Geographic Information Systems in wildlife management

A case study using yellow-eyed penguin nest site data

Ryan D. Clark, Renaud Mathieu and Philip J. Seddon

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ABSTRACT

This report provides a comprehensive yet simple guide to the construction and use of a Geographic Information System (GIS) for collating, analysing, updating and managing data in wildlife management or research projects. The spatial analysis of yellow-eyed penguin (hoiho, *Megadyptes antipodes*) nest site data from Boulder Beach, Otago Peninsula, is used as an example. The report describes the key components used in the construction of the GIS, which included aerial photography, a digital elevation model and habitat map of the study area, and nest site data collected at Boulder Beach between 1982 and 1996. The procedures for estimating the geographic locations of nest sites using historical hand-drawn sketch maps are also described, demonstrating the potential for incorporating and analysing historical datasets in this type of GIS. The resulting GIS was used to conduct simple spatial analyses of some of the characteristics of yellow-eyed penguin nesting habitat selection, as well as the densities of nest sites in each type of nesting habitat at Boulder Beach. The sources of error, uncertainty and other limitations of this and other GIS are described, along with procedures and steps to minimise and avoid them. The yellow-eyed penguin GIS described in this report provides an example of the potential utility of GIS in ecological research and management of both yellow-eyed penguins and many other species.

Keywords: Geographic Information Systems (GIS), yellow-eyed penguin, hoiho, *Megadyptes antipodes*, wildlife management, habitat map, spatial analysis, spatial ecology, New Zealand

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1. Introduction

Spatial ecology is the study of patterns and processes occurring in a geographic space or landscape that influence characteristics of plant and animal populations such as densities, distributions and movements. In recent years, there has been an increased awareness of the importance of incorporating spatial ecology into wildlife management. However, the analysis of spatial (or geographical) patterns and processes can require time and resources that are typically not available. Fortunately, there is a fast-growing repertoire of computer-based tools available to assist with complex spatial analyses.

1.1 GEOGRAPHIC INFORMATION SYSTEMS (GIS)

Geographic Information Systems (GIS) are some of the most important of these computer-based tools, and have rapidly become highly valuable—if not essential—to wildlife managers and researchers. A GIS generally consists of a computer-based program designed for organising, integrating, storing, analysing and creating visual representations (e.g. maps) of information about features of a particular geographic area or landscape. Data incorporated into a GIS usually have (or are given) a spatial reference. This reference links the data to the features they describe in a particular geographic 'space'. A common format of a GIS is a digital, interactive map of an area or location (typically) on the Earth's surface, which is linked to a database containing tables or spreadsheets of data (i.e. feature datasets) associated with some or all of the features displayed on the map (e.g. roads, water bodies, patches of vegetation and/or the locations of wildlife). This configuration enables relatively quick and easy visual assessment of spatial patterns and relationships in the data, as well as the ability to efficiently edit, update, analyse and create displays of potentially very large quantities of data. There are many different types, brands and configurations of GIS available, and most of these are capable of conducting a wide variety of analyses, both statistical and spatial (i.e. an analysis of how features are related to each other in the 'space' represented on a map).

In most GIS, feature datasets can be configured and displayed in the digital map space in raster or vector format. The raster format is generally used for datasets that describe continuous features (i.e. features that occur across the entire landscape, such as elevation or slope), while the vector format is used for discrete features (e.g. water bodies, roads and trees). Raster datasets are displayed as a sheet or grid of equal-sized square or rectangular cells, while vector datasets are displayed as points, lines or polygons. For example, the discrete features (i.e. nest sites) in the nest site dataset used in this study (described in section 2.2.4) were represented as points on the map. Other discrete features can be represented by lines (e.g. roads and rivers) or polygons (e.g. an area covered by a certain type of vegetation). When displayed in the digital map space, each raster or vector dataset represents an individual 'layer' of data, such that when several feature datasets are displayed they are stacked in overlapping layers.

Each type of data in a feature dataset is an attribute (i.e. qualitative or quantitative characteristic) of the feature it is linked or related to in the geographic space represented on the digital map. Spatial or geographic attributes contain data that specifically describe the geographic (or spatial) location and extent of features (e.g. the x and y coordinates or latitude and longitude, and area on the map where a feature occurs). All other attributes (e.g. names, nest site numbers, or virtually any other qualitative or quantitative data) are considered non-spatial because they do not contain inherent spatial information (i.e. they cannot be linked to a 'space' on the map without being paired with associated spatial attributes). The data for each type of feature (i.e. raster or vector dataset) are organised into spreadsheets or tables, where each row in a table represents a single cell in a raster dataset or an individual feature in a vector dataset, and each column represents a different attribute in the dataset.

