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Urban Monitor: Enabling effective monitoring and management of urban and coastal environments using digital aerial photography

Final Report – Transformation of aerial photography into digital raster information products

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Copyright and disclaimer

Important disclaimer

Foreword

This report describes the production of spatial information products useful for making environmental assessments from digital aerial photography as part of the Strategic Assessment of the Perth and Peel Regions in Western Australia. The information generated includes baseline information on elevations, ground reflectance, presence of vegetation and its height, and accompanying meta-data. The information was generated from the Urban Monitor initiative following a request obtained in mid-2012. Given the requirement of the spatial information within two months of the request, it was generated for two time periods only, 2007 and 2009, building on the results from previous research. The spatial information produced will enable further analysis by both State and Commonwealth agencies involved in the Strategic Assessment. The digital data has been provided to enable it to be combined with other datasets. Being the first major use of Urban Monitor products, much has been learned and it is hoped that future use will prove valuable as a mapping and monitoring tool.

The objective of Urban Monitor is an urban monitoring system, based on consistent data and methods that are able to track and communicate changes in features of interest in a way that has previously not been possible. The initiative has included partners with responsibility for management of urban vegetation, river and wetland environments, and scheme and self supply water resources. The Urban Monitor area and monitoring objectives are well aligned with those of the assessment, and when combined with other data, particularly the task of assessing environmental values and the status of reserves and habitats. The report describes the use of the information by providing examples of quantitative summaries of the information by reserve, as well as providing examples of the use of the information for visual communication.

We envisage that, when used in conjunction with other datasets and ground truth information, many questions beyond what may be addressed in this report will emerge. Ideally monitoring is recurrent activity providing information updated with the view to continuously improving the processes and adapting the process to have the ability to respond to new questions. The incorporation of data from 2012 or 2013 would be beneficial to the Strategic Assessment.

Contents

Acknowledgments

The Urban Monitor initiative has included funding and in-kind support from the following agencies – CSIRO, Landgate, Department of Water, Water Corporation, Department of Environment and Conservation, Department of Planning, Department of Agriculture and Food WA, Swan River Trust, WA Land Information Systems, Botanic Gardens and Parks Authority, iVEC, Perth Region NRM and the Rottnest Island Authority. This consortium made financial contributions to purchase the aerial photography used in this project. Analysis of the digital data was carried out mainly by CSIRO and Landgate.

Funding for the generation of spatial information products was provided by the Australian Government as represented by the Department of Sustainability, Environment, Water, Population and Communities.

Executive summary

This project builds on work from the Urban Monitor initiative, which has established quantitative methods, standards and systems for monitoring urban, peri-urban and coastal environments for natural resource management and planning using digital aerial photography and other data. Though still under development, this potentially includes monitoring changes in: estuarine, river and wetland foreshores; non-irrigated native bush areas; urban canopy cover, irrigation uniformity and efficiency in public and private open space; areas undergoing urbanization; and groundwater dependent vegetation. The products have been used to assess changes in urban land use and likely impacts on hydrology and identifying changes in vegetation presence and condition for land managers.

This report describes the generation of spatial information including estimates of ground elevation, heights of features above the ground, vegetation extent and its height. These information were provided in both map and digital formats to agencies engaged in the Strategic Assessment of environmental values in the Perth-Peel region. The purpose of this report is to describe the data and methodology, the information products derived, and the interpretation and use of the products.

1 Introduction

The Strategic Assessment of environmental values in the Perth and Peel Regions was announced following an agreement in July 2011 between the Western Australian Ministers for Planning and Environment and the Commonwealth Minister for Sustainability, Environment, Water, Population and Communities. The Strategic Assessment is led by the Department of the Premier and Cabinet (DPC) in partnership with the Commonwealth Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) and in conjunction with state run processes aims to provide and implement a long term strategic response to matters of national environmental significance [Strategic Assessment, 2012].

In 2006 CSIRO and its state partners commenced the Urban Monitor initiative aimed at establishing methods for monitoring time-series urban and environmental indicators [Caccetta et al., 2011a]. Here we describe the production of spatial information from the initiative for use in the Strategic Assessment.

The Urban Monitor project uses digital aerial photography as its primary data set. It takes advantage of the move from analogue (film) based aerial photography to digital photography to develop a digital monitoring tool that can identify changes in land condition and elevation at a fine scale (e.g. 0.1 to 0.3m). The methods offers unparalleled monitoring capability using routinely collected data provided sufficient digital data are retained and the collection method follows standardised and rigorous protocols.

2 Material and Methods

2.1 Data

Fundamental to monitoring is a consistent time series of data. Having the data geometrically aligned and radiometrically calibrated allows for comparisons through space and time. Using the reporting on nature reserves as an example, this provides information relevant to such questions as “what is the state of this reserve at present relative to its past, and how does this compare with other reserves?”. “How are different areas within the reserve responding to climate, pests, disturbances etc?”.

Apart from being a requirement for deriving trend information, geometrically and radiometrically consistent data aids in the analysis and automation of the derivation of class label information such as maps of irrigated and non-irrigated vegetated areas, roads, roofs and trees. Automation is important in this regard because of the volume of data and the fine scale of information which may be derived.

For the purposes of this project, the data are assumed to have been geometrically and radiometrically aligned, and prepared as 1:25,000 map sheets closely corresponding to the standard cadastral map series. Prepared in this way it also facilitates the data management for subsequent use by other agencies using standard software and hardware.

The primary source of data used for the production of the spatial information product types were;

a) Stereo digital aerial photography;
b) Digital surface models generated from a); and
c) radiometrically-calibrated true orthophotographs calibrated to ground reflectance

We provide a description of each product type in the following sections.

