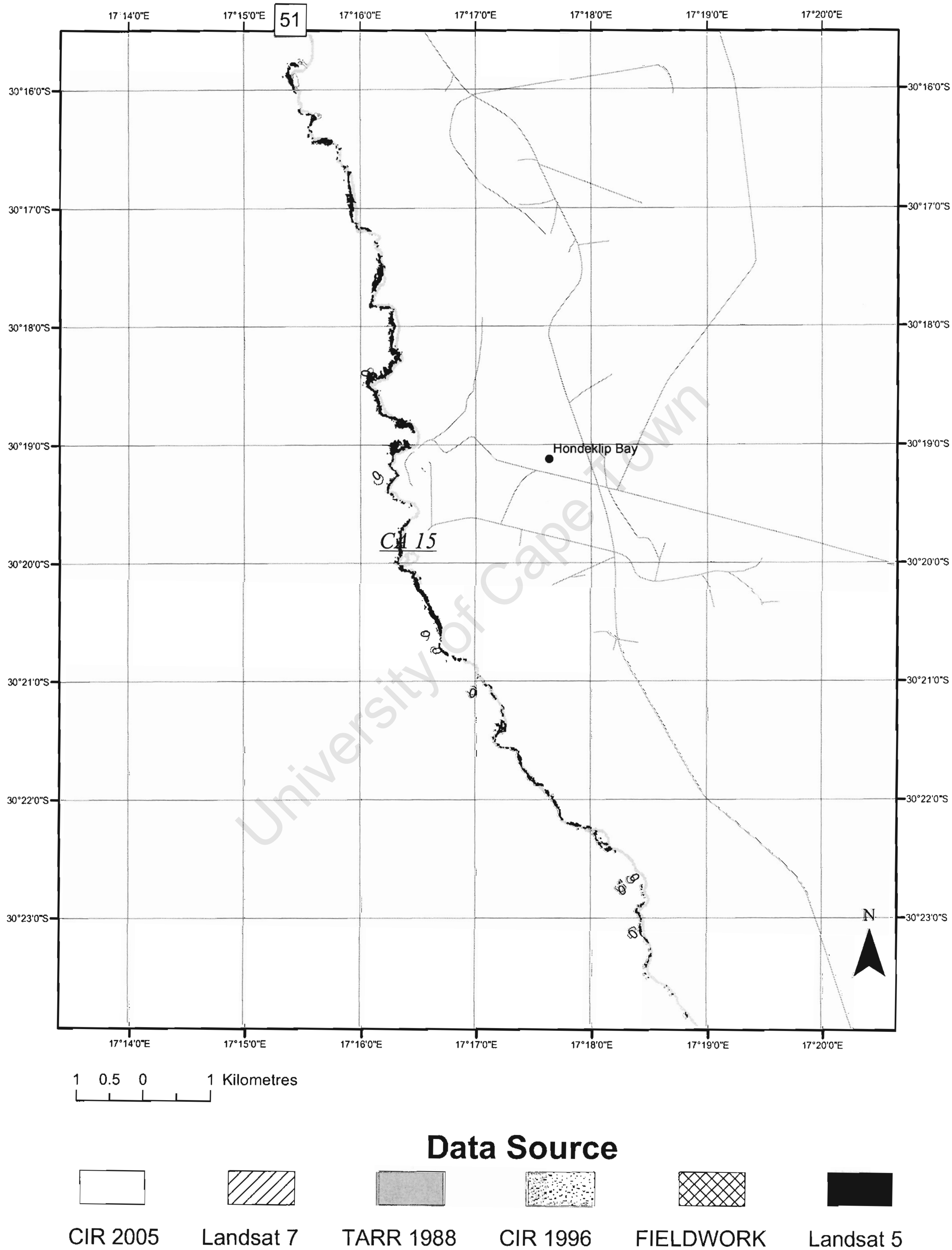
Data Source

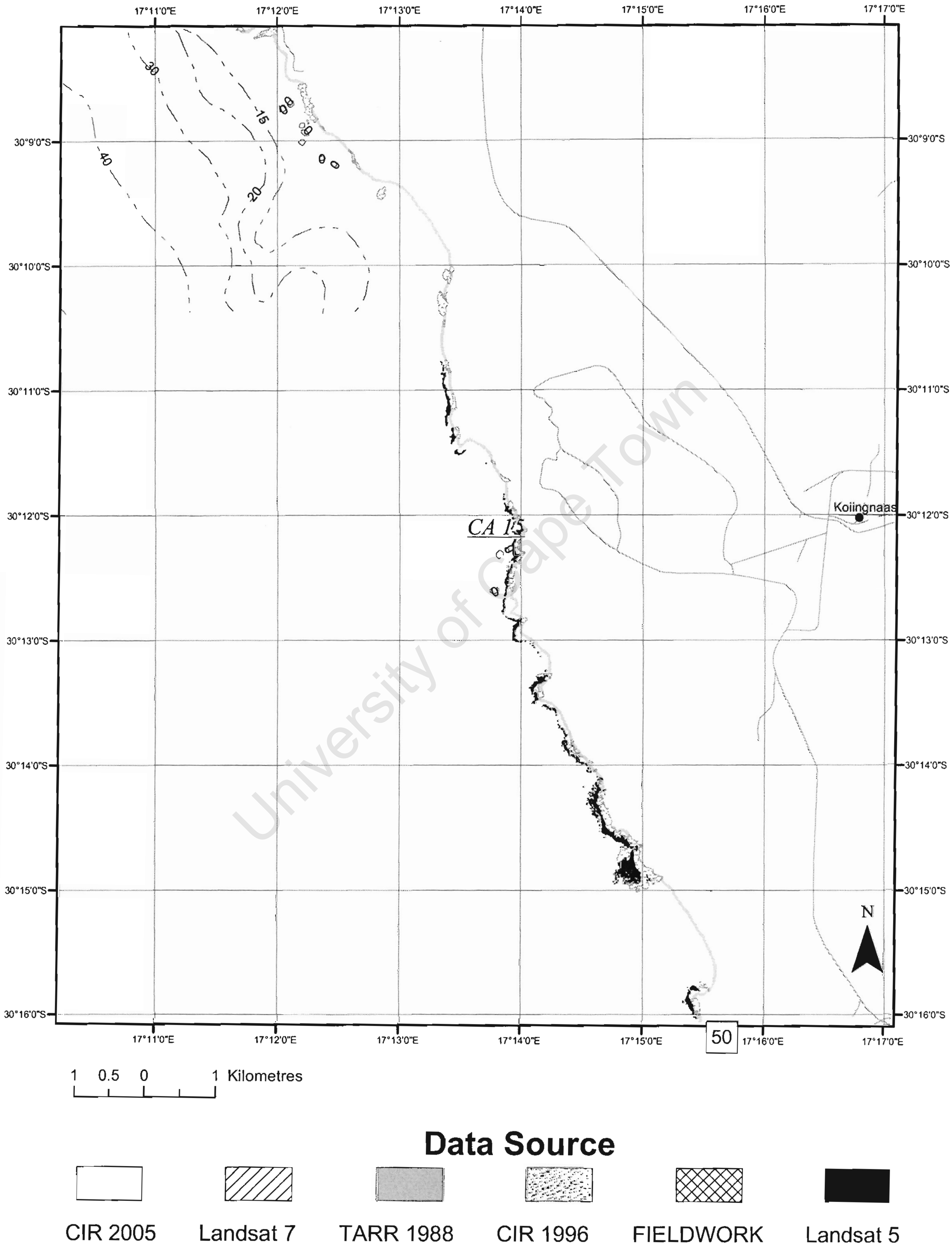
CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5