As with most types of computer-based programs or systems, in GIS there is a unique set of terminology, or jargon, used for referring to common components, features and processes. In addition, despite having similar components and processes, this unique terminology can also vary between different GIS packages or brands (i.e. developed by different vendors). For example, in the ArcGIS® software developed by the Environmental Systems Research Institute (ESRI), vector data are typically stored in 'shapefiles'. Definitions of GIS-related terminology used in this report are listed in the Glossary. A thorough introduction to GIS and their utility in science can be found in Longley et al. (2005).

1.2 THE UTILITY OF GIS IN WILDLIFE MANAGEMENT

In the context of wildlife management, a GIS enables wildlife distributions, movements and habitat use patterns and processes to be mapped and analysed, which can provide valuable information for the development of management strategies (for examples see Lawler & Edwards 2002; Harvey & Hill 2003; Fornes 2004; Gibson et al. 2004; Greaves et al. 2006; Shanahan et al. 2007). Recently, the rapid development and technological improvements in GIS, as well as in remote sensing techniques and global positioning systems (GPS), have significantly increased their availability and utility in ecological management and research (Guisan & Zimmermann 2000). Subsequently, the use of GIS for mapping, monitoring, analysing and modelling the nesting behaviour and habitats of wildlife populations has become increasingly widespread. For example, studies have used GIS to determine the distributions and extents of habitats selected by nesting animals (McLennan 1998; Maktav et al. 2000; Sims & Smith 2003; Fornes 2004; Smith et al. 2004; Beggs 2005; Urios & Martínez-Abraín 2006), and to identify nesting habitats that are potentially available (Lawler & Edwards 2002; Harvey & Hill 2003; Gibson et al. 2004; Clement 2005; Mathieu et al. 2006).

1.3 YELLOW-EYED PENGUIN MANAGEMENT

The yellow-eyed penguin or hoiho (*Megadyptes antipodes*) is a nationally vulnerable (Hitchmough et al. 2007) and globally endangered (Birdlife International 2007) species that is endemic to New Zealand (Marchant & Higgins 1990; Williams 1995). It breeds in coastal habitats along the eastern and southern coasts of the South Island, and on Stewart Island/Rakiura, Codfish Island (Whenuahou), the Auckland Islands, and Campbell Island/Motu Ihupuku (Marchant & Higgins 1990; Williams 1995). Yellow-eyed penguins are the least colonial of all penguin species (Richdale 1957; Jouventin 1982; Darby & Seddon 1990). Breeding pairs commonly select well-concealed nest sites that are spaced relatively far apart and up to 1 km inland (Seddon & Davis 1989; Darby & Seddon 1990).

The importance of the yellow-eyed penguin population to New Zealand's tourism industry, its threatened status, and a general increase in public awareness of the species has increased attention to its conservation (Wright 1998; McKinlay 2001; Ellenberg et al. 2007). Since the 1970s, many penguins have been banded to assist with data collection for biological and ecological studies, as well as population monitoring (Efford et al. 1996). Several studies have sought to provide an improved scientific basis for yellow-eyed penguin management. These studies have resulted in a large collection of data and information about the growth, feeding, breeding success and nesting habits of individual penguins and their offspring (e.g. Darby 1985; Lalas 1985; Seddon & Davis 1989; Darby & Seddon 1990; van Heezik 1990; van Heezik & Davis 1990; Alterio 1994; Moller et al. 1995; Efford et al. 1996; Ratz 2000; Ellenberg et al. 2007). However, although different management strategies have been tested, there has so far been little effort to incorporate the spatial patterns and processes that could be assessed from the large amount of data now available.

1.4 OBJECTIVES

This report describes the construction and basic functionality of an updatable GIS of yellow-eyed penguin nest site data that managers and researchers could use to assist in the development of conservation strategies for the species, and could expand and modify as necessary.

Data collection, field surveys and initial GIS setup were completed in 2005 by Justin Poole for a Bachelor of Science Honours project (Poole 2005). The data and methods used in the construction of the GIS are outlined in section 2 of this report. Section 3 provides examples of analyses using the GIS, plus suggestions for additional uses in ecological research and management of yellow-eyed penguin and other species. The error and uncertainty in the yellow-eyed penguin GIS and some general limitations of GIS are then addressed (section 4), followed by a summary of the main capabilities of the GIS described in this report and recommendations for future studies (section 5).

