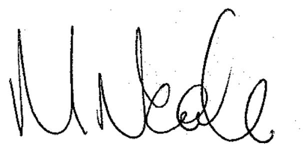
Auckland
Regional Council
TE RAUHĪTANGA TAIAO

Impervious Surface Mapping for the Auckland Region

June 2010 TR 2010/037

Auckland Regional Council
Technical Report No. 037, August 2010
ISSN 1179-0504 (Print)
ISSN 1179-0512 (Online)
ISBN 978-1-877540-93-6

Reviewed by:



Name: Dr Martin Neale

Position: Project Leader - Freshwater

Organisation: Auckland Regional Council

Date: 5th August 2010

Approved for ARC Publication by:

Name: Grant Barnes

Position: Group Manager – Monitoring and Research

Organisation: Auckland Regional Council

Date: 17th August 2010

Recommended Citation:

Pairman, D., McNeill, S & Belliss, S. (2010). Impervious Surface Mapping for the Auckland Region. Prepared by Landcare Research for Auckland Regional Council. Auckland Regional Council Technical Report 2010/037.

Impervious Surface Mapping for the Auckland Region

David Pairman
Stephen McNeill
Stella Belliss

Prepared for
Auckland Regional Council

Landcare Research
PO Box 40
Lincoln 7640
New Zealand

Landcare Report No. LC0910/134

Contents

Reviewed by:

Allan Hewitt

Approved for release by:

Robert Gribb

1 Executive Summary

The Auckland Regional Council (ARC) had maps of the impervious surfaces within Auckland City for 2000/2001 and 2007/2008 prepared by Landcare Research and now require the 2007/2008 maps extended to the whole of the Auckland Region. The original area mapped was the Auckland metropolitan urban limit (MUL), urban expansion areas, and associated catchments; the additional mapping encompasses the more rural pervious-surface areas and was carried out in January–June 2010.

The detailed requirements are:

a) Map, using SPOT satellite imagery, impervious cover for the years 2007/2008 for the Auckland Region.

b) Produce maps and tabular data that indicate the percentage of impervious cover.

c) Document the methodology used to generate impervious cover maps using satellite imagery and provide evidence of sampling accuracy.

d) Provide digital maps, associated Geographic Information System (GIS) files, and a report that captures items (a) to (c).

Small areas from high resolution aerial photographs were classified for impervious or pervious surfaces. These classifications were used as the "truth" data against which regressions were formed to predict the proportion of impervious cover from the satellite imagery.

Accuracy averaged over a territorial local authority is dependent on its size, but, for say 10 000 ha, we estimate the accuracy is better than 0.4%

Five SPOT images were used to assess the impervious fractional cover within the Auckland Region. Imagery ranged in date from 3 January 2007 to 9 April 2008.

The methodology for estimating impervious fractional cover, using high resolution aerial photographs to train models based on satellite imagery, provides an objective and accurate means of assessing this factor and is easily and reliably used for subsequent time intervals when/if changes of impervious surface percent cover through time are required.

2 Introduction

The Auckland Regional Council (ARC) wishes to have the impervious surface cover within the Auckland Region quantified. They already have maps of the impervious surfaces within Auckland city for 2000/2001 and 2007/2008 prepared by Landcare Research (Pairman *et al.*, 2009) and now require the 2007/2008 maps extended to the whole of the mainland Auckland Region, plus the inshore islands. The original area mapped was the Auckland metropolitan urban limit (MUL), urban expansion areas, and associated catchments; the additional mapping, carried out in January–June 2010, encompasses more rural pervious-surface areas to the north and south of this, plus Waiheke, Rangitoto, Ponui, and Kawau islands. The outer islands – Great and Little Barrier – are not included.

Estimating the percentage of impervious surface cover within urban areas can be done to a high degree of accuracy using satellite remote sensing techniques (North and Belliss 2005, 2007). Satellite imagery is relatively easy to correct geometrically and radiometrically so that it faithfully represents spectral reflectance characteristics of the surface cover. While not perfect, impervious surfaces tend to be separable from pervious surfaces especially in their near-infrared characteristics. This is due to the lack of vegetation, which has a characteristically high reflectance in the near-infrared. While the accuracy of the estimation of impervious proportion for individual pixels will be low, average estimates for larger areas, such as a suburb, can be highly accurate.

A second advantage of the remote sensing approach is that it is relatively easy to obtain comparable imagery from different dates, allowing an analysis of the overall increase or decrease in impervious surface cover over time.

Objectives

- Map, using SPOT satellite imagery, impervious cover for the years 2007/2008 for the Auckland Region.
- Produce maps and tabular data that indicate the percentage of impervious cover.
- Document the methodology used to generate impervious cover maps using satellite imagery and provide evidence of sampling accuracy.
- Provide digital maps, associated Geographic Information System (GIS) files, and a final draft report that captures items (a) to (c) above, as a Microsoft Word document for ARC review.
- Provide a final report that takes account of ARC comment, including any changes to the digital maps.

3 Methods

3.1 General approach

The general approach used for impervious surface mapping is to systematically sample small areas from the Auckland Region. The original 46 samples from the metropolitan urban limits, urban expansion areas, and associated catchments already prepared for the central Auckland area have been augmented by 150 more samples taken from additional aerial photography provided by the ARC. For each small aerial photographic sample, detailed estimates of impervious, pervious, and unknown surface cover were generated to coincide with the individual SPOT pixels. A mixture of spectral classification techniques and manual digitisation was used to identify the impervious parts of the aerial photographs. These classified aerial photographic samples form the ground truth for the method.

For each area of ground truth, SPOT satellite imagery was acquired in four spectral bands. The ground truth and reflectance from the satellite imagery were used to form a quantitative model for each image that estimated impervious fraction (value from zero to one) from the four SPOT spectral bands. Then, this model was used to estimate the impervious fraction for the Auckland Region using the full coverage of each SPOT satellite imagery. The mapped impervious fraction was scaled to percent impervious cover, and then quantised to the same ARC-specified levels (0–5, 5–10, 10–15%, etc.) as the previous mapping.

Five SPOT images (2007 and 2008) were required for full coverage of the Auckland Region, and before combining the results, a mask was generated for each one to exclude cloud. Where the images overlapped cloud-free areas, the *average* impervious fraction value was used.

The following sections describe the above steps in more detail.

3.2 Data source

The Auckland Regional Council had already provided aerial photography for 2007 in digital form as orthorectified tiles of variable sizes. Most of these had a spatial resolution of 0.25 × 0.25 m. For the additional work, another set of aerial photographs of the more rural parts of the region were supplied. These were all taken in 2006–2007, are in NZTM projection, and have a spatial resolution/pixel size of 0.63 m. Some additional urban aerial photographic tiles were supplied; these had been flown in 2008.

