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# Mapping of Impervious Surface Cover within the Auckland Region

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# Mapping of Impervious Surface Cover within the Auckland Region

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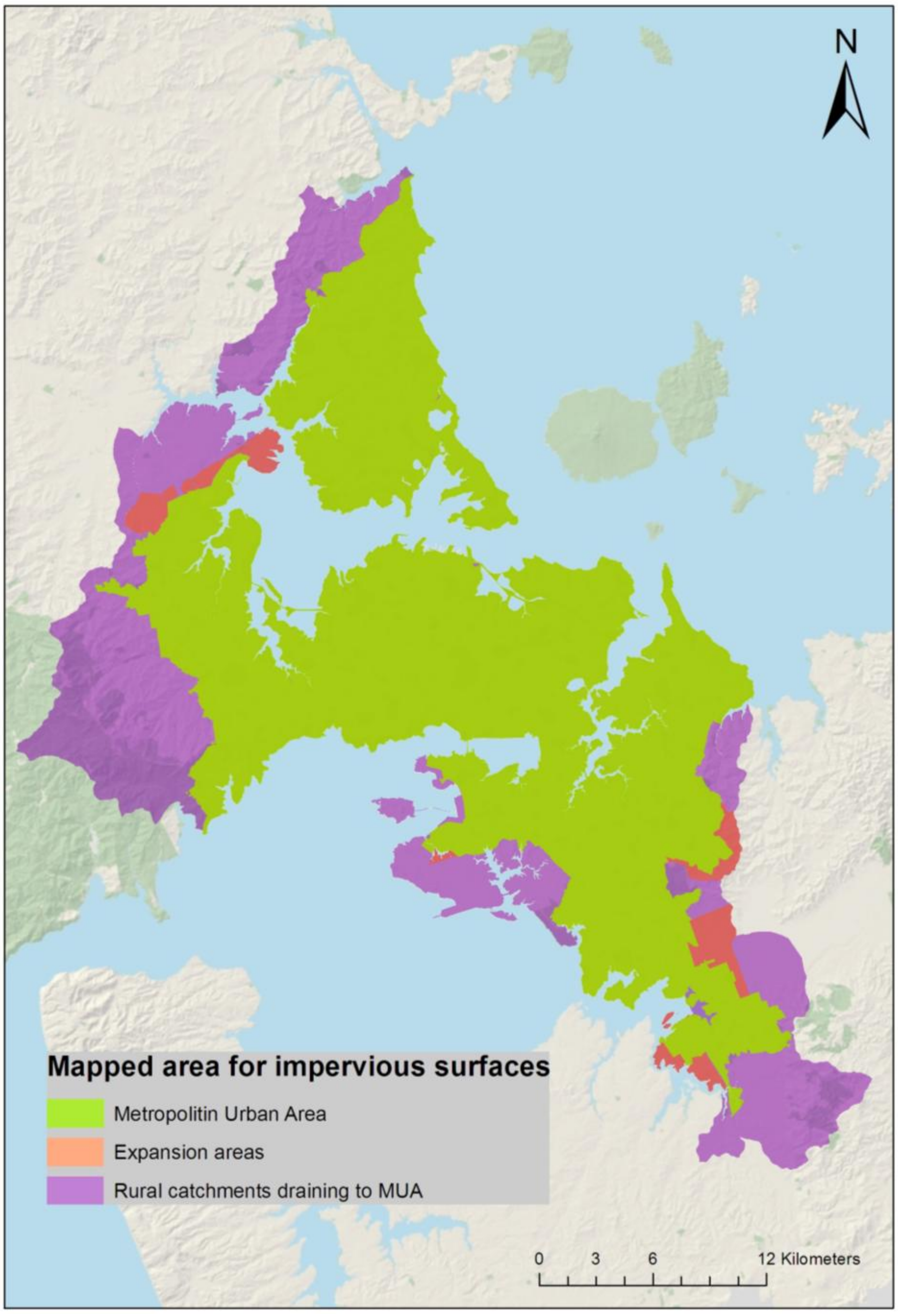
# 1 Requirements

The Auckland Regional Council (ARC) wishes to have the impervious surface cover within the greater Auckland area mapped. The area to be mapped includes the Auckland metropolitan urban area (MUA) as seen in Figure 1 (green), urban expansion areas (pink areas), and associated catchments near MUA (purple).