2.1.1 STEREO DIGITAL AERIAL PHOTOGRAPHY

Data collection commenced in 2007, where approximately 35000 frames of data over a period of 19 cloud-free days, beginning on March 14, was acquired using a Microsoft UltraCAM-D camera (Leberl and Gruber, 2003) flown at a height of approximately 1300m, capturing red, green, blue, and near infrared, along with a panchromatic image. The ground sample distance was approximately 30cm and 10 cm for the multispectral and panchromatic data respectively. The time period corresponds to the end of dry, hot Mediterranean summer weather experienced in Perth at this time of year. It therefore coincides with peak vegetation stress caused by low soil moistures and low groundwater levels before the cooler and wetter winter period starts in April-May. In order to minimize the effect of solar angle (and, in particular, shadowing) on the images, acquisition was constrained to two hours each side of solar noon. The field of view was approximately 50°. The dynamic range of the data as captured by the camera was preserved (i.e. the data were not converted to 8 bit quantisation or compressed using routines converting the data to JPEG formats). Forward overlap of digital frames was about 60% with a 30% side overlap with the neighbouring path. This overlap enables accurate (+/- 0.3 m) digital surface models to be derived from the photographs. These acquisitions were repeated in 2008 and 2009, though with some adjustment to the acquisition specifications towards angular as opposed to time considerations.

2.1.2 DIGITAL SURFACE MODEL

Crucial to the success of monitoring change is the accurate geometric correction and coregistration of images. This requires using a very high-resolution digital surface model (DSM) applicable to the image of

interest. The DSM is automatically extracted from the stereo images. The orthoimages and DSM are generated for the region at a spatial resolution of 0.2m using geometric controls provided by Landgate and software developed by CSIRO.

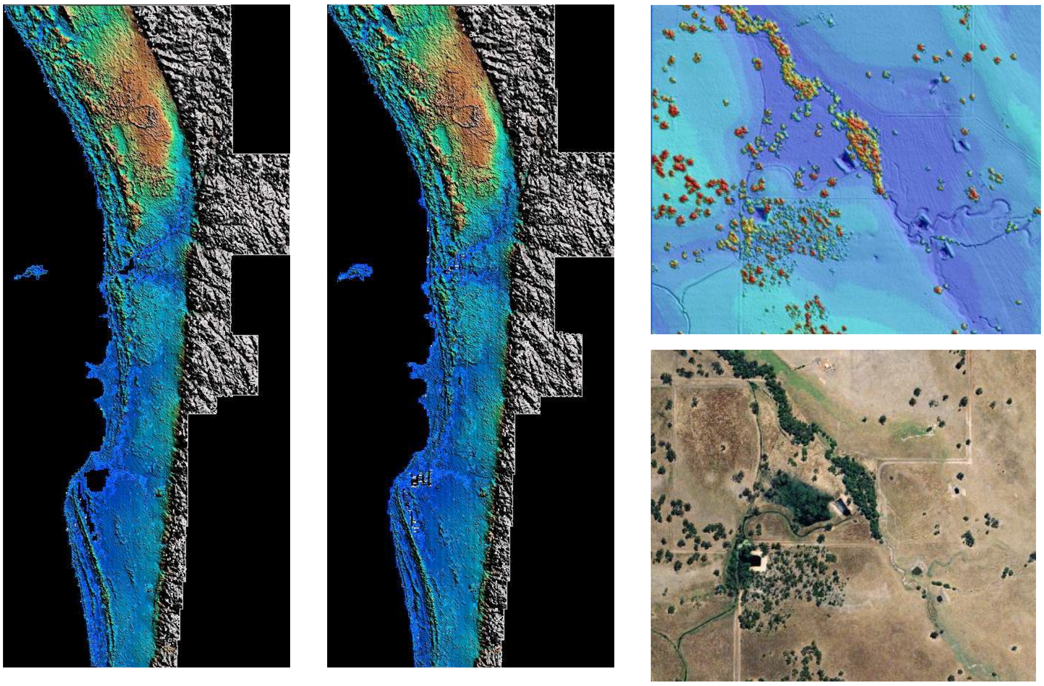


Figure 1. The primary monitoring data consists of radiometrically calibrated true othophotos. Digital surface models are generated for each time period. Here are examples of the DSM for 2007 and 2009 (left and middle), and a local example of the orthophoto and corresponding DSM (bottom and top right respectively). The 'hotter' the colour in the DSMs, the higher the elevation relative to mean sea level.

2.1.3 RADIOMETRICALLY CALIBRATED TRUE ORTHOPHOTOS

To automatically track changes in a time-series of images requires that the same land-cover viewed in different time-steps has the same spectral signature. This can be achieved by radiometrically calibrating the time-series to a reference image or to some other standard . To allow interoperability between sensors we have chosen to calibrate to *ground-reflectance.*

To facilitate the calibration, painted hardboard targets were deployed throughout the region at the time of acquisition. The targets were measured with a spectrometer in the laboratory, both before and after deployment, to allow vicarious calibration of the imagery to these reference values. Details of the vicarious calibration method are described by Collings et al. (2011), and a pictorial representation of the effect of calibration is given in Figure 2 which shows that the calibrated data are significantly more consistent than the original data, making monitoring and quantitative methods possible.

(a)

(b)

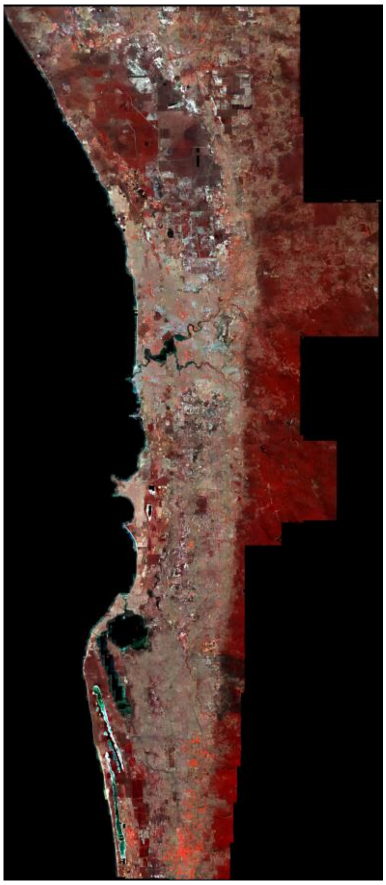


Figure 2. Radiometric calibration of the aerial imagery for the year 2007. Left: Before calibration. Right: After calibration. The striping in the left image is due to data acquired on different flight lines. For the calibrated images on the right, flight line differences are significantly reduced, though some localised differences may still be evident in the final images when viewed at high resolution.