To cover the full Auckland Region, five different SPOT satellite images were used. The two images from 2007 and 2008 that were used in the previous study were also used here. An additional two images from the Ministry for the Environment Whole of Government archive were used to cover the extended area required to the north and south; these images were also from 2007 (Waikato) and 2008 (north). The ARC purchased a fifth custom half-scene to improve coverage of the central city and inshore islands where there was considerable cloud in the original image pair. The characteristics of these are outlined in Table 1 and the imagery in Figure 1. Figure 2 shows the area analysed in the previous mapping exercise.

Table 1

Characteristics of the 2007 and 2008 SPOT images

Satellite	SPOT-5	SPOT-5	SPOT-5	SPOT-5	SPOT-5
ID	5 440-424 07/12/07 22:21:29 2 J Level 1A SAT 0	5 439-424 08/03/20 22:20:24 2 J Level 1A SAT 0	54404250701 032225332J	54394230804 092235322J	54404241080 1082213181J
Instrument	HRG2	HRG2	HRG2	HRG2	HRG1
Path/Row	440/424	439/424	440/425	439/423	440 /424
Date	7 December 2007	20 March 2008	3 January 2007	9 April 2008	18 January 2008
Scene centre	S36.85/E175. 05	S36.86/E174. 48	S37.35/E174. 84	S36.37/E174. 64	S36 55 38/E175 4 38
Incidence angle	8.82°	4.66°	8.10 (L)	29.03 (L)	-4.05 (R)
Sun elevation	62.30°	42.71°	60.44	39.33	56.12
Azimuth	66.09°	46.71°	68.79	35.40	70.42
Original data level	1A	1A	1A	1A	1A
Comments	MfE WoG data also used in previous report	MfE WoG data also used in previous report	MfE WoG data (Waikato)	MfE WoG data (north)	Custom half-scene

MfE WoG = Ministry for the Environment Whole of Government archive.

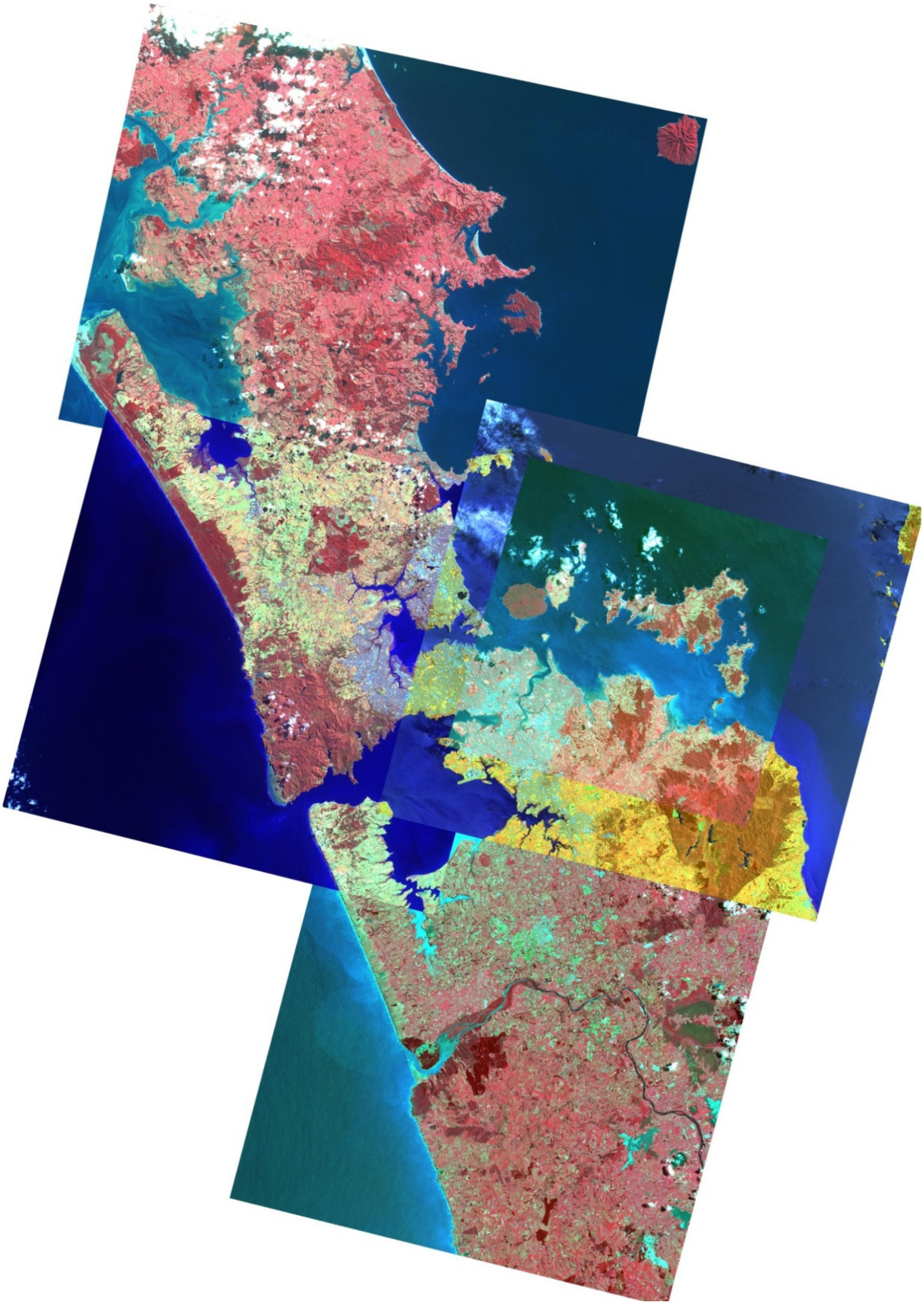


Figure 1

SPOT-5 imagery used. Top: 4 April 2008; centre left: 20 March 2008 and centre right: 7 December 2007 (shown in different false colour combinations to help indicate overlaps between the various datasets); bottom: 3 January 2007; superimposed centre right: 18 January 2008. These extra data were required since the underlying image has cloud over Rangitoto, Motutapu, Motuihe, and part of Waiheke Island.