48
17°29'0"E
17°30'0"E
17°31'0"E
17°32'0"E
17°33'0"E
30°41'0"S
30°42'0"S
30°43'0"S
30°44'0"S
30°45'0"S
30°46'0"S
30°47'0"S
30°48'0"S
CA Groen-Spoeg
N
17°28'0"E
46
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


Page 48
17°23'0"E
17°24'0"E
17°25'0"E
17°26'0"E
17°27'0"E
17°28'0"E
17°29'0"E
17°30'0"E
30°33'0"S
30°34'0"S
30°35'0"S
30°36'0"S
30°37'0"S
30°38'0"S
30°39'0"S
30°40'0"S
CA Groen-Spoeg
N
47
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


17°18'0"E
17°19'0"E
17°20'0"E
17°21'0"E
17°22'0"E
17°23'0"E
17°24'0"E
17°25'0"E
30°24'0"S
30°25'0"S
30°26'0"S
30°27'0"S
30°28'0"S
30°29'0"S
30°30'0"S
30°31'0"S
30°32'0"S
30°33'0"S
CA 15
CA Groen-Spoeg
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


51
17°14'0"E
17°15'0"E
17°16'0"E
17°17'0"E
17°18'0"E
17°19'0"E
17°20'0"E
30°16'0"S
30°17'0"S
30°18'0"S
30°19'0"S
30°20'0"S
30°21'0"S
30°22'0"S
30°23'0"S
Hondeklip Bay
CA 15
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


17°11'0"E
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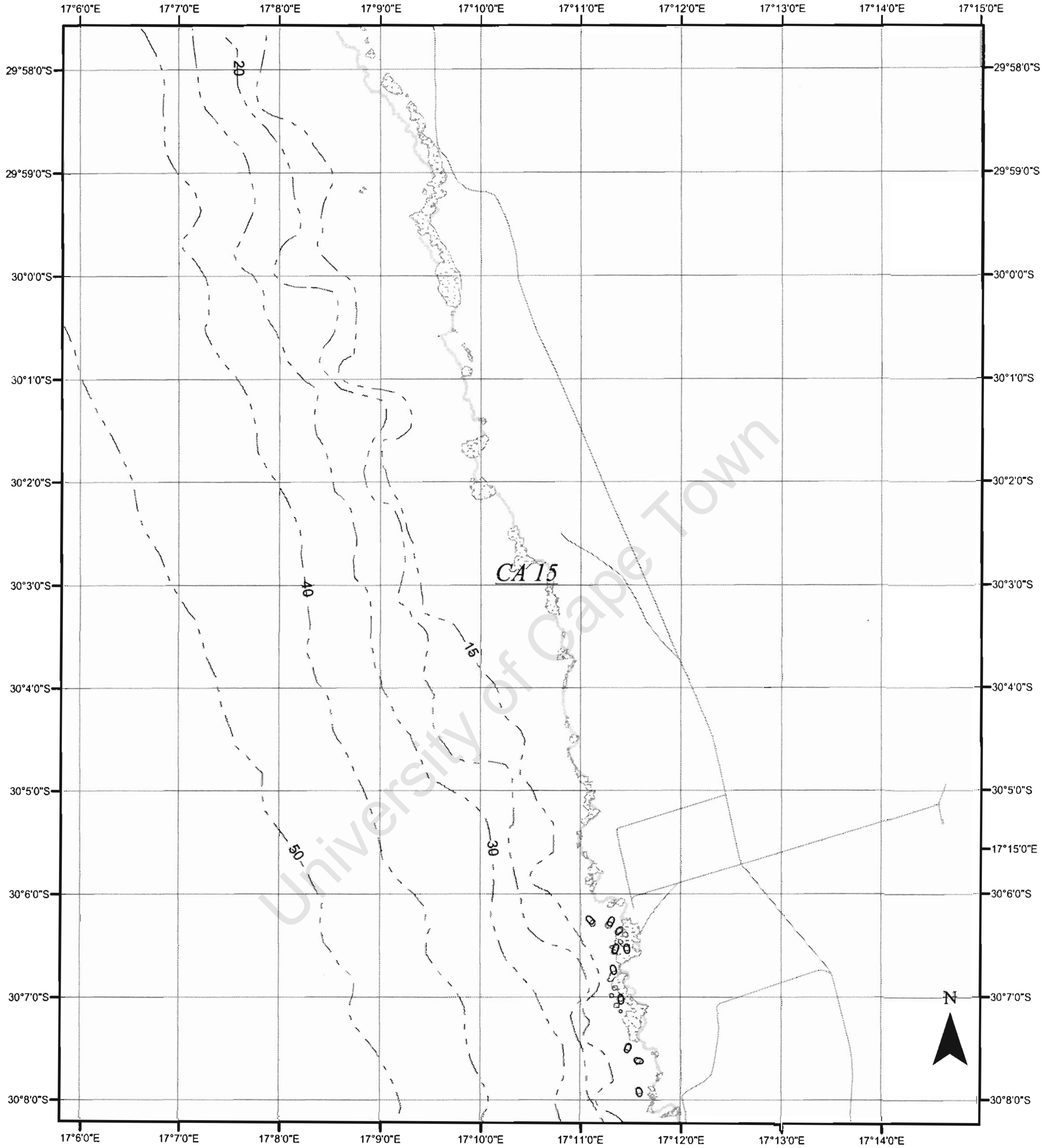
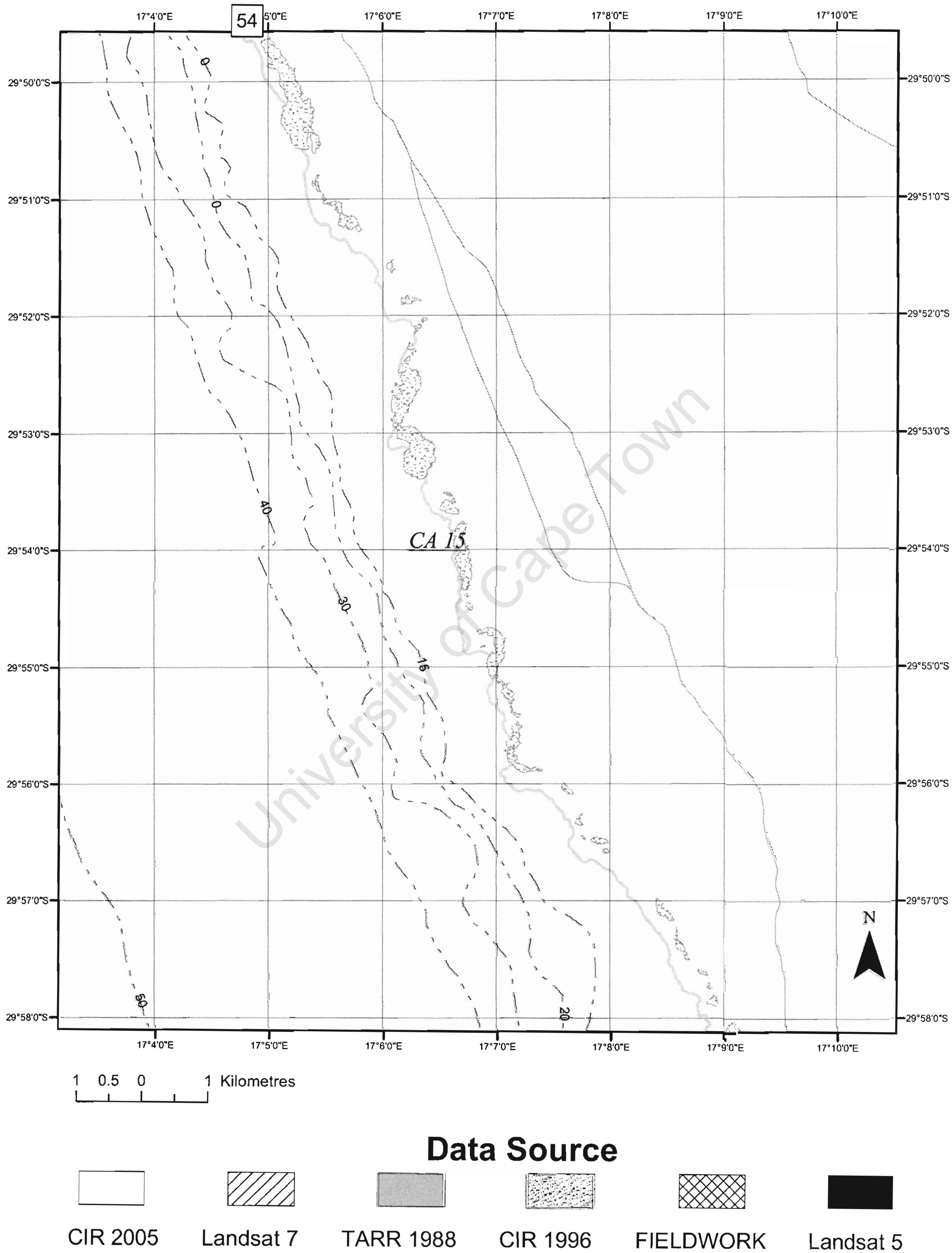
17°13'0"E
17°14'0"E
17°15'0"E
17°16'0"E
17°17'0"E
30°9'0"S
30°10'0"S
30°11'0"S
30°12'0"S
30°13'0"S
30°14'0"S
30°15'0"S
30°16'0"S
30
15
40
20
CA 15
Koiingnaas
N
50
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