**Figure 1** Areas to be mapped for impervious cover in 2000 and 2007.



The detailed requirements are:

- Using SPOT satellite imagery, map impervious cover for the years 2000 and 2007 for the Auckland metropolitan urban area, urban expansion areas and associated catchments.
- Produce maps and tabular data that indicate the percentage of impervious cover for:
    - The total mapped area
    - The metropolitan urban area (MUA)
    - The metropolitan urban area + the extension area (MUA+EXP)
    - The above areas area by Territorial Local Authority (TLA), in 5% categories (i.e. 0–5, 5–10, 10–15% etc).
- Compare the maps from 2000 and 2007 and produce a map of impervious cover change.
- Document the methodology used to generate impervious cover maps using satellite imagery and provide evidence of sampling accuracy.
- Provide digital maps and associated Geographic Information System (GIS) files.

# 2 Methods

## 2.1 General approach

The general approach used for impervious surface mapping was to systematically sample small areas from the Auckland metropolitan urban area, urban expansion areas, and associated catchments, from aerial photography provided by the ARC. For each small aerial photographic sample, detailed estimates of impervious, pervious, and unknown surface cover were calculated to coincide with the individual SPOT pixels. These data formed 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 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 metropolitan urban areas, urban expansion areas, and associated catchments using the full coverage of the SPOT satellite imagery. The mapped impervious fraction was scaled to percent impervious cover, and then quantised to the ARC-specified levels (0–5, 5–10, 10–15% etc.).

The above approach was carried out for 2000, 2007 and 2008 — that is, separate models were formed for each image date. The change in impervious fraction was mapped by subtracting the mapped impervious fraction for 2000 from the mapped impervious fraction for 2007. While a single SPOT image was used for 2000, two SPOT images (2007 and 2008) were required for the later date (nominally 2007), and where they overlapped the average value was used.

Our current technique of estimating the impervious surface fraction using a regression model differs from a previous approach where we used a spectral unmixing technique (North & Belliss 2005, 2007). The previous approach is sensitive to the selection of pure end-members to represent 0% and 100% impervious surfaces; where as our current method effectively uses all the ground truth information.

The following sections describe the above steps in more detail.

## 2.2 Data source

The Auckland Regional Council provided GIS coverage data for the metropolitan urban area and territorial authority boundaries. The ARC also provided aerial photography for 2001 and 2007 in digital form as orthorectified tiles of variable sizes. For the 2000 aerial photographs the pixel sizes were 0.25 × 0.25 m. However, aerial photographic tiles taken in 2007/08 for the later analysis are all coarser resolution at pixels of 0.63 × 0.63 m.

SPOT satellite imagery for 2000 and 2007 was provided from three separate images. One image covered the required area for 2000, but two images were required for 2007 coverage, one dated in 2007 and a second in 2008. The characteristics of the 2000 image are outlined in Table 1 and the image itself in Figure 2; corresponding information for the 2007/2008 set is in Table 2 and Figure 3.

**Table 1** Characteristics of the 2000 SPOT image

| | |
|---|---|
| Satellite | SPOT-4 |
| ID | 4 439-424 00-03-15 22:44:29 2 I Level 1A SAT 0 |
| Instrument | HRVIR2 |
| Path/Row | 439/424 |
| Date | 15 March 2000 |
| Scene centre | S36.86/E174.61 |
| Incidence angle | 29.65° |
| Sun elevation | 47.6° |
| Azimuth | 41.5° |
| Original data level | 1A |

**Figure 2** SPOT-4 March 2000 image of Auckland with the area mapped outlined in green. The mapped area includes the MUA, urban expansion areas and associated catchments.