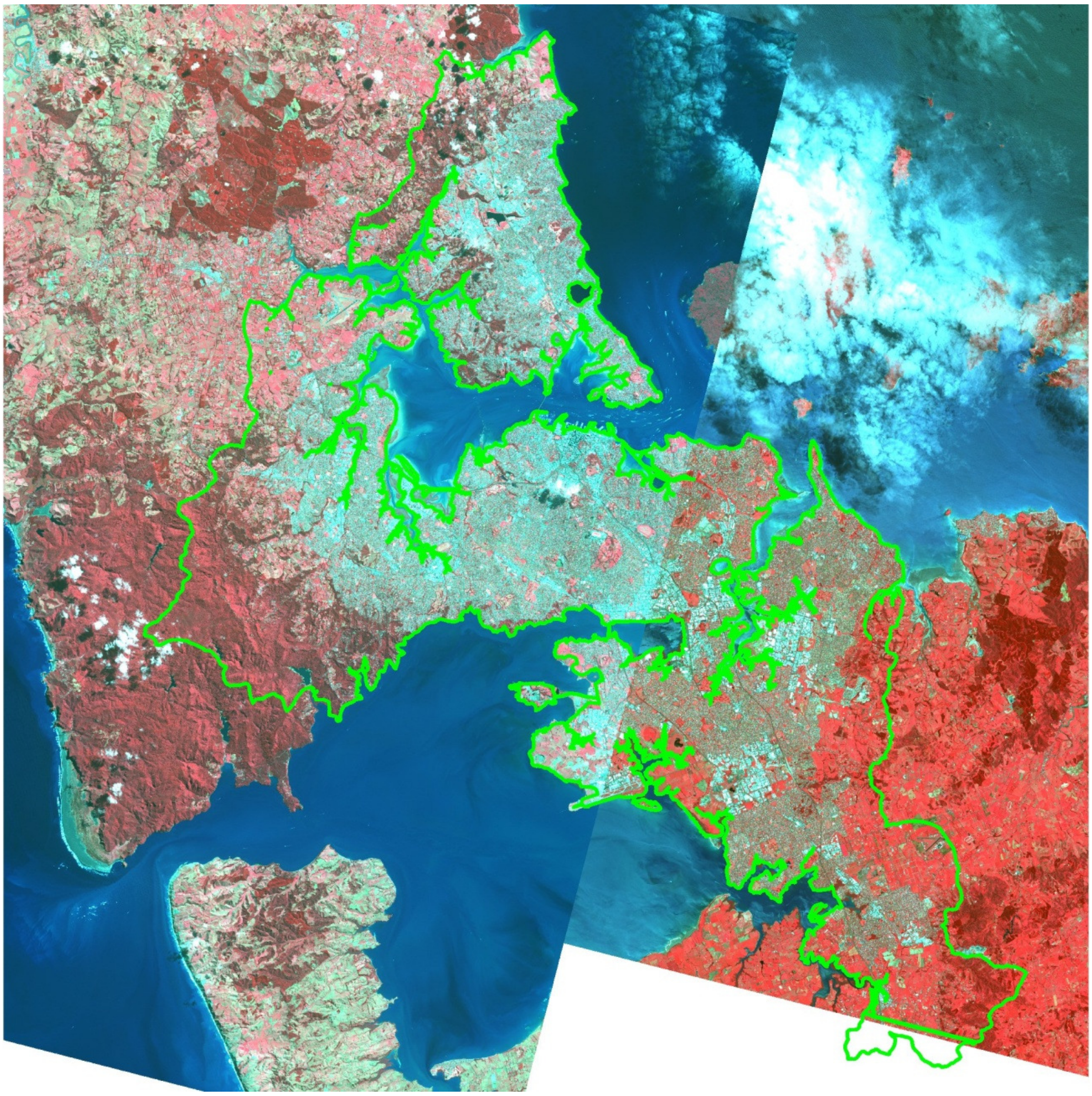


Figure 2
Area covered by the original analysis overlain on the SPOT 5 e original and part of the current impervious surface mapping.

3.3 Sampling

Aerial photographs were provided by ARC for use as ground truth data for mapping the impervious fraction. Those provided for the last mapping were 2007 aerial photography with a tile size of 4.84 × 7.25 km. For the extension areas, some additional urban aerial photographs, taken in 2008, were provided, along with rural aerials taken in 2006–2007. A sampling procedure was adopted to acquire ground truth information on the impervious fraction. The sampling was designed to uniformly sample across the Auckland area, in a procedure that is effectively simple random sampling (Lohr 1999).

For the tiles provided for the extension work, the sampling procedure was to take a subimage from the top left of each tile in the rural parts of the region (it was decided that there were enough urban tiles available from the previous mapping). This gave a total of 156 tiles, thus:

- AY31 0501–0505 (5)
- AZ31 0101–0505 (25)
- AZ32 0101–0102, 0201–0203, 0301–0303, 0401–0402, 0501–0503 (13)
- BA30 0102–0105, 0203–0205, 0304–0305, 0404–0405, 0505 (12)
- BA31 0101–0505 (25)
- BB31 1010–0205, 0302–0305, 0402–0405, 0503–0505 (21)
- BB32 0101–0505 (25)
- BB33 0101–0404 (19)
- BB34 0201, 0301 (2)
- AZ30 0502–0505 (4)
- Plus AZ30_0402, AZ30_0301, AY31_0404, AY31_0402, BA33_0401 (5)

Subimages from the corner of these tiles were classified to pervious, impervious, water, and bare ground. Of these 156 tiles, 46% are 100% vegetation; 34% are mixed; 20% are 100% water. Subsequently, it was decided that the 100% water tiles were of no use and they were removed from the set. This was because the spectral signatures for most water bodies are outliers from the impervious regression model that we are parameterising. As we are not trying to cater for water in the regression we also attempted to mask out water bodies from the final results as much as possible. In addition, all tiles were checked to ascertain if they were under cloud or in cloud shadow in any of the imagery (this includes situations where images overlap and the site was under cloud in one image but cloud-free in the other(s)). Affected tiles were also removed from the set. This left a total of 117 subimages.

The sampling procedure adopted for the original urban work was to select a subimage of 100 × 100 m from the top left corner of each aerial photographic tile. For the 2007 set, which was of a lower spatial resolution, a second subimage (100 × 100 m) was extracted from the centre of each tile. Each sample subimage was then classified using the Leica Imagine software platform into a series of impervious and pervious classes, as well as a water class and an unknown class.

Impervious classes consisted of a variety of targets, such as roofs, concrete, asphalt, or hard-packed soil[1], each with distinct spectral signatures, and pervious classes consisted of similar diversity – forest, shrubland, pasture, dry grasses, etc. Targets within each sampled tile that were unknown were recorded as an "unknown" class. Typically, this latter class consisted of objects in deep shadow.