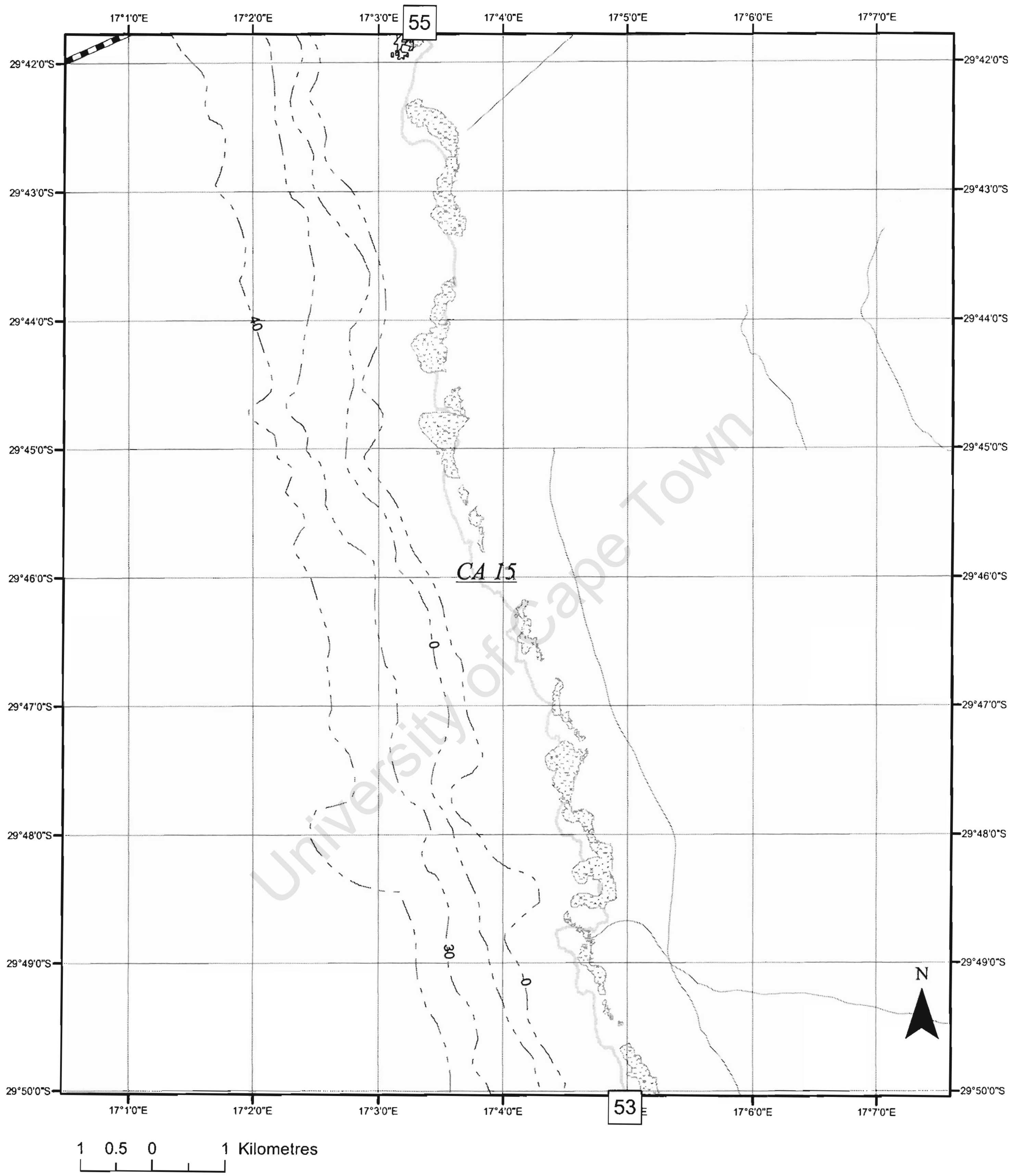


1 0.5 0 1 Kilometres

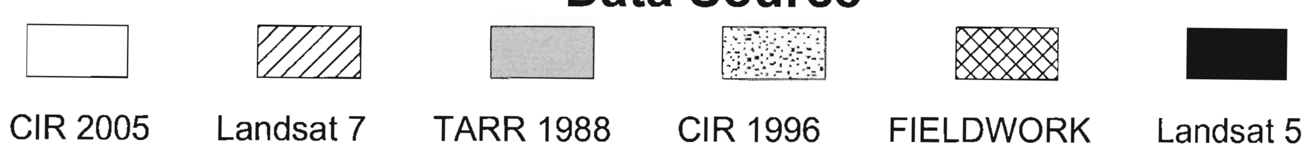
Data Source

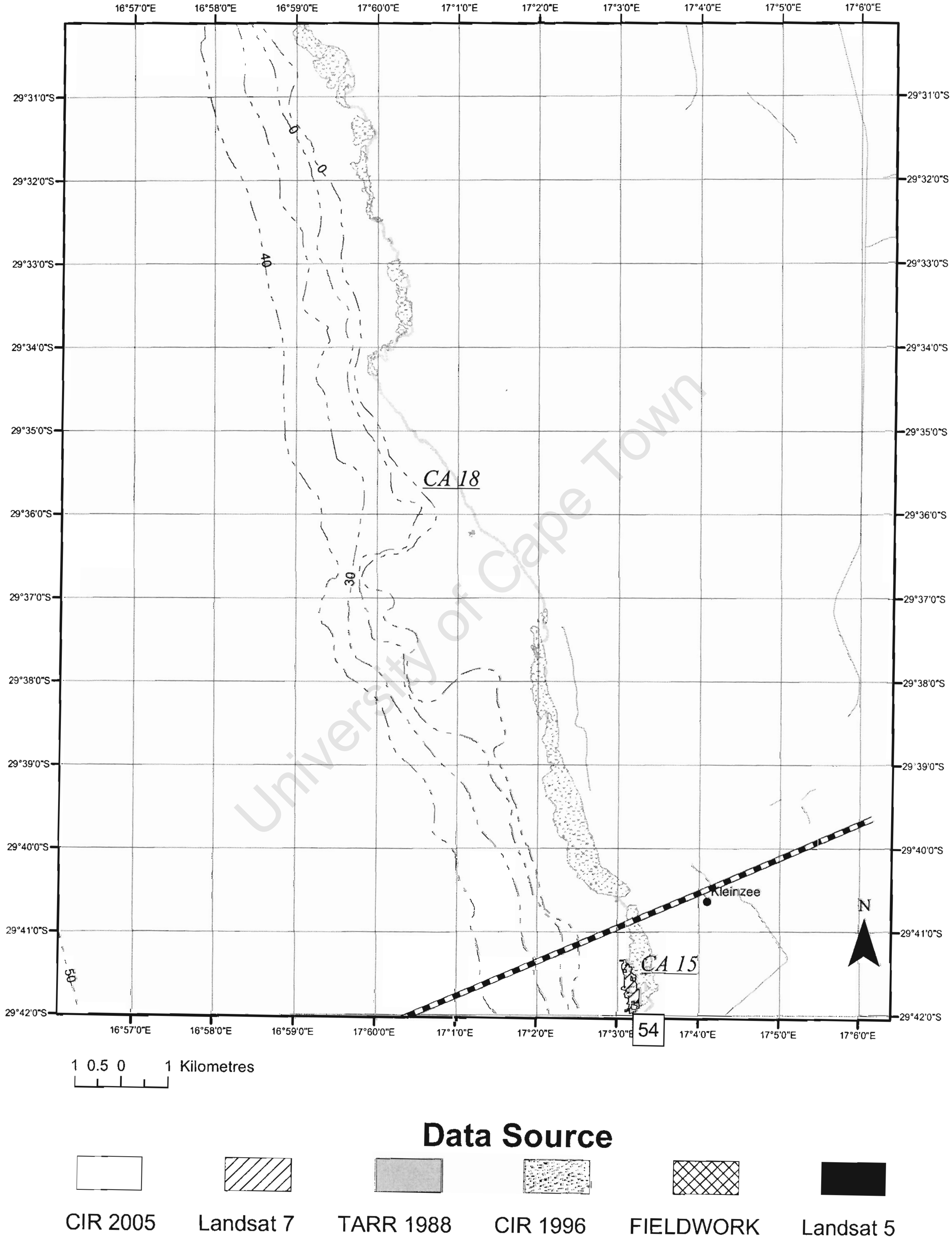
CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5