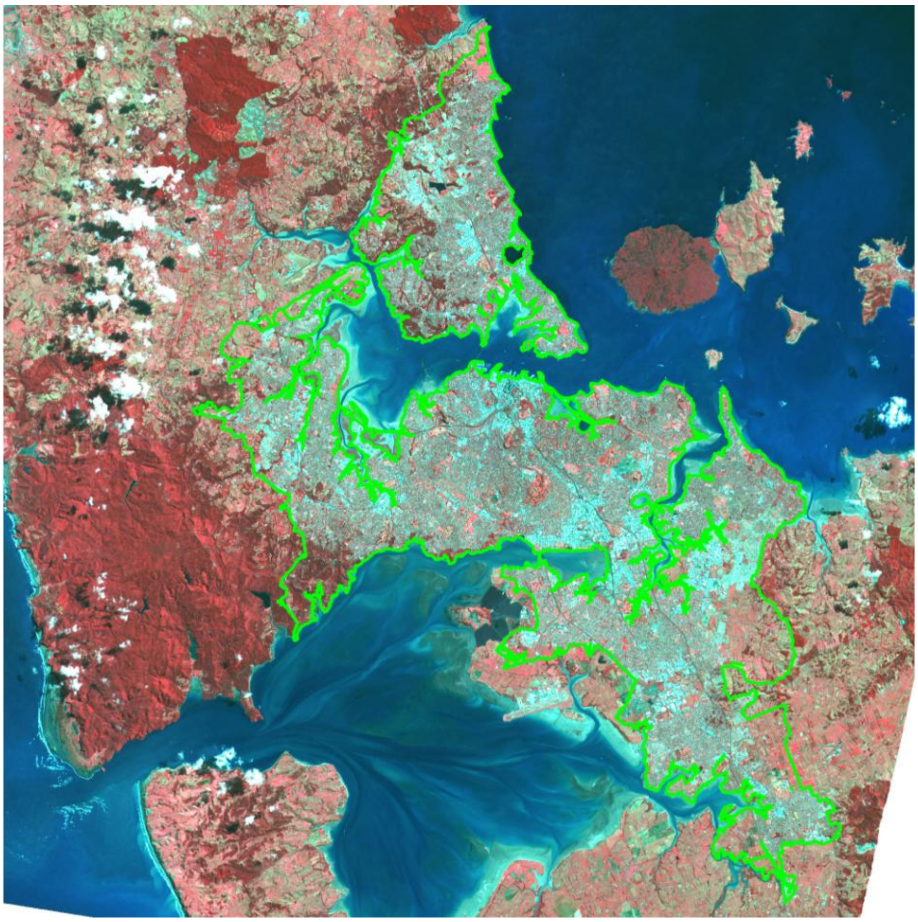
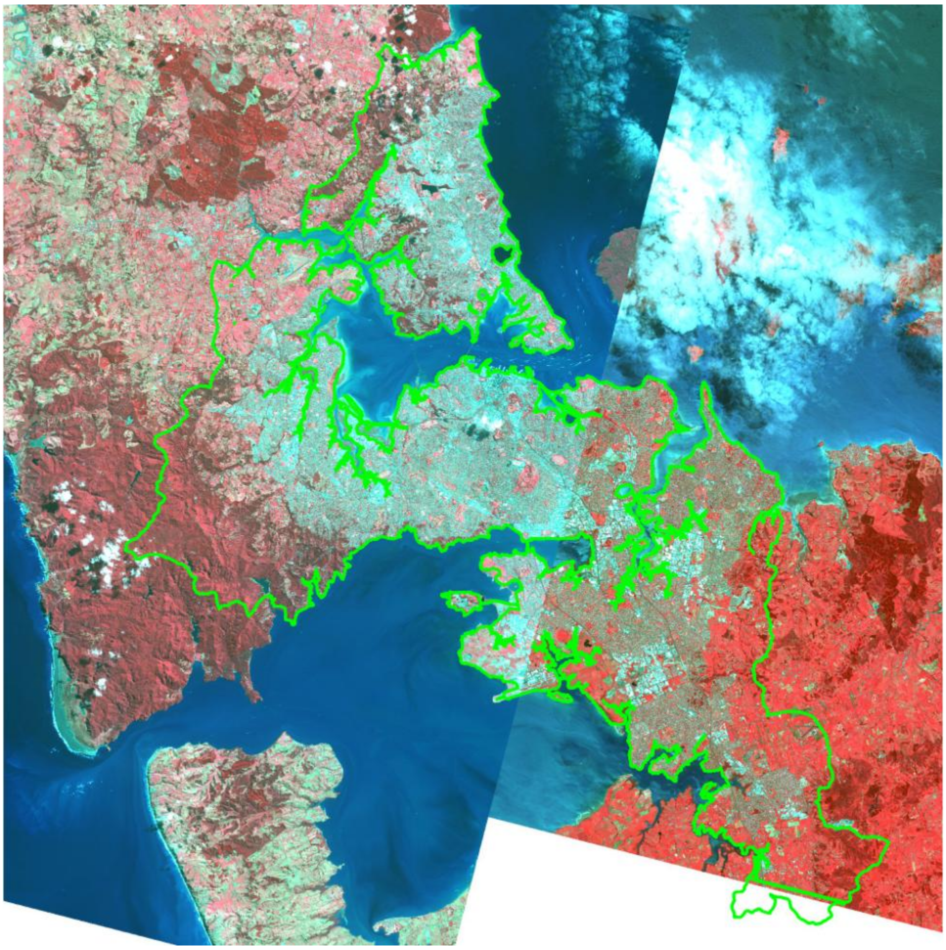


**Table 2** Characteristics of the 2007 and 2008 SPOT images

| | | |
|---|---|---|
| Satellite | 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 |
| Instrument | HRG2 | HRG2 |
| Path/Row | 440/424 | 439/424 |
| Date | 7 December 2007 | 20 March 2008 |
| Scene centre | S36.85/E175.05 | S36.86/E174.48 |
| Incidence angle | 8.82° | 4.66° |
| Sun elevation | 62.30° | 42.71° |
| Azimuth | 66.09° | 46.71° |
| Original data level | 1A | 1A |

**Figure 3** SPOT-5 March 2008 (left) and SPOT-5 December 2007 (right) with the mapped area outlined in green. Note the small portion at the south end of the area of interest that is not covered by imagery. This was excluded from the analysis.