The classification was performed using a mixture of semi-automated spectral techniques and manual digitisation, depending on the nature and complexity of the target ground covers. The initial, automatically derived classifications noted above were manually cleaned, and then combined into the four required classes: impervious, pervious, water, unknown. Figure 3 shows the first steps of this process for a single subimage (100 × 100 m).

For the additional rural tiles, manual digitisation was used since most of them were much less complex (more likely to be 100% vegetation or to contain only a few different cover types). Instead of classifying all the different land cover types and then simplifying them down to pervious, impervious, and unknown, the tiles were manually coded directly to these categories. This was done because it was more time efficient. The end results are the same for both methods.

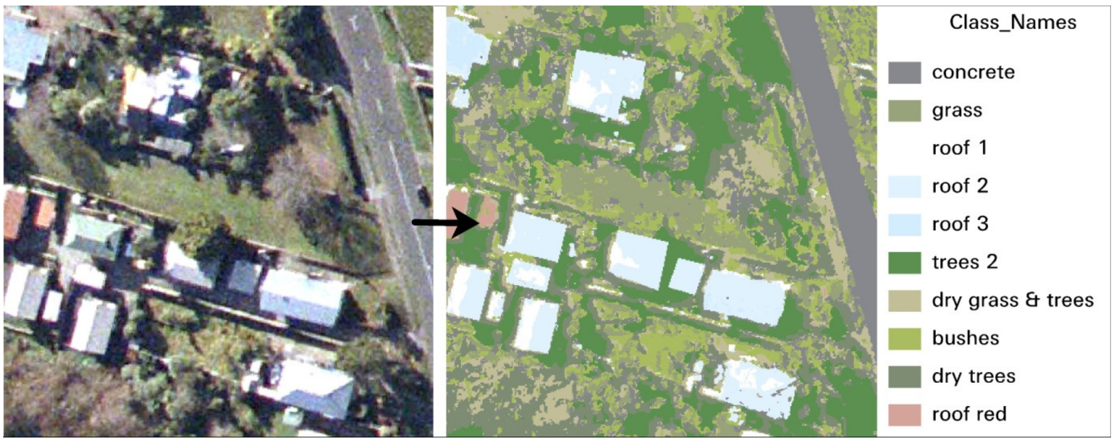


Figure 3
Typical aerial photographic subimage (100 × 100 m) from the original urban classification exercise (left) and the resulting classification (right) after some manual cleaning. The classes are subsequently reduced to four classes: impervious, pervious, water, and unknown.

[1] Note: Soils, especially hard-packed soils, are a problematic class in impervious surface classifications since they may be acting as either a pervious or an impervious surface. For example, soils adjacent to a current building site or an industrial yard are most likely to be hard-packed and operating as impervious surfaces; bare soils such as recently ploughed paddocks are going to be pervious surfaces. Our approach is to ask each individual client how they wish bare soil areas to be treated and to classify accordingly. In the urban environment, soils are more likely to fit the impervious category and, in the case of this Auckland work, are treated as such. An additional advantage of this choice is that soils are generally closer spectrally to other impervious surfaces. In addition areas of bare soil within urban areas are often on development sites and are typically about to become impervious surfaces.

For the five SPOT images used to cover the nominal 2007 year (2007/2008 SPOT coverage), average reflectance values were calculated for the locations of the 100 × 100-m tile sampled from the aerial photography. These reflectance values were recorded, along with the class proportions of the underlying ground truth ("impervious", "pervious", and "unknown") for each date. These values were used to form the model between SPOT reflectance and impervious fraction, as described in the next section.

3.4 Model analysis

A linear model was developed to estimate the impervious fraction. The response variable in the regression was the impervious fraction (0–1), and the explanatory variables were the four SPOT band reflectances ($B_1 \ldots B_4$), an indicator variable for the territorial authority, an indicator variable for the specific SPOT image of the sample, and a vegetation index variable formed from bands 2 and 3 of the SPOT bands:

$$NDVI = \frac{B_3 - B_2}{B_3 + B_2}$$

The indicator variable for the territorial authority was included as a check, in order to ensure that the prediction for impervious fraction did not specifically depend on the conditions in any of the territorial local authorities. Once a suitable regression was found, the indicator variable was dropped from the regression model. The initial regression model using all bands was refined in order to find a smallest number of variables yielding the best results in the regression. For the purposes of this work, the best model had the lowest residual deviance (Kleinbaum *et al.*, 1998). The indicator variable for the SPOT image was included to act as a first-order correction for the radiometric differences between the different SPOT images.

4 Results

4.1 Model analysis

The best model for prediction of impervious fraction, using SPOT bands, the vegetation index, and the indicator variable for the SPOT image number as explanatory variables, had no significant effect for territorial local authority. This means that the model could be used in all parts of the extended Auckland Region with equal effect.

A plot of the impervious fraction calculated from aerial photographic tiles against estimated impervious fraction from the regression involving SPOT bands is given below. This plot was generated by choosing a random sample of points over the extended Auckland Region with impervious values between 0 and 1, over all SPOT images used in the study. The plot shows that the estimated impervious fraction matches the trend in the ground-truth impervious fraction, with some residual level of uncertainty.

Figure 4 shows a normal quantile distribution plot of the standardised residuals for the regression[2]. The residuals follow the expected straight line on the normal quantile plot, with no suggestions of significant outliers. The plots in Figure 4 and Figure 5 suggest that the model developed is a satisfactory one.

[2] The standardised residuals are the estimated-minus-known impervious values, normalised by an estimate of the standard deviation of these values. If the assumption of the normal linear model holds, the standardised residuals will be approximately normally-distributed, and the normal quantile plot is a useful diagnostic test for this assumption.