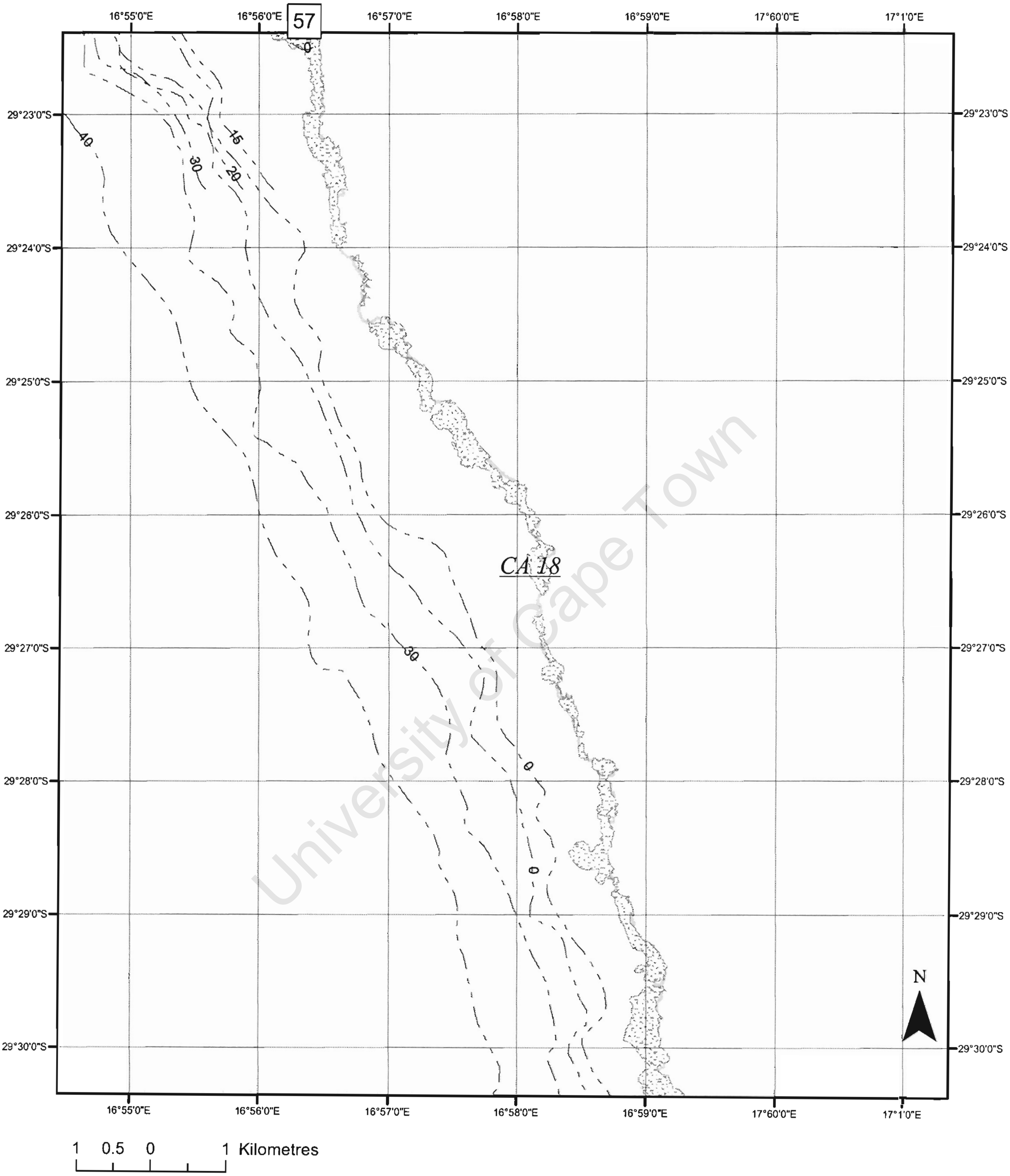

54
17°4'0"E
5'0"E
17°6'0"E
17°7'0"E
17°8'0"E
17°9'0"E
17°10'0"E
29°50'0"S
29°51'0"S
29°52'0"S
29°53'0"S
29°54'0"S
29°55'0"S
29°56'0"S
29°57'0"S
29°58'0"S
0
0
40
30
15
20
50
CA 15
N
17°4'0"E
17°5'0"E
17°6'0"E
17°7'0"E
17°8'0"E
17°9'0"E
17°10'0"E
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


17°1'0"E
17°2'0"E
17°3'0"E
55
17°4'0"E
17°5'0"E
17°6'0"E
17°7'0"E
29°42'0"S
29°43'0"S
29°44'0"S
29°45'0"S
29°46'0"S
29°47'0"S
29°48'0"S
29°49'0"S
29°50'0"S
40
CA 15
0
30
0
N
53
1 0.5 0 1 Kilometres