2.2 Method

In this section we described the methods used to produce the remaining information products from the DSM and the radiometrically calibrated true orthophotos. There were very large data volumes resulting from having a data resolution of the order of 20cm. Therefore the methods and workflows were based on using the greatest possible computer automation combined with some manual intervention to improve the final accuracy of the results. A Quality Assurance process was embedded within the workflow to inform the requirements and record the level and form of intervention taken. The methodology therefore contains automated methods, manual quality checks, manual interventions, recording of the interventions and the level of interventions taken, and documentation of known remaining limitations.

2.2.1 LANDCOVER ANALYSIS

Given a time series of Digital Surface Models (DSMs) and radiometrically corrected true orthophotographs, further information including trajectories of cover intensity, landcover classifications, and segmentations to produce, for example, estimates of ground elevation and tree heights. These were generated by computer algorithms with a high degree of automation with minimal manual intervention.

The basic steps used were:

- A Ground Elevation Model (or GEM) was generated from the digital surface mode (DSM). In this step, candidate ground points were identified (from those that were not ground e.g. trees, houses, etc) and then interpolated to produce the GEM.
- A Relative Elevation Model (REM) was generated by subtracting the GEM from the DSM, resulting in elevation relative to ground (which is zero)
- A classification of green space was generated using the radiometrically calibrated orthophotographs and the REM. The spectral information identifies all growing vegetation, including for example grass, bushes and trees, and the REM was used to label these as grass (at ground height) and trees and bushes (above ground).

The products produced for both 2007 and 2009 were

(1) a digital surface model,
(2) a ground elevation model,
(3) a relative elevation model,
(4) a radiometrically calibrated orthomosaic,
(5) a vegetation/non-vegetation classification,
(6) a vegetation height product,
(7) a vegetation index product,
(8) a map of missing data locations,
(9) a grass/non-grass classification, and
(10) a tree/non-tree classification
(11)Meta files including 'included' and 'excluded' areas.

2.2.2 PROCESSING AND QUALITY CHECKING/CHECKING LEVELS

Products for each 1:25,000 tile were processed to 3 different levels:

(1) Automatically generated output, no manual inspection
(2) Automatically generated output, manual inspection and errors documented Product has been checked and any noticed errors flagged in the error unfixed file (abbreviation: *eru*)
(3) Automatically generated output, manual inspection and some errors remedied using manual digitisation. Unfixed errors are still listed in the *eru*. Fixed errors are listed in the error fixed file (abbreviation: *erf*), occasionally fixes on overlaps between tiles have not been added to all the appropriate *erf* files.

3 SPATIAL PRODUCT DESCRIPTIONS

3.1 Background and example of use – useful displays

In this section we describe the data layers that were produced and provide a graphical sample of each layer. The information products produced are in a form suitable for further quantitative analysis using a GIS and/or an image processing package, rather than for direct visual display.

3.1.1 USEFUL DISPLAYS

Some useful displays may be generated by using combinations of the data layers below. Here we provide some simple compound displays as a sample, noting that it is only a small sample of the combinations that are possible.

Figure 3. Example of compound displays: Top left – orthophoto; Top right – Vegetation/non-vegetation mask in green displayed with sun-shaded elevation model in grey; Bottom left – Irrigated grass mask in green displayed with

sun-shaded elevation model in grey; Bottom right – Tree mask in green displayed with sun-shaded elevation model in grey.

Figure 4: Graphical depiction of the left hand digital orthophotograph (right) showing tree height in increasingly 'hot' colours displayed with a sun-shaded elevation model in grey for unvegetated areas.

3.1.2 BACKGROUND AND EXAMPLE OF USE – GIS ANALYSIS

The data supports analysis within a GIS environment. One such analysis is the summary of the data by GIS region. Regions could include boundaries defining the entities: Shires; Native Vegetation Reserves; Blocks of land proposed for development; or any other geographic unit. If one wished, for example, to have an

indicator reflecting the height structure of a reserve, say ordered from uniform height to mixed height, then one could summarise each region by the variance of tree height.

In the following example we calculate some statistics of the trees and bushes using reserve boundaries provided by the Department of Environment and Conservation. In this analysis we estimate for each reserve the:

a) average height of the trees,
b) canopy area of tall trees (>20m), and
c) variance of the height of the trees.

The results are summarised in the table below.

Table 1 Example of structural statistics of vegetation in managed reserves.

Region	Average height of trees (m)	Variance in tree height (m^2)	Area of vegetation above 20m (m^2)
Austin Bay Nature Reserve	2.8	2.7	0
Black Lake Middle	5.2	12.7	3
Black Lake North	6.8	18.3	1700
Black Lake South	5.7	7.9	20
Goegrup Lake Nature Reserve	6.4	13.2	400
Region 01	3.6	8.9	0
Region 02 (Serpentine River)	6.0	23.9	420
Region 03	2.9	2.7	0

The results may be displayed graphically. In Figure 5, for example, we have coloured the original polygons by the tree height variance, where cool colours (ordered blue, to green) represent low variance (trees having a relatively uniform height within the reserve) to hot colours (ordered yellow to orange to red) representing high variances (trees having a high variation in height). In this display mixed height forest structures will appear red compared with areas of regeneration or under management practices which result in uniform forest height structure.

It would be of interest to generate such metrics for all reserves with the view to performing a comparative analysis with the view to generating a ranking indicator. For example, if tall trees were the focus due to bird nesting habits, then a ranking of reserve based on Area of vegetation above 20m, say, might be appropriate. In practice, such rankings would need to take into many other factors; here we merely allude to the potential for the information presented in this report.

Figure 5: graphical depiction of Digital orthophotograph (right); and Tree height in colour displayed with sun-shaded elevation model in grey.