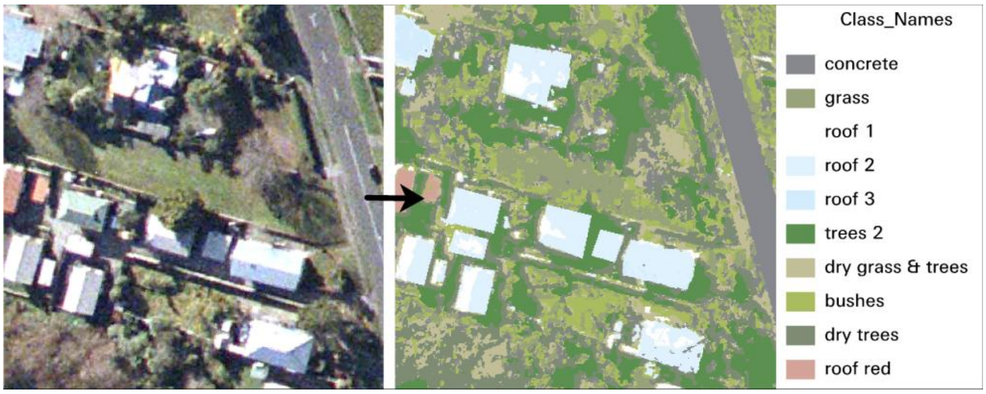
## 2.3 Sampling

Two sets of aerial photographs were provided by ARC for use as ground truth data for mapping the impervious fraction. The first was 2001 with tile sizes varying from ~ 0.9 × 1.2 km to 2.4 × 4.0 km. The second set was 2007 aerial photography with a tile size of 4.84 × 7.25 km. For both 2001 and 2007 aerial photographic coverage, 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).

The sampling procedure adopted 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 100 × 100-m subimage 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 initial, automatically derived classifications noted above were manually cleaned, then saved for later analysis. At a later stage in the processing, these manually cleaned classifications were combined into the four required classes: impervious, pervious, water, unknown. Figure 4 shows the first steps of this process for a single 100 × 100-m subimage.

**Figure 4** Typical 100 × 100-m aerial photographic subimage (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 three SPOT images used to cover the nominal 2000 and 2007 years (2000 and 2007/08 SPOT coverage), average reflectance values were calculated for the locations of the 100 × 100-m tile sampled from the appropriate date of 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, along with the TLA for each of the sampled tiles. These values were used to form the model between SPOT reflectance and impervious fraction, as described in the next section.

## 2.4 Model analysis

A logistic regression 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 ( $B_1 \dots B_4$ ), an indicator variable for the territorial authority, 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 TLAs. 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).