Data Source

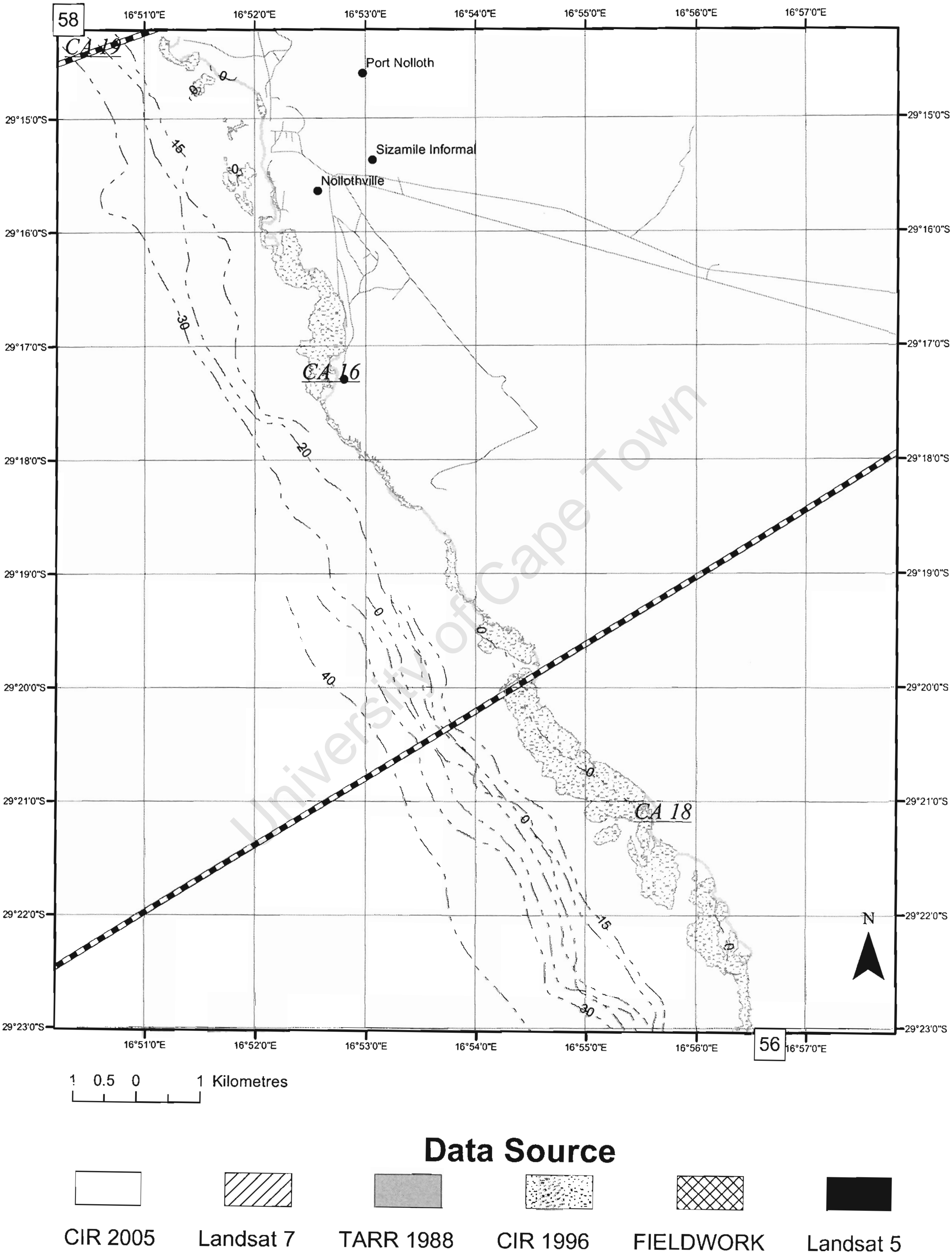

CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5

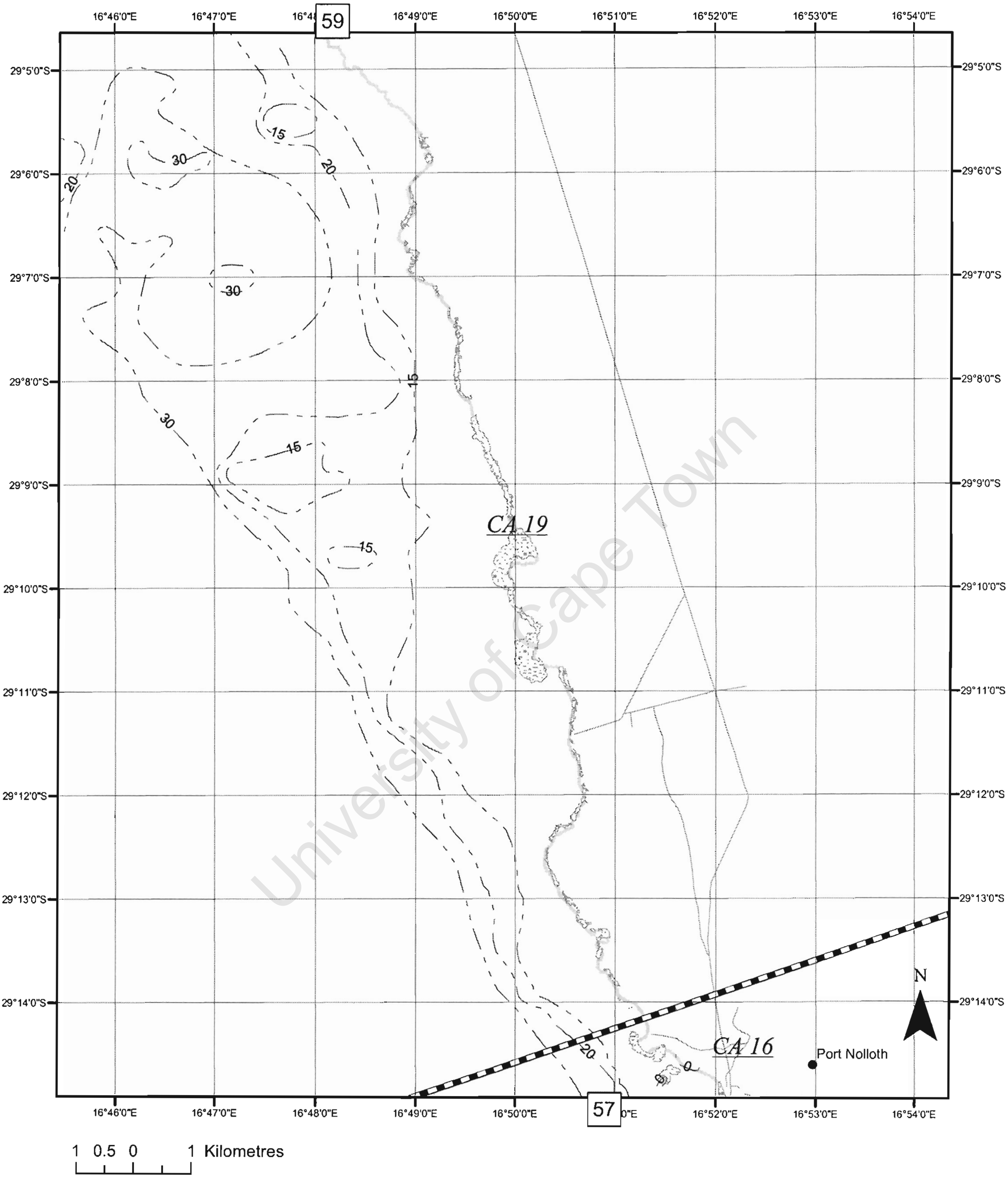

16°57'0"E
16°58'0"E
16°59'0"E
17°60'0"E
17°1'0"E
17°2'0"E
17°3'0"E
17°4'0"E
17°5'0"E
17°6'0"E
29°31'0"S
29°32'0"S
29°33'0"S
29°34'0"S
29°35'0"S
29°36'0"S
29°37'0"S
29°38'0"S
29°39'0"S
29°40'0"S
29°41'0"S
29°42'0"S
0
0
40
30
50
CA 18
CA 15
Kleinzee
N
54