3.2 Digital Surface Model

This product contains the height above sea level for each pixel/object. Units are in millimetres (mm) above sea level. When compared with the ground elevation model it gives the height above ground surface for each object (e.g. tree heights). The digital surface model can be displayed as a pseudo-colour (below), and as a sunshaded display whcih has proved useful for visual inspection of the edge of features. NULL values (-320 000) correspond to missing, corrupted, or extremely (erroneously) high or low heights, or to locations outside the Urban Monitor extents.

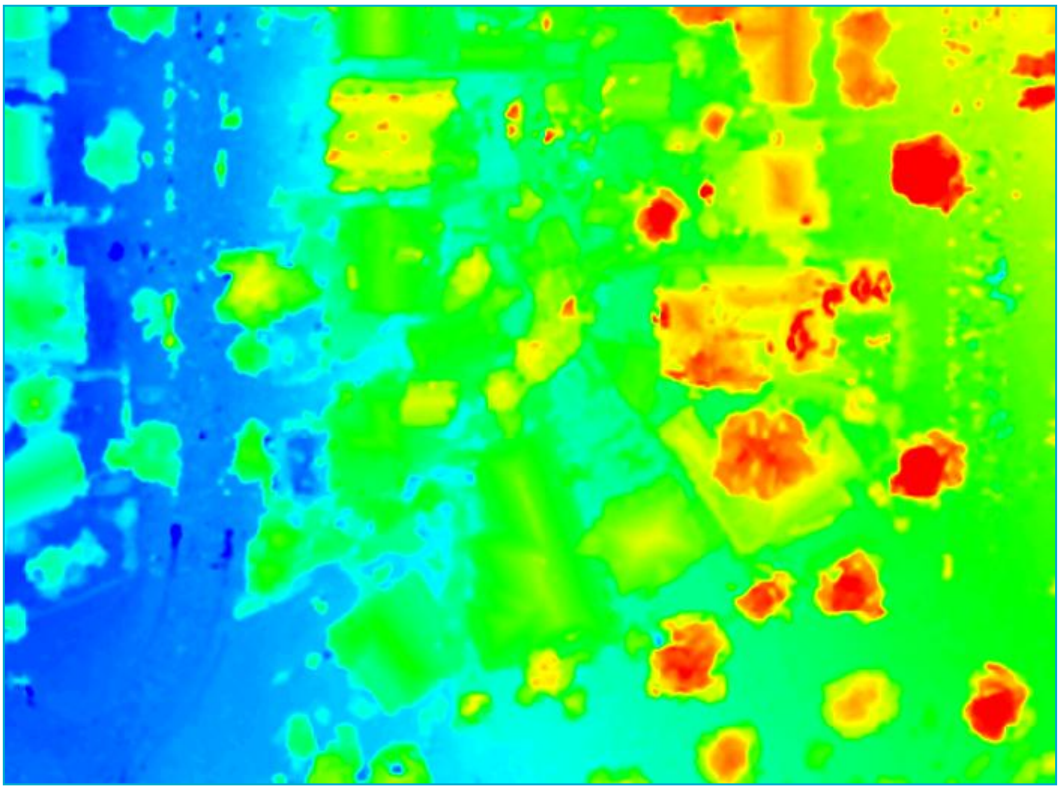


Figure 6: A pseudo-colour display of the digital surface model. Hot colours are high pixels (relative to sea level), cool colours are low pixels.

3.2.1 FORMAT

This raster (gridded) data is stored as signed 32bit integers. Units are in millimetres above sea level with the NULL value being -320 000. File names contain the abbreviation *dsm*.

3.2.2 LIMITATIONS

The stereo matching technique used to create the digital surface model is less reliable where:

(1) there are no objects, or texture (such as large dry lakes)
(2) materials are reflective (eg. water and large glass roofs)
(3) there is movement between two image pairs (eg. cars on roads, water)
(4) the surface discontinuous or thin such as sparse tree crowns and clouds
(5) the location and direction of the camera is incorrect.

Particularly for cloud related errors, cloud shadows may occur without the cloud itself being in the mosaicked multispectral images.

There is some variation in the shape of objects due to the camera angle. This variation is expected to be relatively small but has not been characterised completely.

3.3 Ground Elevation Model

The ground elevation model (GEM) gives the height in millimetres (mm) of the bare ground above sea level. This product is also known as a Digital Elevation Model (DEM). As with the digital surface model, a pseudo-

colour is a good display (below). NULL values (-320 000) correspond to missing, corrupted, or incorrect height data.