2. Configuration and construction of the yellow-eyed penguin GIS

2.1 STUDY AREA

Boulder Beach, located at 45°53′S, 170°37′E on the southern coast of the Otago Peninsula (Fig. 1), was selected as the study area for demonstrating the capabilities of a GIS database in yellow-eyed penguin management. Boulder Beach contains one of the largest breeding populations of yellow-eyed penguins on the South Island of New Zealand and is a protected reserve owned by WWF and administered by the New Zealand Department of Conservation (DOC). It is considered to be one of the most important, and is one of the most intensely studied, of all yellow-eyed penguin breeding areas (Darby 1985; Seddon et al. 1989; Efford et al. 1996). An extensive range of data has been collected from the breeding yellow-eyed penguin population at Boulder Beach for more than 25 years.

The Boulder Beach area consists of two main sections, which are usually managed and studied separately: Midsection and Double Bay (see Fig. 1). Vegetation cover at both sections consists of dense stands of flax (*Phormium tenax*) interspersed with open areas of bare ground and/or grass, as well as patches of coastal scrub composed primarily of *Hebe elliptica, Lupinus arboreus, Myoporum laetum* and *Ulex europaeus*.

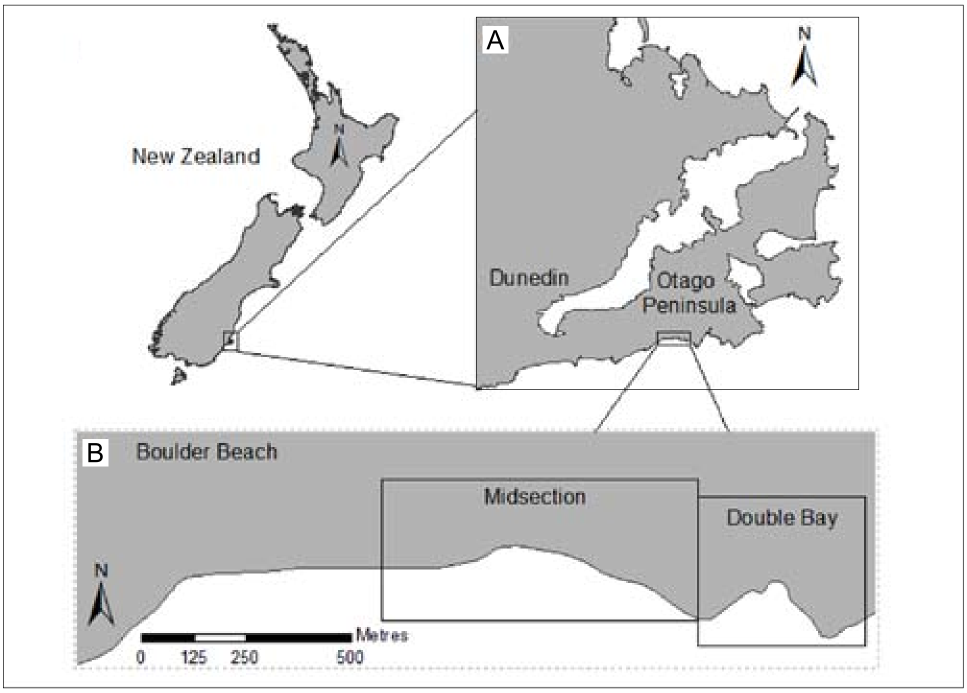


Figure 1. Map of New Zealand showing A. the location of the Otago Peninsula and B. the location and extent of the yellow-eyed penguin (*Megadyptes antipodes*) nesting areas at Midsection and Double Bay at Boulder Beach on the southern coast of the Otago Peninsula.

2.2 GIS CONSTRUCTION

As described previously, a common GIS configuration is essentially a digital, interactive map linked to a database that contains several datasets related to features in the map space. The yellow-eyed penguin GIS follows this general configuration, and was constructed using ArcGIS® 9.1 (ESRI).

For the construction of the yellow-eyed penguin GIS, four key feature datasets, or data layers, were required for the Boulder Beach study area: base map imagery, elevation data, habitat data and nest site data. The procedures for acquiring, collating, deriving and implementing these datasets into the GIS are described below.

2.2.1 Base map imagery

A base map is often an important data layer in many GIS. It provides fundamental information that can be used for the extraction of data for geographic features (e.g. the extent of different types of land cover or habitats), and as a reference for localising or overlaying other feature datasets (e.g. the locations of nest sites).