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



Data Source

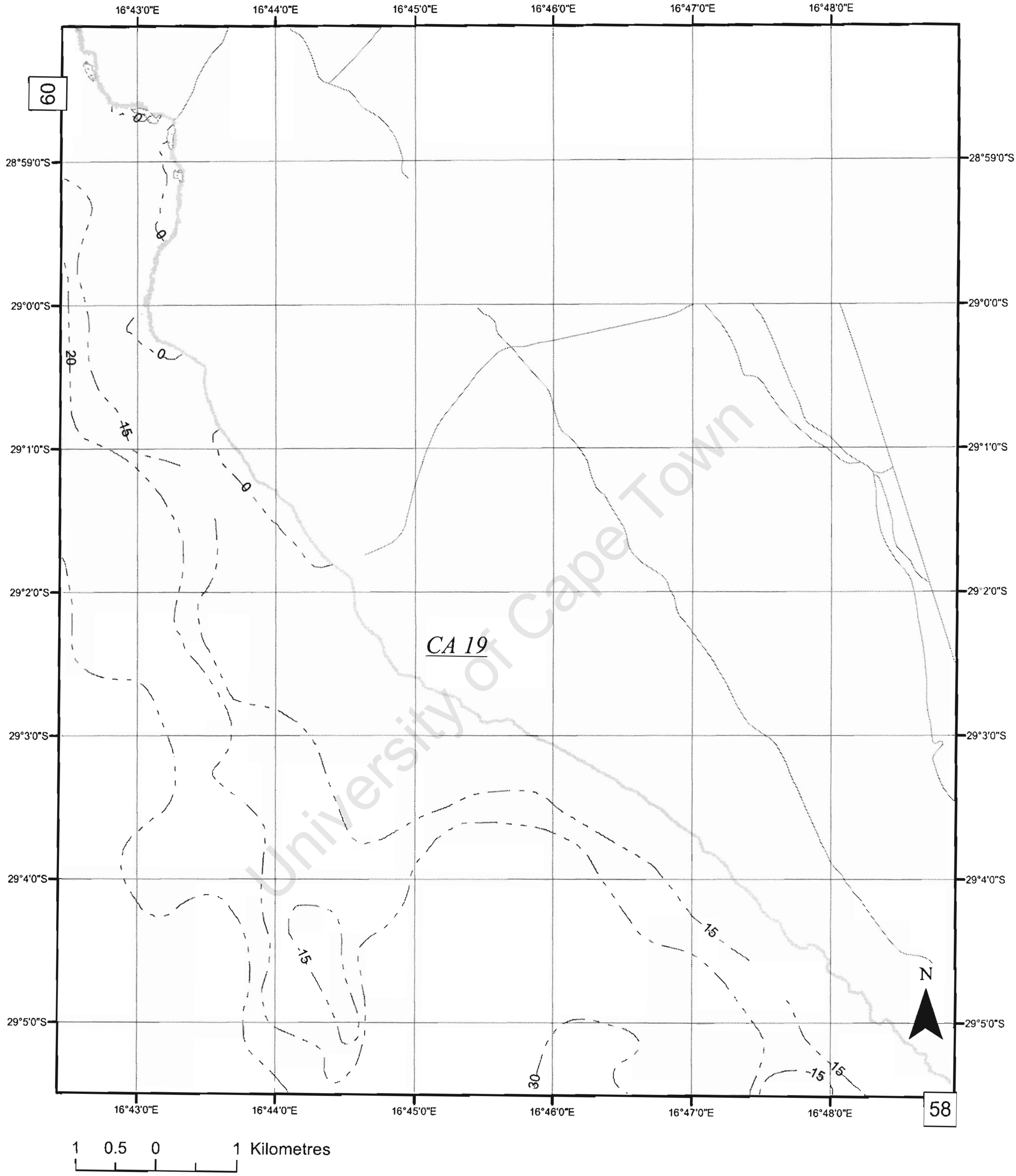
CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5


58
56
CA 19
CA 16
CA 18
Port Nolloth
Sizamile Informal
Nollothville
16°51'0"E
16°52'0"E
16°53'0"E
16°54'0"E
16°55'0"E
16°56'0"E
16°57'0"E
29°15'0"S
29°16'0"S
29°17'0"S
29°18'0"S
29°19'0"S
29°20'0"S
29°21'0"S
29°22'0"S
29°23'0"S
N
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