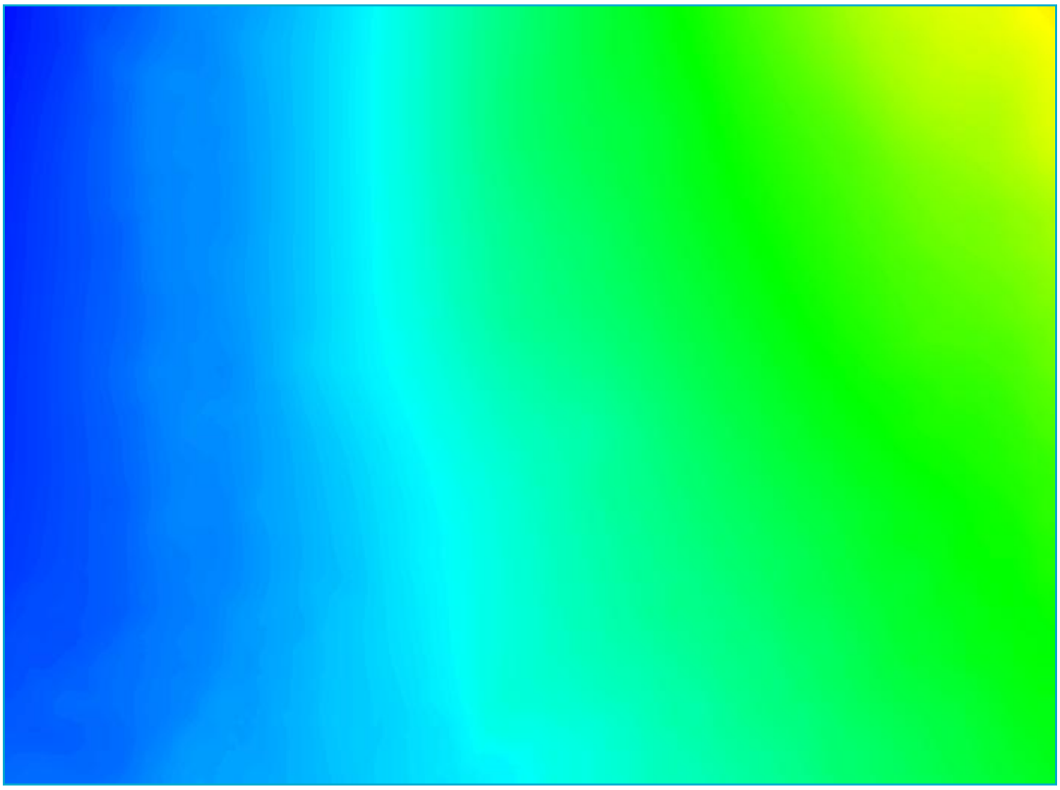


Figure 7: A pseudo-colour display of the ground elevation model. Hot colours are high elevation, cool colours are low elevation.

3.3.1 FORMAT

This raster data set is stored as signed 32bit integers. Units are in millimetres above sea level with the NULL value being -320 000 (same as the digital surface model). File names contain the abbreviation *gem*.

3.3.2 LIMITATIONS

Limitations of the ground elevation can be broadly divided into three categories:

(1) The true ground has sharp variations that the GEM smooths out. This often occurs at bridges, retaining walls, cliffs, highway barriers and the occasional steep dune system. The effects are usually localised and small in magnitude.

(2) The surface occasionally includes roofs of large industrial/commercial buildings and thick plantations forests where the ground is obscured over large areas. Efforts have been made to manually repair most of these errors.

(3) Not enough bare ground leads to knolls, hills, or valleys being omitted. This is known to only occur a few times, and only in extensive dense forests.

3.4 Relative Elevation Model

This product gives the heights of objects relative to the ground. The data is in millimetres, and always positive. This data is used to determine vegetation and building heights. It is often viewed as a pseudo-colour. NULL values (-320 000) correspond to missing/corrupted data or locations outside the Urban Monitor extents. The location of NULL values can be found using the no data mask.

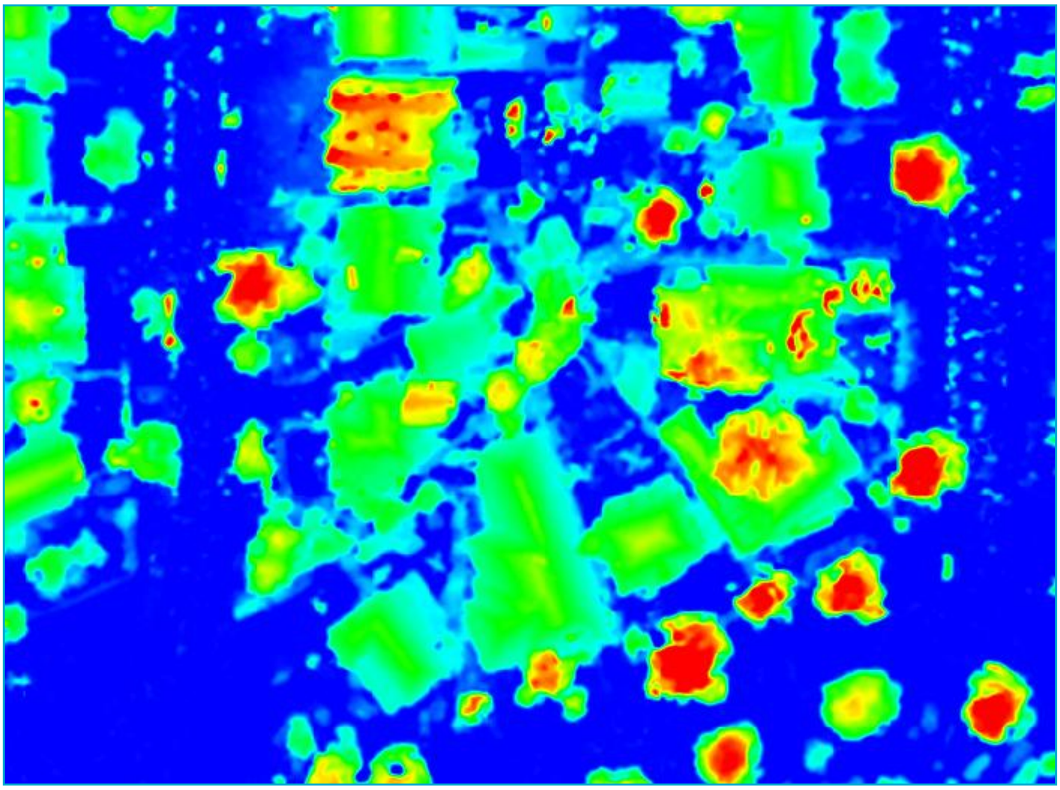


Figure 8: A pseudo-colour display of the relative elevation model. Hot colours represent tall objects; cooler colours are low lying objects/ground.

3.4.1 FORMAT

This raster data set is stored as signed 32bit integers. Units are in millimetres above ground with the NULL value being -320 000. The heights are always 0mm or greater. File names contain the abbreviation *nsm*.

3.4.2 LIMITATIONS

The limitations of the relative elevation model are directly related to the limitations of the DSM and the GEM. It is less reliable where:

(1) The area is flat with no objects, or texture (such as large dry lakes)
(2) the materials are reflective (eg. water and large glass roofs)
(3) there is movement between two image pairs (eg. cars on roads, water). Often the heights in water are wildly incorrect with values of 100m and higher

(4) the surface is discontinuous or thin such as sparse tree crowns and clouds
(5) the location and direction of the camera is incorrect.