A base map often consists of one or more aerial photography or satellite imagery raster datasets. When selecting the imagery for the base map of Boulder Beach, it was important to consider the resolution or pixel size (i.e. the detail to which the location and shape of geographic features were depicted) and scale (i.e. the size of objects or features in the imagery relative to their actual size) required, as these would influence the accuracy of subsequent analyses, and the interpretation and classification of features (Burrough & McDonnell 1998; Henderson 1998). For example, it would have been difficult to distinguish small patches of vegetation with small-scale (i.e. where objects or features were very small relative to their actual size) and/or low-resolution (i.e. large pixel size) imagery.

The imagery acquired for the yellow-eyed penguin GIS was a stereopair of colour aerial photographs of Boulder Beach (Fig. 2) taken in 1997 by Air Logistics (now GeoSmart© Ltd). Amongst the different sets of imagery available, the 1997 stereopair provided the most suitable resolution (scanned pixel size = 0.5 m) for the interpretation, classification and extraction of habitat data, and estimation of the geographic locations of nest sites (described in sections 2.2.3 and 2.2.4, respectively).

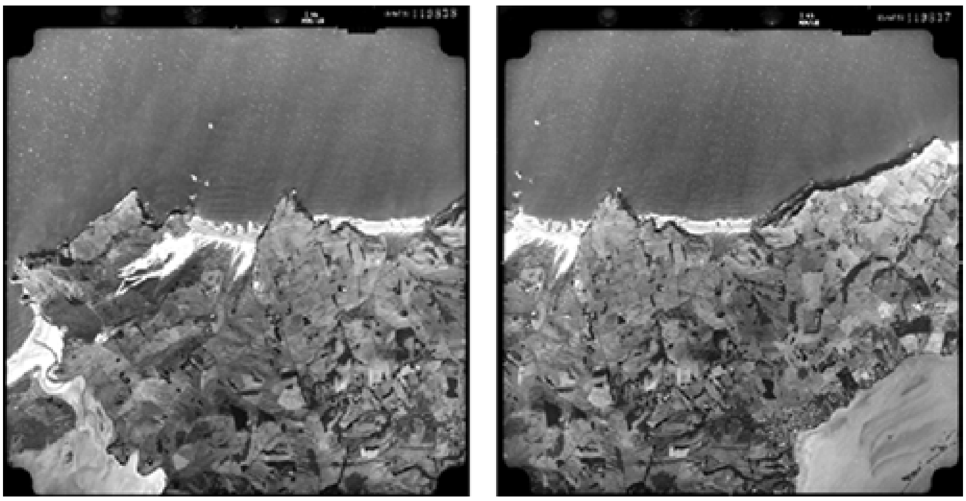


Figure 2. The raw (i.e. un-orthorectified) stereopair of aerial photographs of Boulder Beach used to create the orthorectified base map image in the yellow-eyed penguin (*Megadyptes antipodes*) GIS. These are black and white images of the original colour photographs taken in 1997 by Air Logistics (now GeoSmart© Ltd).

2.2.2 Elevation data

Before the 1997 aerial photography of Boulder Beach could be used for analysis, interpretation or extraction of other data layers, the imagery needed to be registered to a projection coordinate system. Measurements made from raw aerial photography or satellite imagery are generally not reliable due to geometric distortions caused by camera or sensor orientation, terrain relief, curvature of the Earth, film and/or scanning distortion, and/or measurement errors (Thomas 1966; Wolf 1983; Jensen 1996). Therefore, photogrammetric modelling is used to remove these errors through the process of orthorectification, which generates planimetrically true images that have the geometric characteristics of a topographic map combined with the visual quality of a high-resolution photograph.

Several software programs are available for relatively easy and rapid orthorectification of digital or scanned aerial photographs. The Leica Photogrammetry Suite (LPS) V8.6 (Leica Geosystems 2003) software package was used to orthorectify the scanned 1997 stereopair of aerial photographs of Boulder Beach. This process consisted of the following steps: collection of ground control points, definition of the interior and exterior orientation parameters, extraction of a digital elevation model, and image resampling (Li et al. 2002).

Ground control points

Ground control points (GCPs) are accurate coordinates for specific and distinct positions that appear in the imagery to be orthorectified. GCPs are collected to provide a reference for registering imagery to a projection coordinate system via a process called georeferencing. When collecting GCPs for the Boulder Beach imagery, the following methodology was followed to ensure accurate and effective orthorectification:

- The GCPs were collected with a GPS device capable of obtaining a relatively high level of positional accuracy (i.e. a GIS or mapping-grade GPS capable of obtaining positions with less than ± 5 m error).
- A sufficient number and spatial coverage (both horizontal and vertical) of GCPs were collected to adequately represent the geographic area and type of terrain depicted in the imagery.
- The GCPs were collected at distinct features or locations that were easily identifiable in the imagery (e.g. road or track intersections, the corners of distinct buildings or fence lines, and/or the centre of large solitary boulders or trees).