# 3 Results

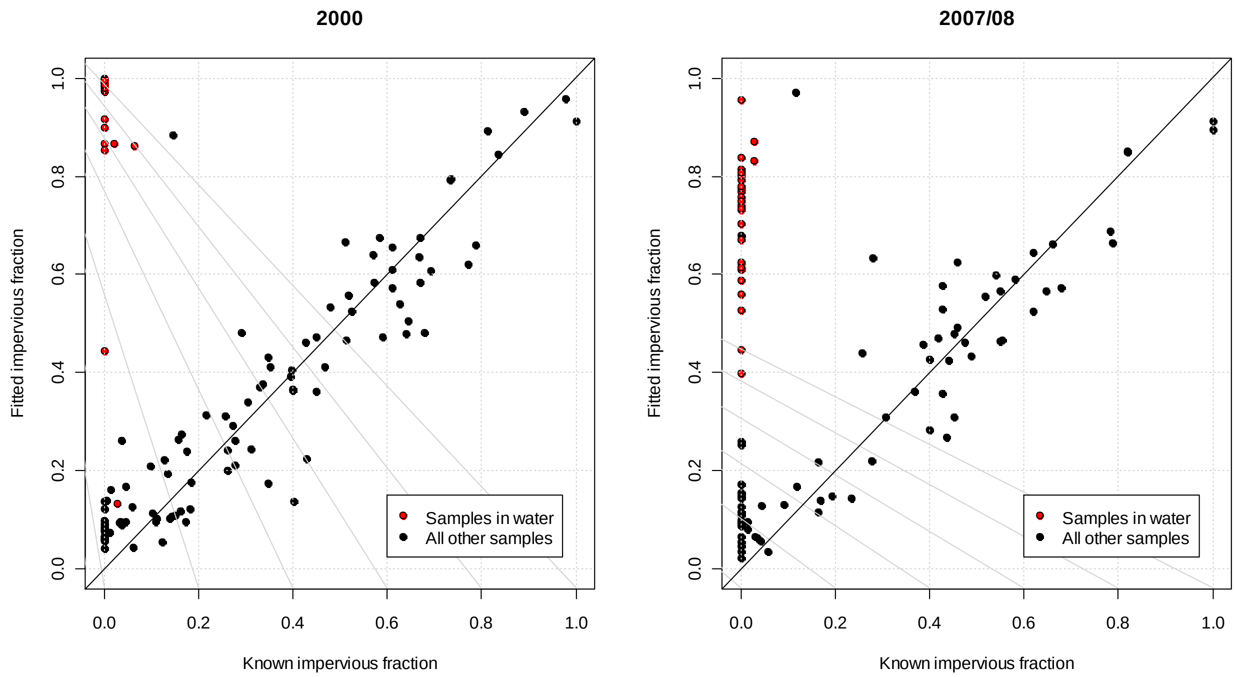
## 3.1 Model analysis

The best model for prediction of impervious fraction, using SPOT bands and the vegetation index as explanatory variables, had no significant effect for TLA. This means that the model could be used in all parts of the 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. The nature of the logistic regression means that the fitted impervious fraction estimates are constrained to lie in the range of zero to one.

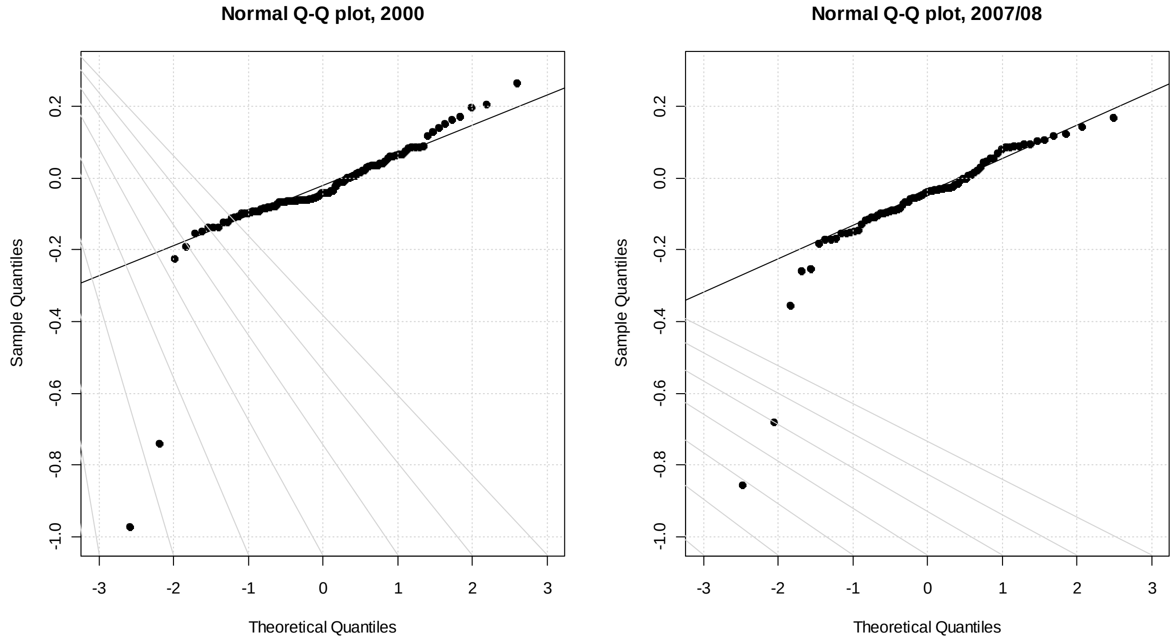
It should be noted that there are some obvious outliers with zero values of impervious fraction (fully pervious surfaces). By colouring targets that happen to be in water in Figure 5, it is clear that these outliers are associated with the surrounding water. Although there are a small number of non-water outliers, none of those are highly influential.