And where roofs or forest canopy are included in the GEM then the relative elevation model is close to 0. Similarly when not enough bare ground leads to knolls, hills, or valleys being omitted from the GEM it causes the relative elevation to by incorrect.

3.5 Multispectral, Radiometrically Calibrated, True Orthophotographs

These images contain four bands of spectral data, are calibrated to ground reflectance and are orthorectified. The bands are red, green, blue and near-infrared. The order is different to normal multispectral data because band 4 corresponds to near-infrared data.

For vegetation related products a false colour display is recommended.

Figure 9: False colour image (red = band 4; green= band 1; blue=band 3)

The true colour display is also quite useful, especially for those unfamiliar with remote sensing.

Figure 10: True colour image (red = band 1; green = band 2; blue = band 3)

3.5.1 FORMAT

This raster data is stored as signed 16bit integers. It contains 4 bands:

Band 1: red
Band 2: green
Band 3: blue
Band 4: near-infrared

The units are in percent ground reflectance x 100. So ideally the spectral values range from 0 to 10 000, however the statistical nature of the calibration means that some values are outside this range.

NULL pixels are represented by all the reflectance in all 4 bands being set to 0.

Rottnest (1934SE_rottSE) was not radiometrically calibrated due to the difficulty of transporting calibration targets to the island. Its digital orthomosaic is stored in *unsigned* 16bit integers.

File names contain the abbreviation *dom*.

3.5.2 LIMITATIONS

The calibration cannot overcome illumination differences caused by cloud and cloud shadows. The appearance of actual clouds in the mosaic is very rare. However shadows cast by clouds are fairly frequent in some areas.

At very fine scales errors in the DSM can cause orthorectification errors make buildings and vegetation appear distorted.

The statistical nature of the calibration method means that spectral values can sometimes be negative. Usually it is acceptable to think of these as 0, but sometimes they contain useful data.

3.6 Vegetation/non-vegetation (two class) classification

This product classifies pixels into either green growing vegetation, or everything else. Green trees and irrigated lawns have a value of 1, all other areas cover types, including shadows and NULLs have a value of 0. Areas where there is no spectral data can be found using the no data mask product.

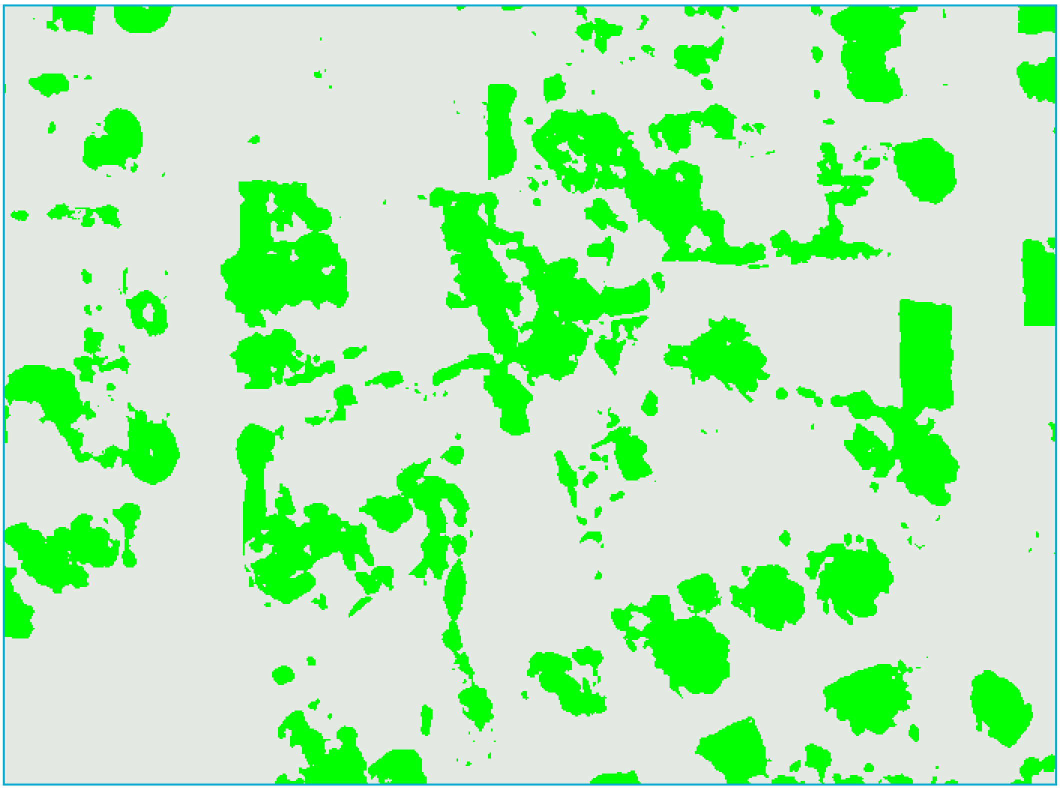


Figure 11: The vegetation/non-vegetation mask (green = vegetation, grey = everything else)

3.6.1 FORMAT

This raster data is stored as unsigned 8bit integers. Pixels determined to be vegetation have been assigned a value of 1. All other pixels, including missing data are assigned a value of 0 which corresponds to the NULL value of the dataset. File names contain the abbreviation *veg*.

3.6.2 LIMITATIONS

The vegetation mask does not include dry, brown vegetation such as heath, brown grass, forest litter or brown trees. Shadowed, green growing vegetation is also not included.

The classification relies heavily on the multispectral images and it inherits many of its errors: vegetation is occasionally missed in cloud shadows; it is completely missed in areas of cloud; and orthorectification issues can cause slight location inaccuracies. However the vegetation mask performs well over water, it is very rarely labelled as vegetation.

The classification is also confused by green synthetic materials (tennis courts) and blue materials (empty swimming pools and blue roofs).

Some subtle calibration differences has caused over classification in some forested areas in the 2007 data. We have endeavoured to fix most of these, but some remain. This issue did not occur in the 2009 data.

3.7 Vegetation height

This product contains the height of vegetation pixels relative to the ground in millimetres (mm). It is best viewed as a pseudo-colour. All non-vegetation pixels or pixels without height/spectral information are NULL.