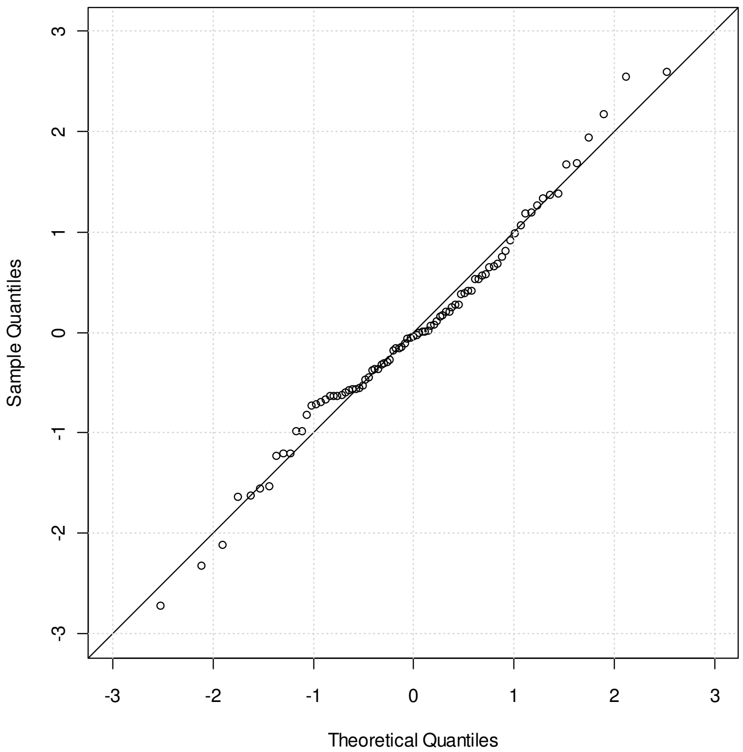


Figure 4

Quantile–quantile normal plot of standardised residuals from the impervious surface regression for all SPOT images.

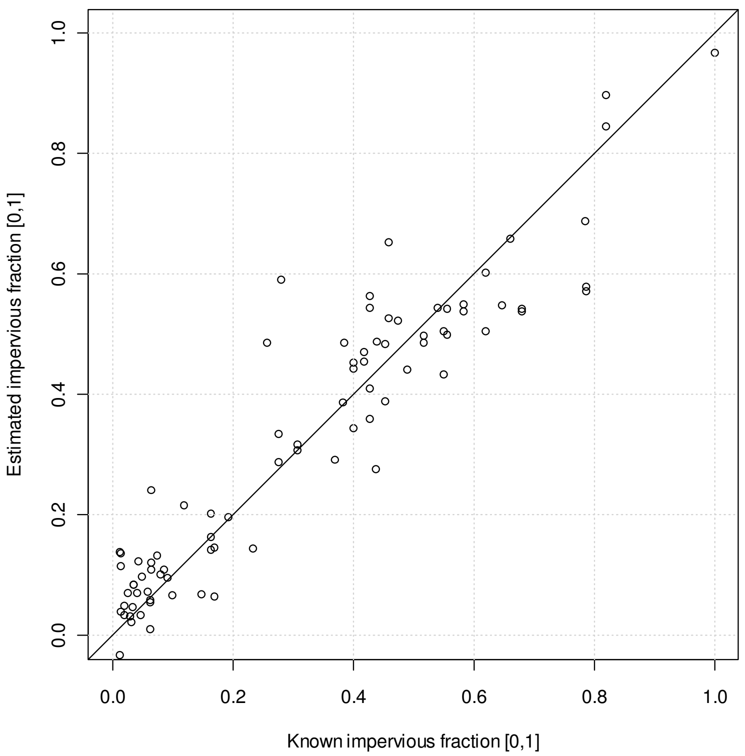


Figure 5
Plot of fitted against ground-truth-derived impervious fraction for a random selection of points across the extended Auckland Region.

4.2 Mapping of impervious fraction

There are four bands for each SPOT image ($B_1 ... B_4$), and five different images ($I_1 ... I_5$). To calculate the impervious fraction, the procedure below was followed:

1. Given SPOT bands B_1 to B_4, calculate the normalised difference vegetation index (NDVI) and treat it as a fifth band as follows

$$NDVI = \frac{(B_3 - B_2)}{(B_3 + B_2)}$$

2. Centre the band values as follows:

$$B_i = (B_i - C_i)$$

where

Band #	C_i
1 (B_1)	109.7867238
2 (B_2)	93.4891890
3 (B_3)	123.5814211
4 (B_4)	131.7855628
5 (NDVI)	0.1253237

3. Using the five centred bands (four SPOT bands and the NDVI), calculate the principal components. Only four of the five are needed (PC1, PC2, PC3, PC5). Use the following table for the PC multipliers:

PC #	B_1	B_2	B_3	B_4	NDVI
1	0.2009775066	0.188458551	0.641208254	0.7161995704	0.001251912
2	–0.5492363414	–0.618975652	0.536994325	–0.1637753477	0.004828446
3	0.6596102484	–0.027490344	0.462425597	–0.5918743830	0.002425441
5	-0.0005925268	0.005067903	-0.003648692	0.0003514089	0.999980264

4. Using the four PC components (PC1, PC2, PC3, PC5), calculate the impervious fraction z as follows:

$$z = a_0 + I_j + a_1.PC1 + a_2.PC2 + a_3.PC3 + a_5.PC5$$

using the coefficients from the following table:

Term	Coefficient
a_0	0.525848406
a_1	–0.001709406
a_2	–0.005678677
a_3	0.006158042
a_5	–0.876661842

and the offset I_j is specific for each SPOT image being processed, as follows

Image date	Offset I_j
Apr 2008	0.0000000
Dec 2007	–0.3212161
Jan 2007	–0.4549141
Jan 2008	–0.7164963
Mar 2008	–0.3864945

5. If the estimated impervious fraction from the previous step is below 0 or above 1, set it to 0 or 1, respectively.

A mask was generated for each of the five images to identify; cloud, water, and invalid pixels in the rectified data that are outside the imaged area. These masks were generated from a series of spectral rules. However, it proved extremely difficult to cleanly separate even such basic classes using spectral information alone. Clouds, sand, estuarine mud flats, bare ground and built-up areas all significantly overlap. Often there is also a smooth graduation from open water to rivers and estuaries, right through to the muddy estuaries and river banks. A significant amount of manual re-editing of the masks was necessary to achieve satisfactory results.

The model outlined in the five-step procedure above was applied to each SPOT image with the appropriate offset parameter I_j. The five resulting impervious fraction images were then combined into a single composite image as seen in Figure 6.