For the orthorectification of the Boulder Beach imagery, 12 GCPs were collected with a Trimble® GeoExplorer3™ GPS receiver. The specified accuracy of the receiver was ± 1–5 m after post-collection processing of the data with GPS Pathfinder® Office 3.0 software. The post-collection processing involved differential correction using data collected at the Trimble 4000SSE permanent reference station on the roof of the University of Otago's School of Surveying building, which is c. 9 km (along a straight line) from the Boulder Beach study area. Following post-collection processing, the GCPs were projected in the New Zealand Transverse Mercator (NZTM) coordinate system, which is the most current and accurate of the nationally accepted projected coordinate systems for New Zealand.

Interior/exterior orientation

Interior orientation refers to the internal geometry of the camera or sensor used to capture the imagery. Defining the interior orientation of an image identifies and corrects distortions that arise from the curvature of the sensor lens, the focal length and perspective effects (Leica Geosystems 2003). The procedure involves the establishment of the position (i.e. the '*x*' and '*y*' image coordinates) of the principal point of an image with respect to the fiducial (i.e. standard reference) marks of the sensor frame. The information required to define the interior orientation of an image is generally obtained through the process of camera calibration. The interior orientation parameters for the 1997 imagery of Boulder Beach were obtained from a camera calibration report provided by Air Logistics, the supplier of the aerial photographs.

The exterior orientation parameters of an image define the position and angular orientation of the camera or, more specifically, the perspective centre of the film or sensor, at the time of image capture. Due to the constant movement and positional changes that occur during the process of capturing aerial photographs, the exterior orientation parameters are different for each image. The process of defining the exterior orientation of an image involves a transformation from the image coordinate system (i.e. '*x*' and '*y*') to a projection coordinate system (i.e. easting and northing) (Leica Geosystems 2003). This results in the imagery being projected in the same NZTM coordinate system that was used for the GCPs.

A handful of methods are available for computing the exterior orientation parameters of imagery. In this study, we used the LPS software package, which uses the space resection by collinearity technique (Leica Geosystems 2003). After manually identifying the locations and registering the projected coordinates (i.e. easting, northing and height (elevation) in metres) of the 12 GCPs on the stereopair imagery of Boulder Beach, the LPS software automatically computed the exterior orientation parameters for both images using triangulation. The accuracy of the triangulation was indicated by the root mean square error (RMSE) of the residuals of the GCPs (see Appendix 1). These values equated to c. ± 0.22 m on the ground, which was adequate for the accuracy requirements of the yellow-eyed penguin GIS.

Digital elevation model extraction

With the interior and exterior orientation parameters defined, the stereopair of aerial photographs of Boulder Beach could be viewed as a single image in three dimensions with an appropriate stereo-viewing device. However, for use in a GIS, it was necessary to generate an orthorectified image, which is a two-dimensional image (i.e. visible in the '*x*' (easting) and '*y*' (northing) plane) that is adjusted to account for terrain or relief distortion (i.e. distortion in the '*z*' (height or elevation) plane). Orthorectification required the extraction of height or elevation data from the stereopair of aerial photographs. This was achieved using the principle of parallax, which refers to the apparent shift in the position of an object or feature when viewed from two different angles. For the Boulder Beach imagery, the two different angles were determined by the height and perspective centre (see previous section) of the camera sensor for each of the two photographs in the stereopair. Triangulation was then used to estimate the distance of different objects or positions in the imagery from the camera sensor. Smaller distances of objects or positions equated to higher elevation values, while larger distances equated to lower elevation values.

The elevation data required for the orthorectification of the Boulder Beach imagery was automatically extracted using the LPS software. The output of the extraction provided a digital elevation model (DEM) of Boulder Beach. Aside from its utility in image orthorectification, a DEM is often a very useful raster data layer from which other datasets related to topography can be derived (e.g. aspect, slope). After extraction, some manual editing of the Boulder Beach DEM was required to correct failed or incorrect elevation values, and to smooth out irregularities. For example, water features (i.e. the ocean) were given a constant elevation value of zero (i.e. sea level), and anomalies such as sudden dips or rises in elevation were smoothed over using a nearest neighbour method (a type of averaging).