Data Source

CIR 2005	Landsat 7	TARR 1988	CIR 1996	FIELDWORK	Landsat 5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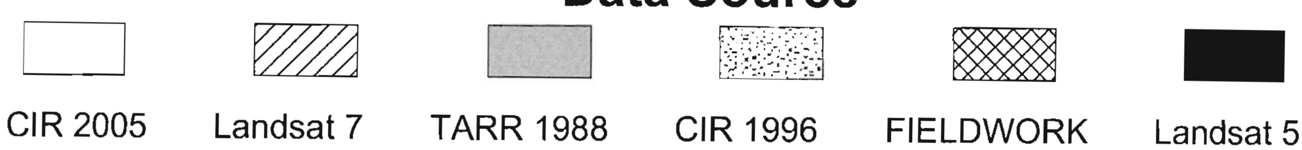
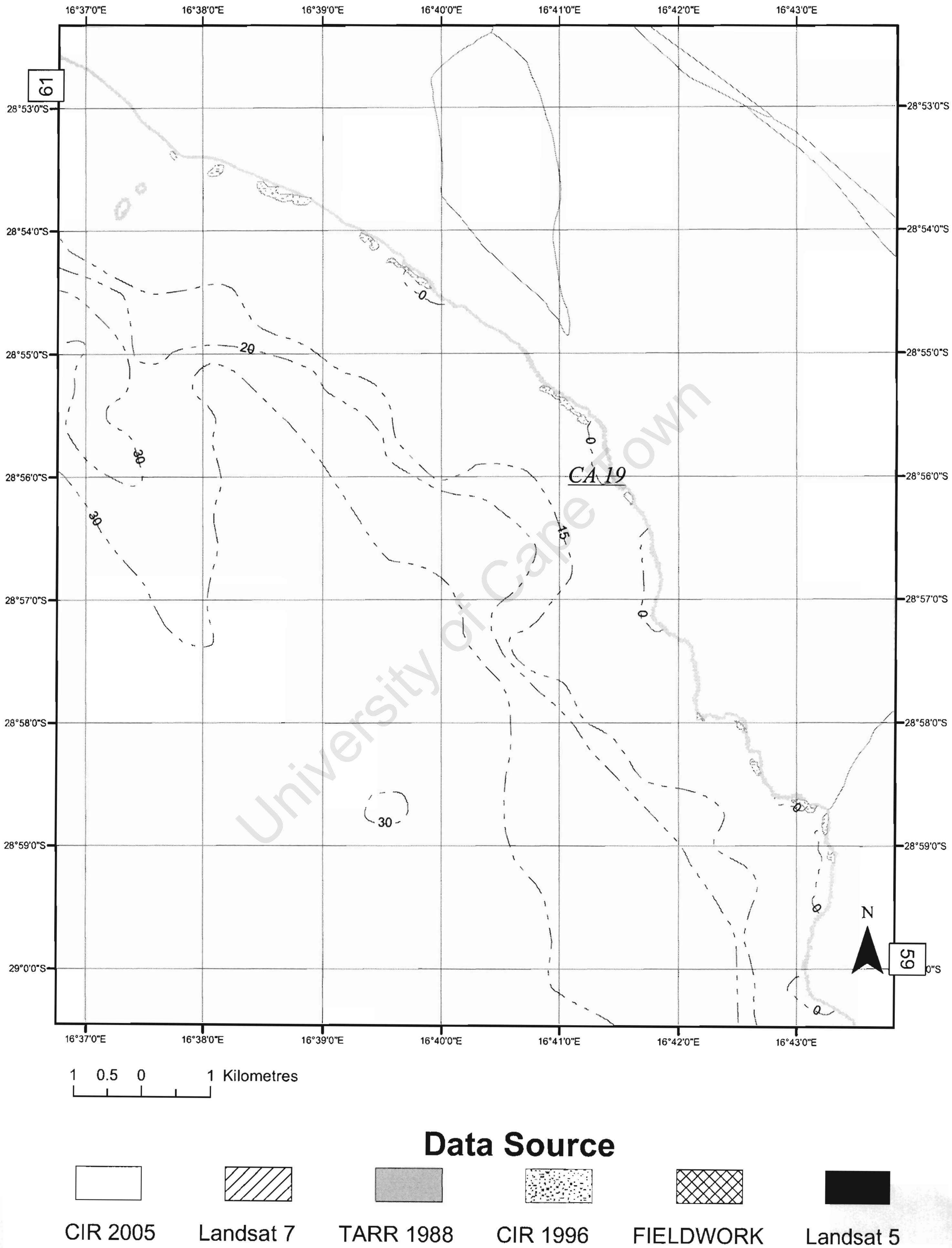
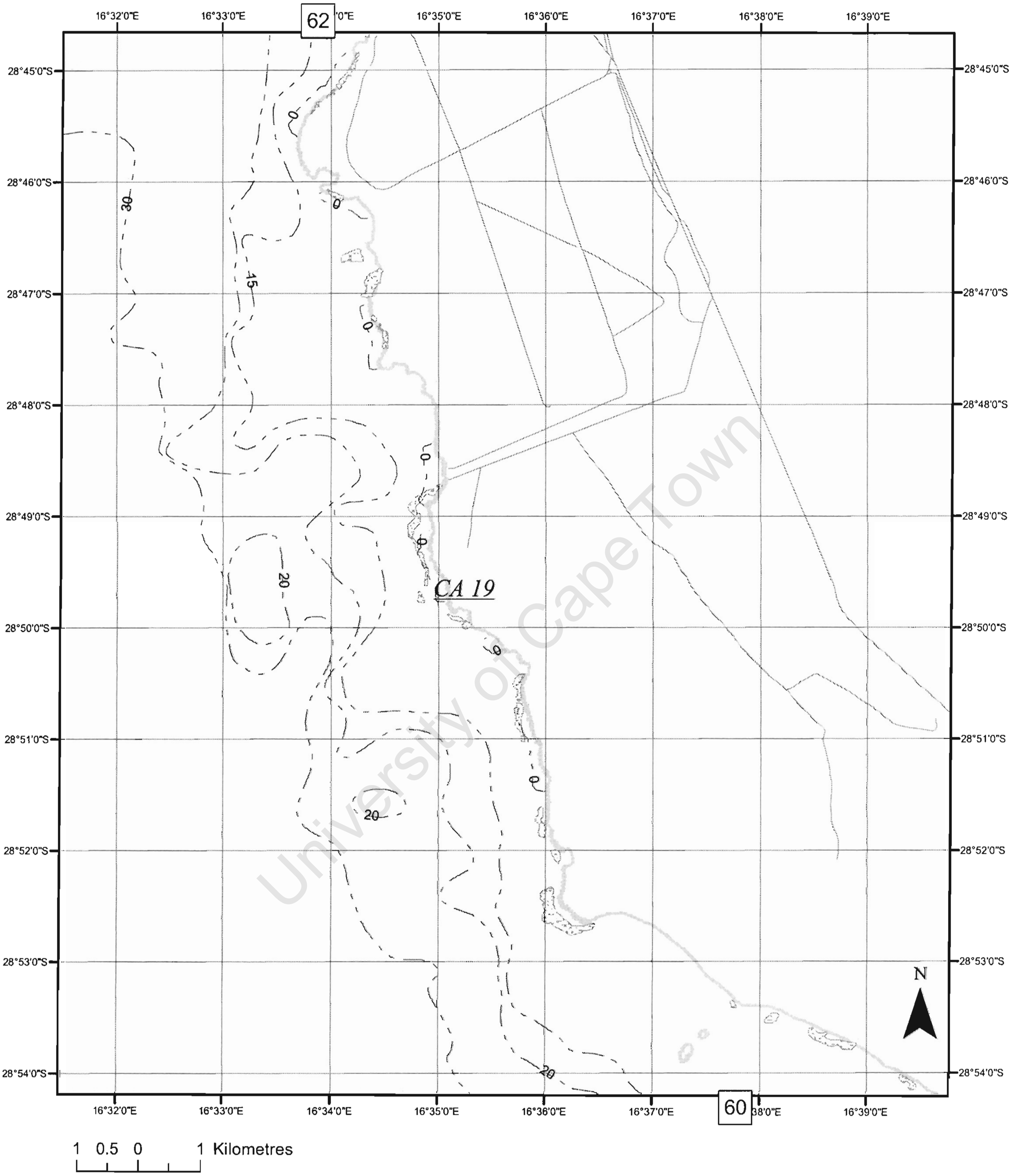
16°44'0"E
16°45'0"E
16°46'0"E
16°47'0"E
16°48'0"E
60
28°59'0"S
29°0'0"S
29°1'0"S
29°2'0"S
29°3'0"S
29°4'0"S
29°5'0"S
CA 19
N
58
1 0.5 0 1 Kilometres