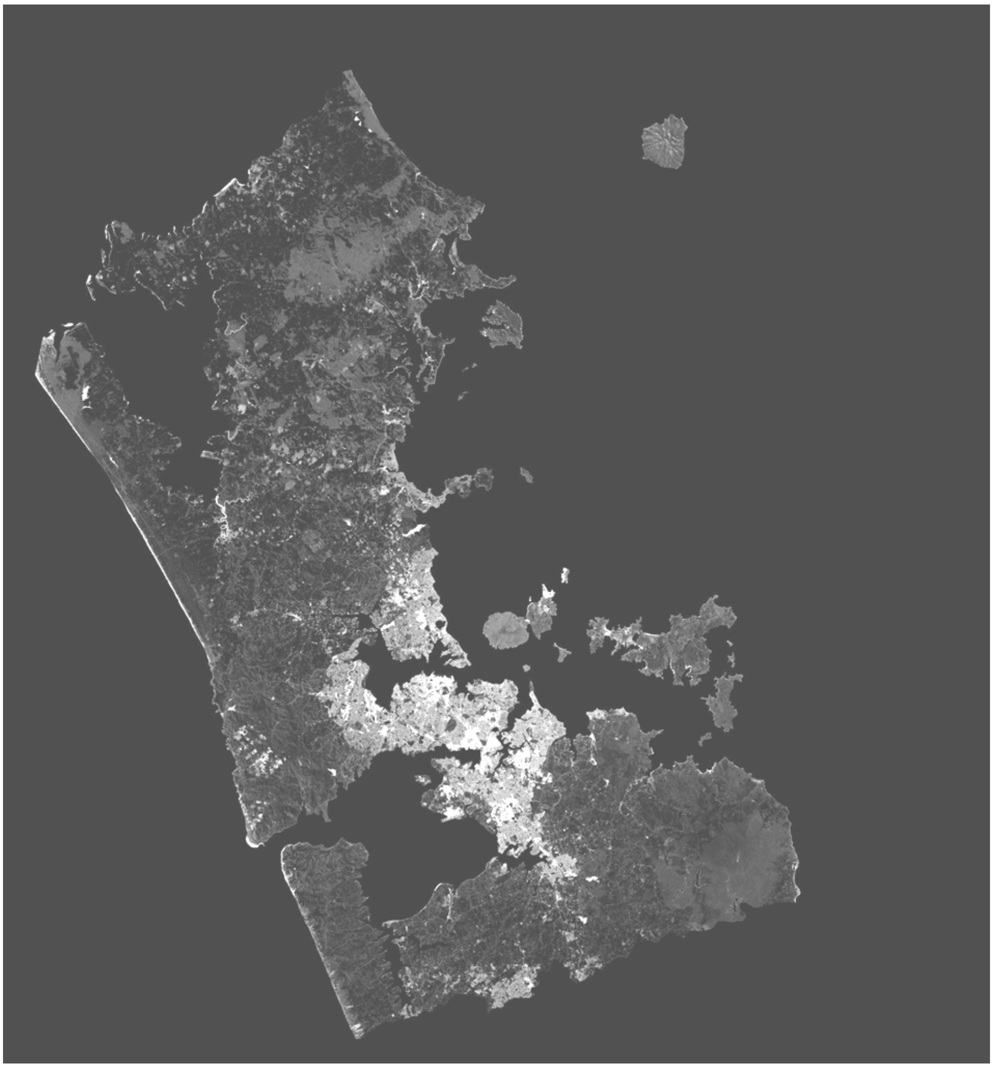


Figure 6
Combined impervious fraction images.

In the earlier study for ARC (Pairman et al. 2009), a number of shape files were provided as listed below.

- disslv_mul.shp – the metropolitan urban limit
- disslv_mul_exp.shp – the metropolitan urban limit and extension area
- dissolv_mappedarea.shp – the total mapped area
- tla2006dcdb.shp – the TLA boundaries.

Each shape file was converted to an ARC/INFO coverage and for each area of interest an additional coverage was generated by intersecting with territorial local authority coverage. Leica Imagine was then used to extract the mean impervious fractional coverage for each region. An analysis was done to extract and compare the 2000 and 2007/2008 impervious fractions both for the entire shape file and for the territories within each shape file.

Additional images were used in the current study and these new images overlap with some of the coverage analysed earlier. In addition, a different regression algorithm was developed based on all the additional ground truth data and all five SPOT images. While the regression was a good fit (see section 5.3), as a check we analysed the extracted average impervious fraction for the largest of the areas from the previous study (dissolv_mappedarea) and all the territories within it. Table 2 shows the result, and it can be seen that, despite the different imagery and model used, an identical impervious fraction is found for the total area.

Table 2

Average impervious fraction within the dissolve_mappedarea shape file, and also broken down to territorial authority areas within the same shape file

Territorial Authority	Area (ha)	Average Impervious		
		2000	2007/08	2007/08 ext
Dissolve_mappedarea	75671	0.31	0.35	0.35
Auckland City	15378	0.48	0.50	0.51
Franklin District	133	0.08	0.17	0.06
Manukau City	19165	0.35	0.44	0.43
North Shore City	12693	0.33	0.32	0.36
Papakura District	7403	0.18	0.29	0.24
Rodney District	1748	0.11	0.13	0.16
Waitakere City	18938	0.20	0.20	0.22

Only an extremely small portion of Franklin and Rodney districts were included in the dissolve_mapped area so the figures for these two areas are not very significant. The increase for North shore and decrease for Papakura was due to a combination of new imagery in the overlap area, cloud clearing, and the use of a different model, which was fitted to the whole Auckland Region. In fact, the latest figures seem more reasonable in comparison to the year 2000 figures as one would expect a gradual increase of impervious fraction due to new developments. We had previously hypothesised that an apparent decrease in the North Shore could be due to very new developments appearing artificially barren compared with the norm for the same impervious fraction.

In Figure 6 it can be seen that most of the rural area is a dark grey rather than black (0% impervious). In fact much of it appears as 5–10% impervious and sometimes higher, whereas from a visual inspection it is clearly farm land or other vegetation which should be 0% impervious. The model used to estimate impervious fraction is designed to be sensitive to a typical mix of pervious and impervious surfaces found in urban settings. While it is producing relatively low values for the rural areas, their average will be biased due to the large areal extent of the rural contribution. To counter this tendency for bias we have produced a second analysis (Figure 7) where the impervious fraction is suppressed to zero unless a pixel is within three pixels of a clearly impervious feature – for which we use a threshold of 60% impervious.

Possibly some partially impervious pixels, containing features such as narrow roads, will be lost by this process. This is somewhat offset by some pervious surfaces appearing impervious such as bare ground as discussed above.

The statistics for the various territorial authorities within the Auckland Region were extracted from this analysis with low values suppressed in rural areas. Table 3 summarises the regional statistics and Figure 7 shows these territories overlaid on the image.

The impervious fractional image for these data (Figure 7) were converted to binned ranges representing 0–5, 5–10, 10–15%, etc. Resulting images are all in Leica Imagine format and are named as shown in Table 4.

Table 3

Average impervious fraction for Auckland Region. Note: Auckland City includes inshore islands (Waiheke, Rangitoto, Ponui and Kawau Islands) that were not considered in the earlier study.