Image resampling

The final step in the orthorectification process involved the resampling of the Boulder Beach imagery with the edited DEM. The resampling procedure involved the use of a nearest neighbour technique in LPS, which matched the position of each pixel of the DEM with its equivalent position in the imagery (Leica Geosystems 2003). This process is the actual orthorectification of the imagery. A portion of the resulting orthorectified image of Boulder Beach as of 1997 is displayed in Fig. 3.

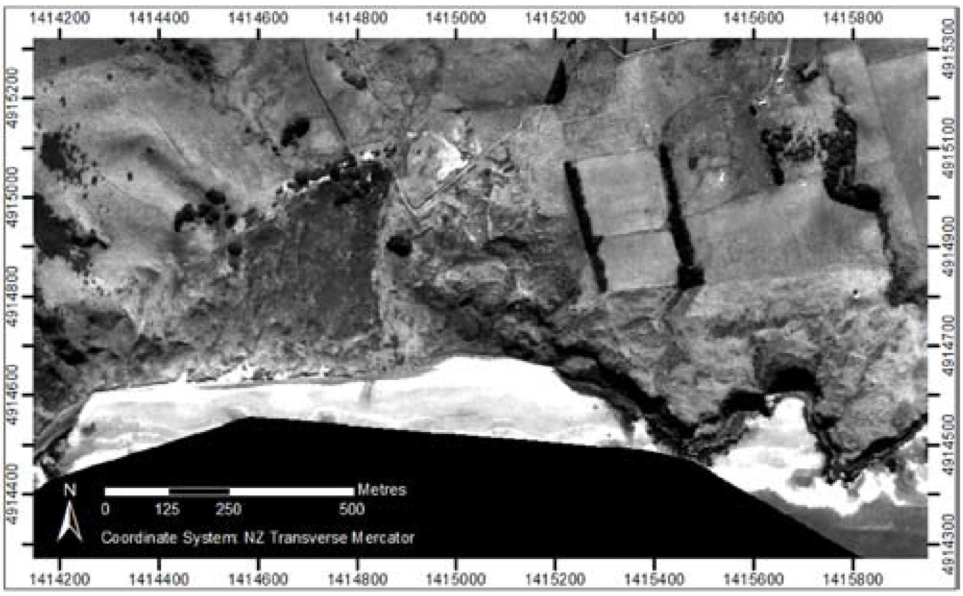


Figure 3. A portion of the orthorectified 1997 image of Boulder Beach, Otago Peninsula. This image was used as the base map in the yellow-eyed penguin (*Megadyptes antipodes*) GIS (described in section 2.2.

2.2.3 Habitat data

The next step in the construction of the yellow-eyed penguin GIS was the extraction of land cover data from the orthorectified image of Boulder Beach to create a habitat map data layer. This data layer was required to analyse the effects of habitat type on yellow-eyed penguin nest site selection and density at Boulder Beach. The creation of the habitat map consisted of the following two steps: defining a set of land cover classes (hereafter termed 'habitat classes') known to exist in the study area, and then using a remote sensing technique to classify the orthorectified imagery based on the pre-defined set of classes.

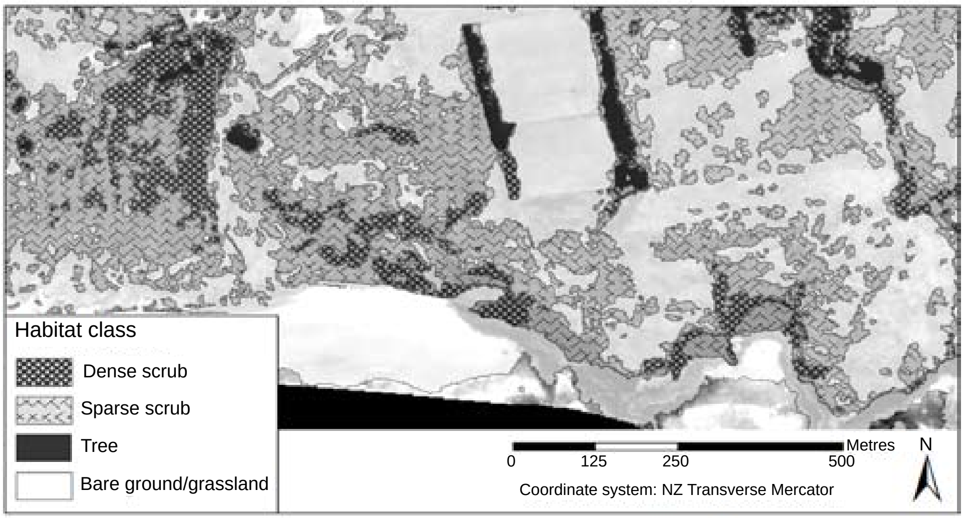
Five broad habitat classes were defined for the habitat map of Boulder Beach:

1. Dense scrub: patches greater than 100 m^2 that contained dense coverage of primarily mature *Phormium tenax* and/or *Hebe elliptica*.
2. Sparse scrub: loosely dispersed, younger *P. tenax* and *H. elliptica* mixed with other species (e.g. *Cortaderia* sp., *Meuhlenbeckia australis, Myoporum laetum,* and *Pteridium* sp.).
3. Tree: primarily exotic *Macrocarpa* species.
4. Bare ground–grassland: all remaining types of land cover other than water, e.g. sand, boulders, and native and exotic grass covered areas.
5. Water: the ocean.

There were a variety of remote sensing techniques to choose from for classifying the orthorectified image of Boulder Beach, each with a different level of complexity and accuracy. The simplest technique may have been to manually draw polygons for each habitat class in ArcGIS® 9. However, the accuracy of this technique was subject to a potentially high level of observer bias and error. Therefore, a semi-automated, object-oriented technique was employed using the eCognition™ software program (Definiens® Imaging 2004). Rather than analysing individual pixels, the object-oriented technique identified groups of similar pixels as distinct objects in the image (e.g. buildings, patches of distinct vegetation and water bodies) based on several spectral and spatial parameters (Mathieu et al. 2007).

The classification process in eCognition™ consisted of three steps. Initially, the Boulder Beach image was automatically segmented into objects based on a combination of four pre-defined factors: scale, colour, smoothness and compactness (Mathieu et al. 2007). The software then needed to be 'trained' to classify the image objects into the five pre-defined habitat classes. This is known as a supervised classification and it required habitat information that was collected during a preliminary field survey of Boulder Beach. Information from photographs and written descriptions of distinct patches of each habitat class that were easily visible in the imagery were used as references for classifying the image objects. Samples of manually classified objects were then used by eCognition™ to calculate statistics (e.g. mean and standard deviation) of spectral (e.g. brightness and colour) and spatial (e.g. distribution and scale) parameters for each habitat class. These statistics were used to automatically classify the remaining objects in the image. The output of the classification was manually checked and edited where obvious errors occurred. The final classification dataset, hereafter termed the 'habitat map data layer', was then imported into ArcGIS® 9 as a polygon shapefile. Figure 4 displays the habitat map for the Midsection and Double Bay areas.

Figure 4. A habitat map of the Midsection and Double Bay yellow-eyed penguin (*Megadyptes antipodes*) nesting areas at Boulder Beach. Four of the five broad classes of the habitat map are overlaid on the orthorectified 1997 imagery of Boulder Beach from which the map was derived (as described in section 2.3.3); water is excluded.



2.2.4 Nest site data

To demonstrate how historical data (i.e. data collected before GIS, GPS and related technologies were in use) could be incorporated and analysed in a GIS, yellow-eyed penguin nest site data that had been collected at Midsection and Double Bay from 1982 to 1996[1] were obtained from DOC in an Excel® spreadsheet. This nest site dataset contained information about several attributes of nest sites, including nest site identification codes, band numbers of nest-attending adults, types of nest site vegetation cover, and nest fate and fledging information (see Appendix 2 for a complete list of attributes in the yellow-eyed penguin nest site dataset).

Since it was already in a spreadsheet format, the nest site dataset could be easily imported into ArcGIS® 9. However, the dataset did not contain spatial attributes (i.e. data on specific geographic locations of nest sites), which were necessary for displaying the locations of nest sites on the digital base map and for completing any spatial analyses on the nest site data. The only information about the geographic locations of the nest sites were a collection of sketch (i.e. hand-drawn) maps of Midsection and Double Bay compiled by John Darby while working at the Department of Zoology, University of Otago. These sketch maps were originally designed to assist with nest site surveys in subsequent years and were drawn by different field surveyors, so there was variation in map scale and style between years.

On the sketch maps, the location of a nest site was indicated by either the nest site number alone or both the nest site number and a cross or point (see Fig. 5 and Appendix 3 for examples). To convert this information into spatial features that could be added to the nest site dataset, the sketch maps first needed to be incorporated into the GIS, and then georeferenced and overlaid on the orthorectified image of Boulder Beach. This was achieved by importing digitally scanned versions of the sketch maps into ArcGIS® 9, and then using the georeferencing tool in ArcMap™ (part of ArcGIS® 9) to manually connect and overlay distinct features in the sketch maps with their equivalent positions that

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[1] The locations of nest sites in more recent years have primarily been recorded using GPS technology.