**Figure 5.** Plot of fitted against ground-truth-derived impervious fraction for 2000 (left) and 2007/08 imagery (right)




If the water targets are omitted, Figure 6 shows a Quantile-quantile (Q-Q) normal distribution plot of the residuals for the regression. Aside from a small number of points, none of which are influential, the residuals follow the expected straight line. The plots in Figure 5 and Figure 6 suggest that the model developed is a satisfactory model.

**Figure 6** Quantile-quantile normal plot of residuals from the regression for the 2000 data (left) and 2007/08 data (right)




## 3.2 Mapping of impervious fraction

The regression used to estimate the impervious fraction from the 2000 SPOT image was implemented using the following steps:

1. Given SPOT bands $B_1$ to $B_4$, calculate the normalised difference vegetation index (NDVI) as $V_{NDVI} = (B_3 - B_2)/(B_3 + B_2)$
2. Calculate the regression value $F$ using:

$$F = a_0 + a_1.\,(B_1 + B_2) + a_2.V_{NDVI} + a_3.\,(B_1 - B_2) + a_4.B_3 + a_5.B_4 + a_6.V_{NDVI}.\,(B_1 + B_2) + a_7V_{NDVI}.\,(B_1 - B_2) + a_8V_{NDVI}.B_4$$

| Term | Coefficient |
|---|---|
| (Intercept) | −2.504993 |
| $B_1+B_2$ | 0.027279 |
| $V_{NDVI}$ | −9.175794 |
| $B_1-B_2$ | −0.019715 |
| $B_3$ | −0.012869 |
| $B_4$ | −0.021373 |
| $(B_1+B_2)* V_{NDVI}$ | 0.005062 |

| | |
|---|---|
| $(B_1-B_2)*V_{NDVI}$ | 0.029606 |
| $B_4*V_{NDVI}$ | 0.074101 |

3. Invert the regression value $F$ to obtain the impervious fraction $Z$ using $Z = \exp(F)/(1 + \exp(F))$. The result will be in the range [0, 1].

The regression used to estimate the impervious fraction from the 2007/08 SPOT images was more complex as it required a variable for the year and it was also found best to regress against principal components rather than the image and NDVI values directly. The regression used was implemented using the following steps:

1. Given SPOT bands $B_1$ to $B_4$, calculate NDVI as $V_{NDVI} = (B_3-B_2)/(B_3+B_2)$
2. Centre the four SPOT bands and the NDVI as follows:

| |
|---|
| $B1' = B1 - (132.54992500)$ |
| $B2' = B2 - (107.04269231)$ |
| $B3' = B3 - (99.41706346)$ |
| $B4' = B4 - (128.06204423)$ |
| $V_{NDVI}' = V_{NDVI} - (-0.03561827)$ |

3. Calculate the principal components using the centred variables and the following coefficients:

| | PC1 | PC2 | PC3 | PC4 | PC5 |
|---|---|---|---|---|---|
| $B_1'$ | −0.5414012992 | −0.295851558 | −0.531748971 | −0.580171271 | −0.0009039525 |
| $B_2'$ | −0.4264306206 | −0.567300352 | −0.018577442 | +0.704241551 | +0.0050944151 |
| $B_3'$ | −0.3065653451 | +0.716519807 | −0.499394755 | +0.378419506 | −0.0045399995 |
| $B_4'$ | −0.6565505927 | +0.277865556 | +0.683734572 | −0.155687483 | +0.0007036785 |
| $V_{NDVI}'$ | +0.0007532256 | +0.005680235 | −0.003134491 | −0.002284622 | +0.9999760612 |

4. Calculate the regression value $F$ using:

$$
\begin{aligned}
F \;=\; & a_0 + a_1.P_{PC1} + a_2.Y \\
& + a_3.P_{PC2} + a_4.P_{PC3} + a_5.P_{PC4} + a_6.P_{PC5} \\
& + a_7.P_{PC1}.Y + a_8 P_{PC2}.Y + a_9 P_{PC3}.Y + a_{10}.P_{PC4}.Y + a_{11}.P_{PC5}.Y
\end{aligned}
$$

| Term | Coefficient |
|---|---|
| (Intercept) | 0.897859 |
| $P_{PC1}$ | 0.010886 |
| $Y$ | −2.907267 |
| $P_{PC2}$ | −0.037980 |
| $P_{PC3}$ | 0.013478 |

| | |
|---|---|
| $P_{PC4}$ | 0.026461 |
| $P_{PC5}$ | 6.930575 |
| $P_{PC1} * Y$ | –0.006569 |
| $P_{PC2} * Y$ | –0.003572 |
| $P_{PC3} * Y$ | –0.018549 |
| $P_{PC4} * Y$ | 0.032914 |
| $P_{PC5} * Y$ | –9.646511 |

(Note that $Y$ is either 0 (for 2007) or 1 (for 2008))

5. Invert the regression value $F$ to obtain the impervious fraction $Z$ using $Z = \exp(F)/(1 + \exp(F))$. The result will be in the range [0, 1], where 0 is interpreted as 0% impervious (or 100%pervious) and 1 is interpreted as 100% impervious (or 0% pervious).
6. Where there is an overlap between the 2007 and 2008 images, use the mean of the two estimates.