Territorial Authority	Area (ha)	Average Impervious 2007/08 ext
Full Auckland Region	470921	0.07
Auckland City	33948	0.26
Franklin District	87041	0.02
Manukau City	54032	0.15
North Shore City	12717	0.32
Papakura District	11793	0.14
Rodney District	235377	0.02
Waitakere City	36013	0.11

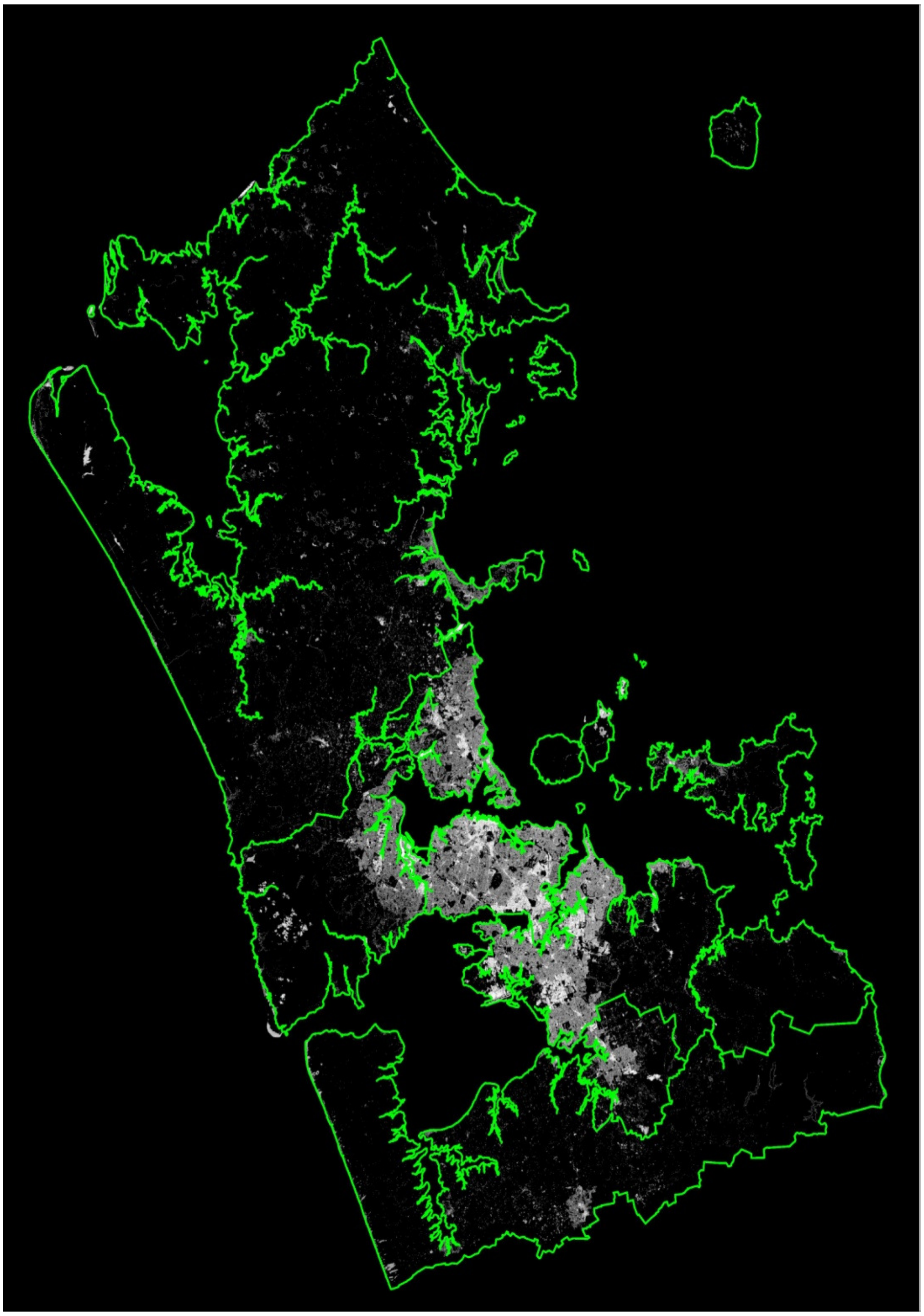


Figure 2
Impervious fraction with low rural values suppressed

Table 4
Delivered result options

File name	Content
Impervious_0708_extension.img	32-bit real impervious fraction for 2007/08
Impervious_0708_extension_cleaned.img	As above, with low rural values supressed
Impervious_0708_binned	8-bit image, grouped into 5% ranges

4.3 Error estimate of impervious fraction

There are two issues that need to be covered when producing some kind of estimate of error for the estimation of the impervious fraction. Precision refers to the repeatability of an estimate of impervious fraction; more precise estimates of impervious fraction are, on average, more closely clustered about the true impervious fraction. The accuracy (or uncertainty) is how close the estimate of impervious fraction is to the true value. Often, there is a balance to be sought between the precision of impervious fraction estimates and their accuracy. In many practical cases, it is sufficient to define precision by stating that the method is unbiased, or if not, to define the level of bias inherent in the estimation method. The most common way to measure accuracy (or uncertainty) is by way of confidence or prediction intervals for a given impervious fraction estimate.

The method used to estimate impervious fraction uses general linear regression, and the nature of the general linear regression means that there should be no bias. This is most clearly seen in Figure 8, which is a plot of regression-modelled impervious fraction against known (or "true") impervious fraction. An unbiased regression will have all the points in this plot centred on the one-to-one line. In Figure 8 this is the case, although it is not true for certain ground targets – for example, the impervious fraction calculated in water is strongly biased. In practice, water is masked out from the impervious fraction estimation process.

The accuracy (or uncertainty) of the impervious fraction estimation method is defined by the residual variation in the estimates of impervious fraction after the impervious fraction component estimated from the SPOT satellite bands is accounted for. This uncertainty is defined by the standard error of the regression residuals. Furthermore, the precise level of uncertainty will depend on the values of reflectance of the SPOT satellite image bands.

As the result of the above considerations, it is difficult to provide a single number for the accuracy of impervious fraction estimates. One useful way to show the model accuracy is to estimate the uncertainty for all the test points in the regression. On average, these should provide a realistic view of the accuracy one might expect over the Auckland Region. Figure 8 shows a plot of the known impervious fraction against the regression-modelled impervious fraction. (Technically, the lines define the 95% prediction interval for the impervious fraction.) The circles represent the regression estimates, while the vertical bars show the 95% interval for the predictions of the impervious estimate. It should be noted that the vast majority of points have uncertainties that cross the one-to-one line, as might be expected. The exceptions to this rule are estimates of impervious fraction over water targets, and the occasional outlier.