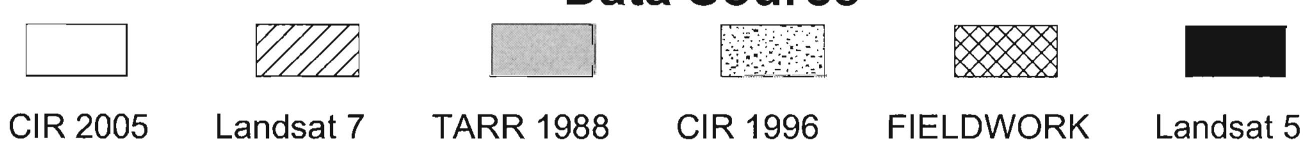
Data Source

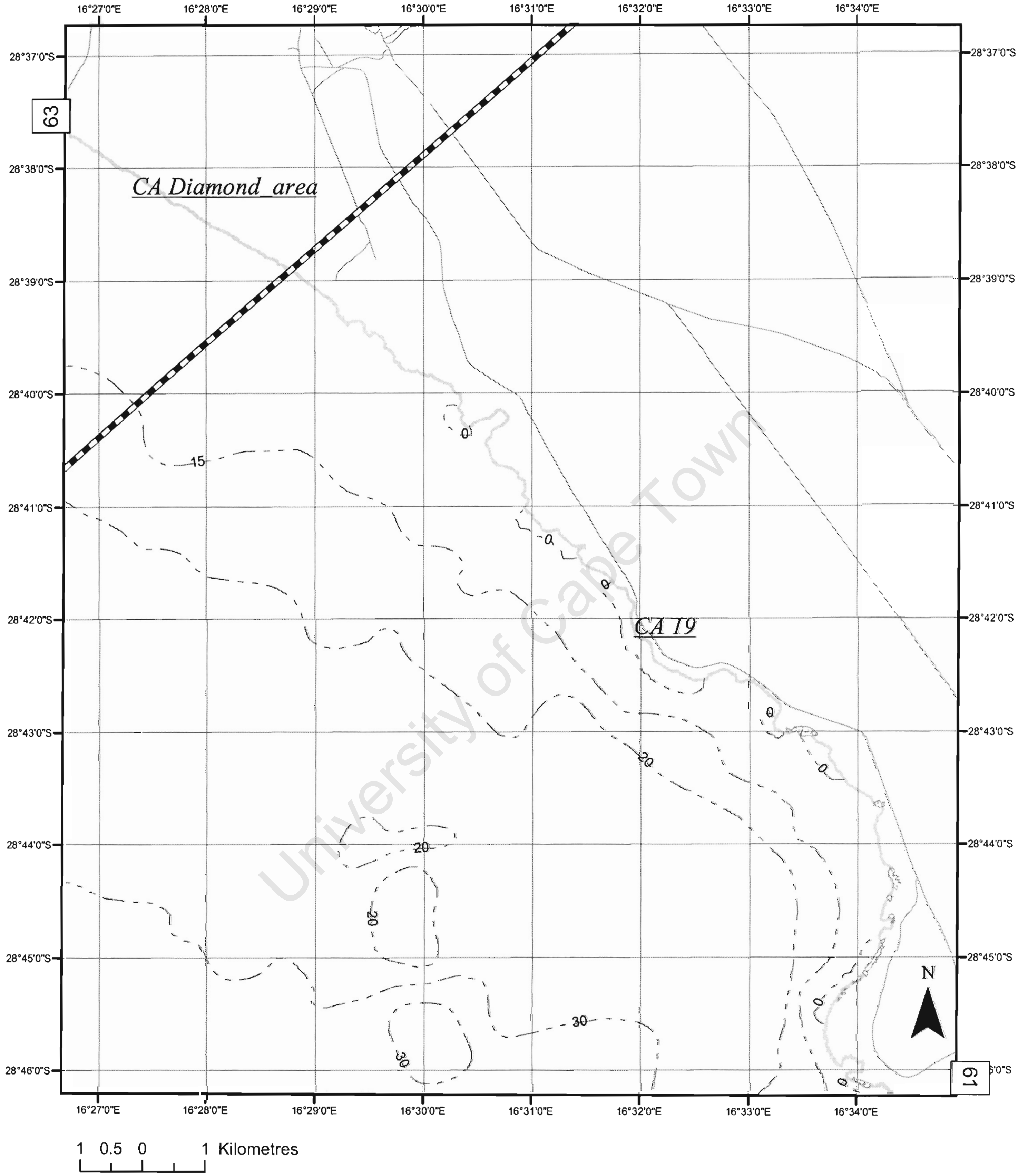

CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


16°37'0"E
16°38'0"E
16°39'0"E
16°40'0"E
16°41'0"E
16°42'0"E
16°43'0"E
28°53'0"S
28°54'0"S
28°55'0"S
28°56'0"S
28°57'0"S
28°58'0"S
28°59'0"S
29°0'0"S
61
59
N
CA 19
0
15
20
30
1 0.5 0 1 Kilometres
Data Source
CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5


62
16°32'0"E
16°33'0"E
16°35'0"E
16°36'0"E
16°37'0"E
16°38'0"E
16°39'0"E
28°45'0"S
28°46'0"S
28°47'0"S
28°48'0"S
28°49'0"S
28°50'0"S
28°51'0"S
28°52'0"S
28°53'0"S
28°54'0"S
30
15
20
0
CA 19
N
60
16°34'0"E
1 0.5 0 1 Kilometres

Data Source


CIR 2005
Landsat 7
TARR 1988
CIR 1996
FIELDWORK
Landsat 5



Data Source

CIR 2005 | Landsat 7 | TARR 1988 | CIR 1996 | FIELDWORK | Landsat 5