The regressions produced two images of impervious fractional cover for the nominal dates of 2000 and 2007 respectively. From these we are able to extract statistics for any region of interest. The ARC supplied the following shape files:

- disslv_mul.shp – the metropolitan urban area,
- disslv_mul_exp.shp – the metropolitan urban area and expansion areas,
- dissolv_mappedarea.shp – the total mapped area, which includes sub catchments near the metropolitan area where freshwater quality and or macroinvertebrate monitoring is undertaken, and
- tla2006dcdb.shp – the TLA boundaries.

Each shape files was converted to an ARC/INFO coverage. For each area of interest an additional coverage was generated by intersecting with TLA coverage. Leica Imagine was then used to extract the mean impervious fractional coverage for each region. Note: polygons smaller than half a hectare, generated by the intersection process, were ignored. Tables 3–5 show the area and average impervious fraction for each of the areas of interest, and also broken down into the TLAs within the area.

**Table 3** Average impervious fraction within the metropolitan urban area shape file, and also broken down to TLAs within the same shape file.

| Territorial authority | Area (ha) | Average impervious fraction | |
|---|---|---|---|
| | | 2000 | 2007/08 |
| Metropolitan urban area | 51203 | 0.40 | 0.44 |
| Auckland City | 15376 | 0.48 | 0.50 |
| Manukau City | 14441 | 0.37 | 0.36 |
| North Shore City | 10580 | 0.37 | 0.36 |
| Papakura District | 2477 | 0.27 | 0.37 |
| Waitakere City | 8279 | 0.32 | 0.29 |

**Table 4** Average impervious fraction within the metropolitan urban area and expansion areas shape file, and also broken down to TLAs within the same shape file.

| Territorial authority | Area (ha) | Average impervious fraction | |
|---|---|---|---|
| | | 2000 | 2007/08 |
| Metropolitan urban area and expansion areas | 53649 | 0.39 | 0.42 |
| Auckland City | 15376 | 0.48 | 0.50 |
| Manukau City | 14910 | 0.39 | 0.49 |
| North Shore City | 10584 | 0.37 | 0.36 |
| Papakura District | 3523 | 0.27 | 0.37 |
| Waitakere City | 9198 | 0.32 | 0.29 |

**Table 5** Average impervious fraction within the total mapped area shape file, and also broken down to TLA's within the same shape file

| Territorial authority | Area (ha) | Average impervious fraction | |
|---|---|---|---|
| | | 2000 | 2007/08 |
| Total mapped area | 75671 | 0.31 | 0.35 |
| Auckland City | 15378 | 0.48 | 0.50 |
| Franklin District | 133 | 0.08 | 0.17 |
| Manukau City | 19165 | 0.35 | 0.44 |
| North Shore City | 12693 | 0.33 | 0.32 |
| Papakura District | 7403 | 0.18 | 0.29 |
| Rodney District | 1748 | 0.11 | 0.13 |
| Waitakere City | 18938 | 0.20 | 0.20 |