Figure 9 shows a plot of the known impervious fraction (as calculated from high resolution aerial photographs supplied by ARC) against the size of the error bars from Figure 8 (the size of the 95% prediction interval). Aside from water bodies and one outlier, the total size of the uncertainty bars has an average value of about 0.36 (or certainly less than about 0.4), more or less independent of the impervious fraction. Note that each of these points represents a random 100 × 100 m (1 ha) area. With the analysis of a larger area, errors will tend to average out and the estimate becomes more accurate. For example, for a suburb with an area of 10 000 ha we estimate that the accuracy is better than 0.004 in impervious fraction, or 0.4%.

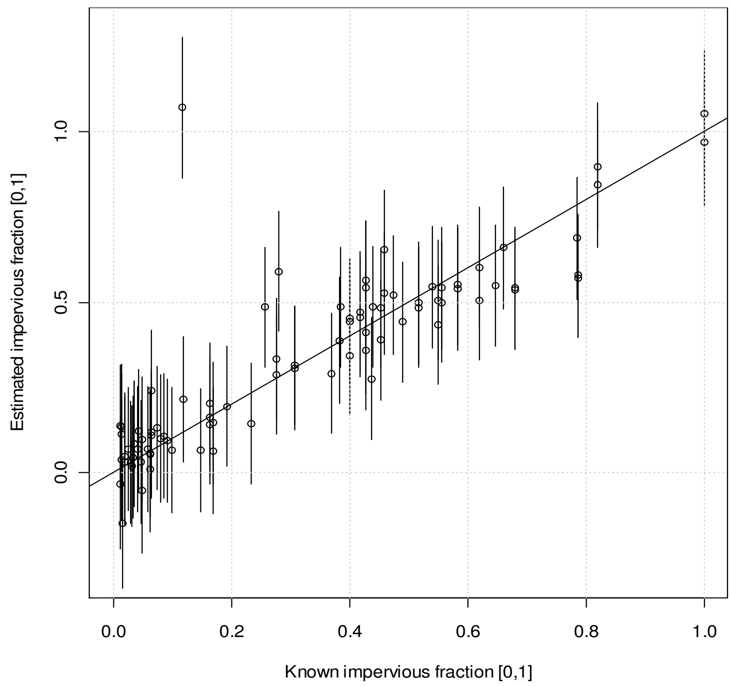


Figure 3

Plot of regression-derived impervious fraction against known impervious fraction. The markers denote the point estimates, while the vertical lines denote the 95% prediction intervals for the impervious estimate.

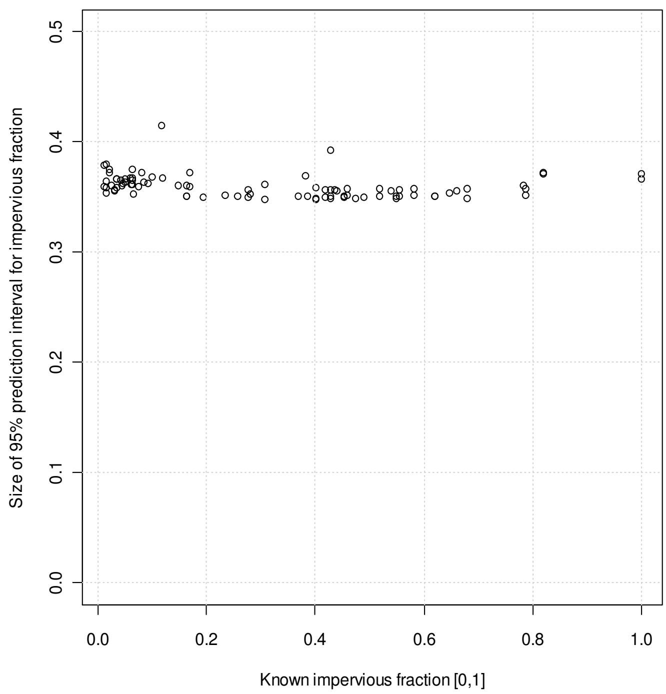


Figure 4

Plot of the size of the 95% prediction interval for the impervious estimate against known impervious fraction.

5 Conclusions

The regression approach used both here and in our previous work relies on there being a general relationship between imperviousness and spectral characteristics. While the aerial photographs are classified and manually cleaned to generate "ground truth" information to parameterise the regression, the SPOT data itself is not classified as such. Therefore there may well be instances of impervious surfaces that appear closer to the spectral characteristics of a pervious surface and vice versa. While such errors may be apparent at the fine (pixel) scale, they should average out in the statistics for a whole region. The plots in Figure 8 and Figure 9 indicate that the regression is very good for the five-image set used in this study.

As we have only expanded the area covered in the earlier comparative work (Pairman et al. 2009) for the 2007/2008 time-step, we cannot make a comparison back to 2000 for the whole region. A comparison with the previous work, using the largest (dissolve_mappesarea) of the three coverages used in that study, indicates that these results are very close. The biggest differences at the territorial level were in the North Shore and Papakura. If anything, these latest results appear more reasonable than the earlier ones, as we would normally expect a slight increase of impervious surfaces in urban areas over time.

The results in Table 2 should be treated with care. The technique is not suitable to give an accurate result for single pixels or even for small areas. Once a larger area such as a full territory is considered the results should be accurate to better than 0.5%. Some of the TLA regions intersecting with the areas of interest in Table 2 are very small and therefore less reliable. This is especially true for Rodney and Franklin where less than 1% of these districts were included in the dissolve_mappedarea coverage. However, those in Table 3 cover the whole of the territorial districts and are therefore more accurate estimates.

6 References

Kleinbaum DG, Kupper LL, Muller KE, Nizam A 1998. Applied regression analysis and other multivariable methods. Pacific Grove, CA:Duxbury Press.

Lohr SL 1999. Sampling: design and analysis. Pacific Grove, CA:Duxbury Press.

North HC, Belliss S 2005. Accuracy assessment of Christchurch City impervious surface maps derived from satellite imagery. Landcare Research Contract Report LC0405/088 prepared for Christchurch City Council, April 2005. 35p.

North HC, Belliss SE 2007. Mapping impervious surfaces in Hastings District from satellite imagery. Landcare Research Contract Report LC0607/129 prepared for Hastings District Council. May 2007. 23p.

Pairman D, McNeill SJ, Belliss SE 2009. Mapping of impervious surface cover within the Auckland region. Landcare Research Contract Report LC0809/095 prepared for Auckland Regional Council. March 2009. 23p.