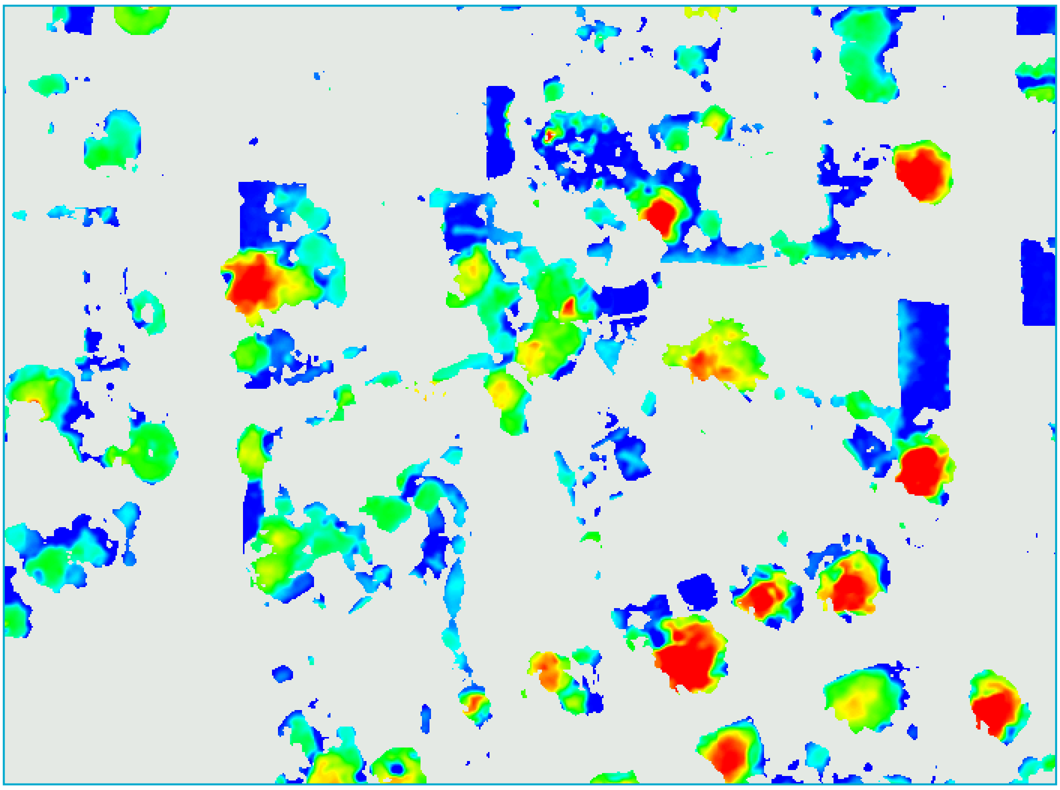


Figure 12: Hot colours are tall trees; dark, cool colours are grasses/low-lying vegetation

3.7.1 FORMAT

This raster data set is stored as signed 32bit integers. Units are in millimetres above ground with the non-vegetation and missing data represented by the NULL value of -320 000. The heights are always 0mm or greater. File names contain the abbreviation *vht*.

3.7.2 LIMITATIONS

This product inherits its limitations from the vegetation classification and the relative elevation model. Of particular importance to the vegetation height data are:

(1) When the GEM includes forest canopy the result is erroneous

(2) Where dense forests obscure real features in the terrain then the tree heights will show taller or shorter regions.

(3) Sparse tree crowns that are missed in the DSM result in vegetation with a 0 score. The frequency of sparse tree crowns was much higher in 2009, possibly as a result if recent fry years and much lower groundwater levels.

(4) For extremely tall buildings, such as in the Perth CBD, vegetation on the occluded side of the building can be assigned very tall heights.

3.8 Vegetation Index

This is simply the normalised digital vegetation index (NDVI) calculated by *(b4-b1)/(b4+b1)* for every vegetation pixel (with robust handling of negative values). It ranges from -1 to 1, although most vegetation pixels will have an index greater than 0.2. High values relate to dense, actively transpiring vegetation (e.g. irrigated areas) and low value to sparse or dormant vegetation.