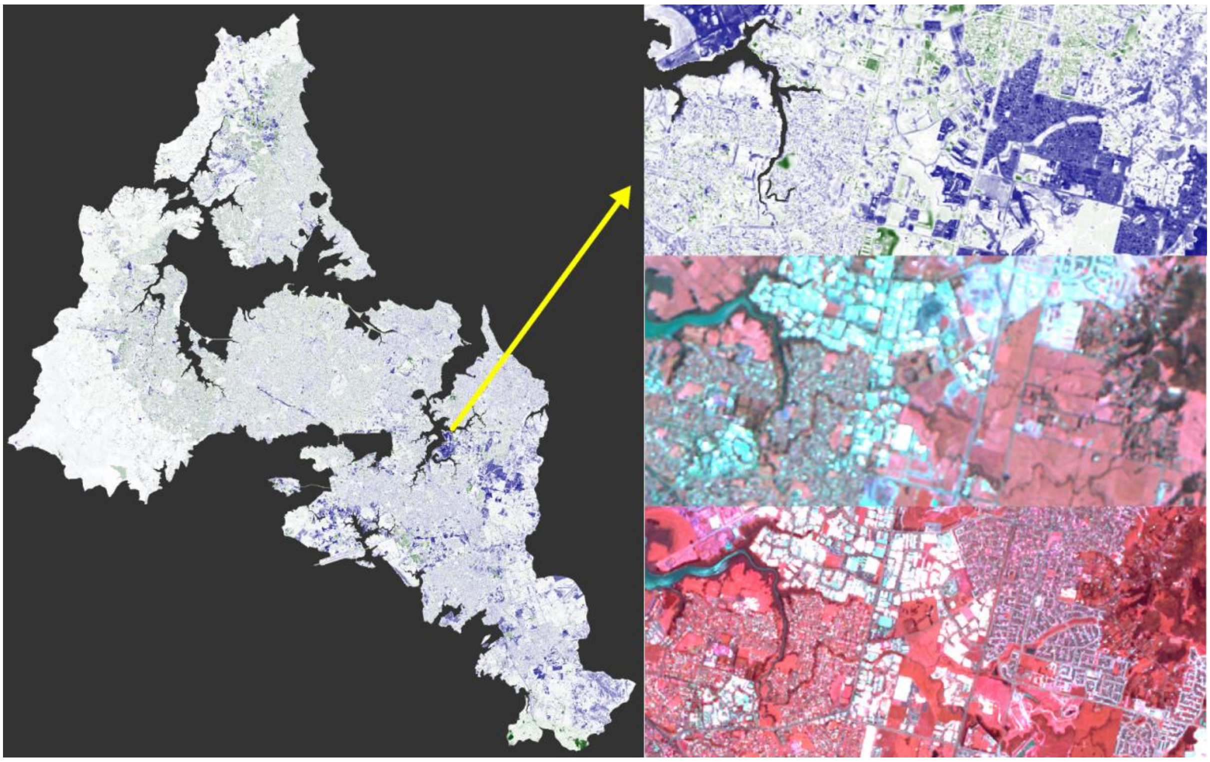
The impervious fractional image for each date was converted to binned ranges representing 0–5, 5–10, 10–15% etc. An image representing the difference between the two images was generated by simply subtracting them and a second by subtracting and binning into 5% ranges. These images are all in Leica Imagine format and are named as shown in Table 6.

**Table 6** Delivered results in Leica Image format (*.img)

| File name | Content |
|---|---|
| impervious_2000.img | 32-bit real impervious fraction for 2000 |
| impervious_0708.img | 32-bit real impervious fraction for 2007/08 |
| impervious_2000_binned | 8-bit image, grouped into 5% ranges |
| impervious_0708_binned | 8-bit image, grouped into 5% ranges |
| 2000-0708_unmixed_diff8.img | 8-bit signed integer representing % change |
| 2000-0708_unmixed_diff_binned.img | 8-bit signed integer, binned to 5% ranges |

The images that portray the difference between 2000 and 2007/08 both contain a pseudo colour table with a colour graduation moving from dark green for areas that have become less impervious through light green to white (for no change), and then through light purple and finally dark purple for areas that have become more impervious Figure 7 illustrates this colour scheme.

**Figure 7** Difference in imperviousness between the 2000 and 2007/08 analyses (left image), where the green shade indicated areas becoming less impervious and the purple shade indicated areas becoming more impervious. A blow-up is shown on the right top with the same area from the original 2000 imagery in the centre and the 2007 imagery at the bottom.



# 4 Discussion and conclusion

Both the regression approach used here and previous work using spectral unmixing rely 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 5 and Figure 6 indicate that the regression is very good for both the 2000 image and the 2007/08 pair.

Figure 7 clearly shows significant green fields development as purple areas. It also shows some "greening" of subdivisions already existing in 2000. The latter observation probably indicates that bare ground or relatively barren sections in a newly formed subdivision will result in an initial overestimation of the impervious proportion. It is likely that this is not just a result of bare soil being classified as impervious, although that was the treatment for the training data. Rather it is probably also a result of those newly developed subdivisions being atypical to the majority of the urban area that was used to form the regression. There is probably less, and a different mix of vegetation covering the pervious areas – for instance smaller trees and less developed gardens.

The results in Table 3 through Table 5 should be treated with care. Some of the TLA regions intersecting with areas of interest are very small and therefore less reliable. This is especially true for Rodney and Franklin. Most regions show an increase in their impervious surface fraction. Those TLAs showing a slight reduction in impervious fraction, notably the North Shore and parts of Waitakere, may be partially impacted by the effect of new subdivisions just before 2000 as noted above.

Changes in either direction can be masked if a larger rural area is also included – see data from Waitakere in Table 5 compared to data from Tables 3 and 4 for Waitakere.

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