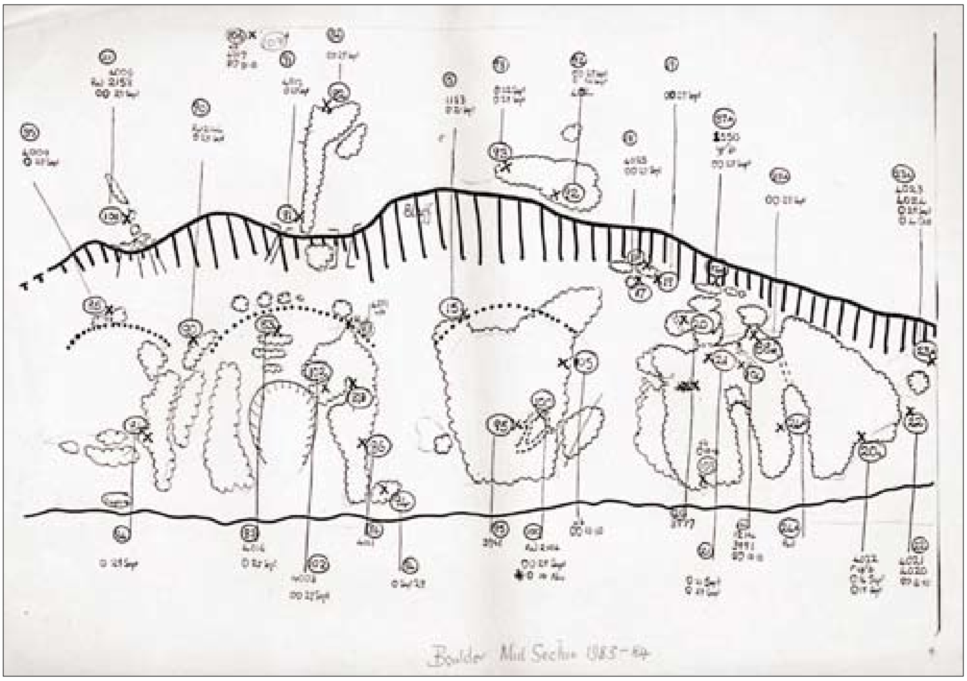

Figure 5. An example of a hand-drawn sketch map of historical yellow-eyed penguin (*Megadyptes antipodes*) nest site locations at the Midsection area of Boulder Beach, Otago Peninsula (see Appendix 2 for additional examples).

were clearly visible in the Boulder Beach image. Georeferencing was concentrated on the features in the sketch maps that were closely associated with nest site locations. An acceptable level of accuracy of georeferencing could be obtained only for the features in the sketch maps that were most easily recognisable in the Boulder Beach image. In this case, the accuracy of the georeferencing was indicated by an average residual RMSE of less than 7 m.

To obtain the specific geographic locations (i.e. projected in NZTM coordinates) of the historical nest sites, printed copies of the georeferenced sketch maps and the orthorectified Boulder Beach image were used, along with the assistance of John Darby, in a field survey of Midsection and Double Bay. During the field survey, the Trimble® GeoExplorer3™ GPS receiver was used to record the NZTM coordinates (i.e. easting and northing) of nest site locations on the sketch maps that were positively identified in the field. Where a nest site was listed in the DOC dataset but not in the sketch map for a particular year, it was only recorded if a nest site location for the same yellow-eyed penguin breeding pair was noted in a sketch map from the previous or subsequent year. Where nest site locations could not be positively identified in the field, the NZTM coordinates of the nearest locations that contained the densest vegetation were recorded. This tended to occur in areas where there was not a good match between vegetation patches on the sketch maps and the Boulder Beach image, which was a result of changes in vegetation cover (i.e. growth or removal) between the years when the sketch maps were drawn and when the aerial photographs were taken (a period ranging from 3 to 14 years).

NZTM coordinates were recorded for approximately 90% of the nest sites in the DOC dataset, for the years 1983–96 for Midsection and 1982–96 for Double Bay (see Fig. 6). This information was added to the DOC nest site spreadsheet, which was subsequently imported into ArcGIS® 9 and then converted to a point shapefile data layer. This data layer displayed the locations of the nest sites as points on the habitat map and the base map, and completed the construction of the yellow-eyed penguin GIS.

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