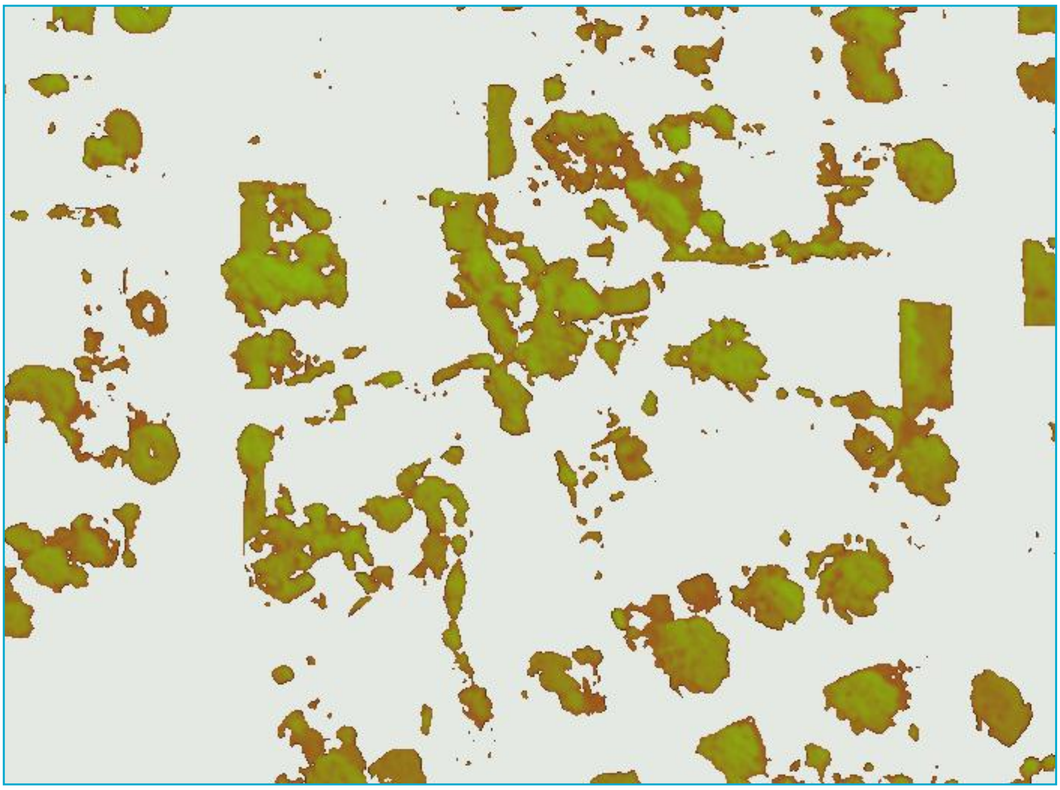


Figure 13: The vegetation index. Green colours have high index, browner colours correspond to low index. White is non-vegetation.

3.8.1 FORMAT

This raster data set is stored as IEEE 4byte reals (floating points). The data ranges from -1 to +1. Pixels not in the vegetation class (from the vegetation/non-vegetation classification) are NULL. File names contain the abbreviation *vin*.

3.8.2 LIMITATIONS

The vegetation index contains a lot of variation, and often contains obvious changes between flight line boundaries due to calibration differences. The index in moisture-rich areas can be lower than it should be due to water absorbing near-infrared radiation.

3.9 No data mask

This product is useful for displaying the location of missing pixels for all the other products except the DSM and GEM. The values represent:

0=no missing data,
1=height data missing (either dsm, gem or both),
2=missing spectral data and
3=missing both spectral and height data

To find missing data for the vegetation mask and vegetation index products, a union of class 2 and class 3 was used. Missing data in the relative elevation model would be the union of class 1 and class 3. The vegetation heights, grass mask, and tree mask rely on both the relative elevation model and the vegetation classification so the appropriate missing data mask would be the union of classes 1, 2 and 3.

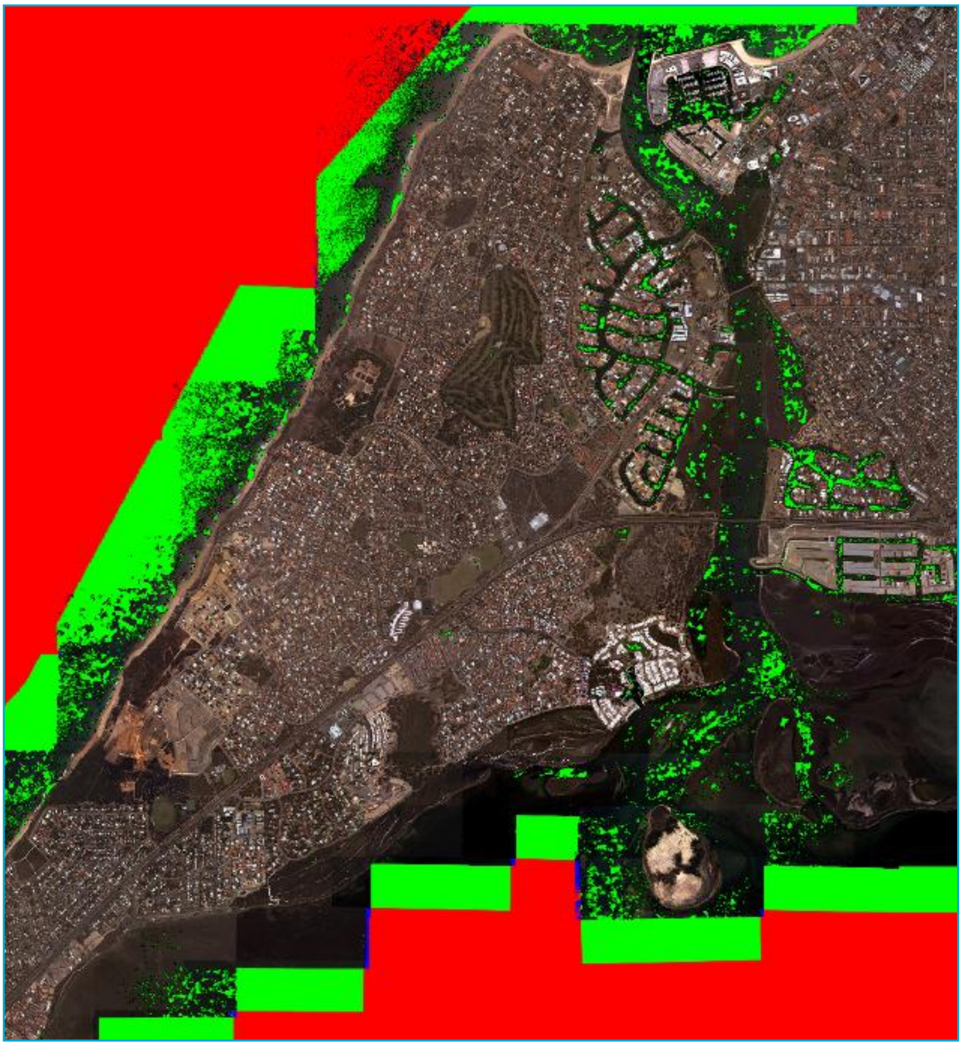


Figure 14: A no data mask, with a true colour image behind. Blue = missing multispectral data only; green = missing height data only; red = missing both multispectral and height information.

3.9.1 FORMAT

This raster data is stored as unsigned 8bit integers.

0 (also the NULL value) corresponds to pixels that have both spectral and height data

1 corresponds to pixels that have height data (in the ndsm, gem and dsm) but no spectral data
2 corresponds to pixels that have spectral data but no height data.
3 corresponds to pixels have neither height data, nor spectral data.

File names contain the abbreviation *msk_nod*

3.10 Grass and low bush mask

This is a mask of all the vegetation below 0.5m in height and it is best viewed as a bright green layer.

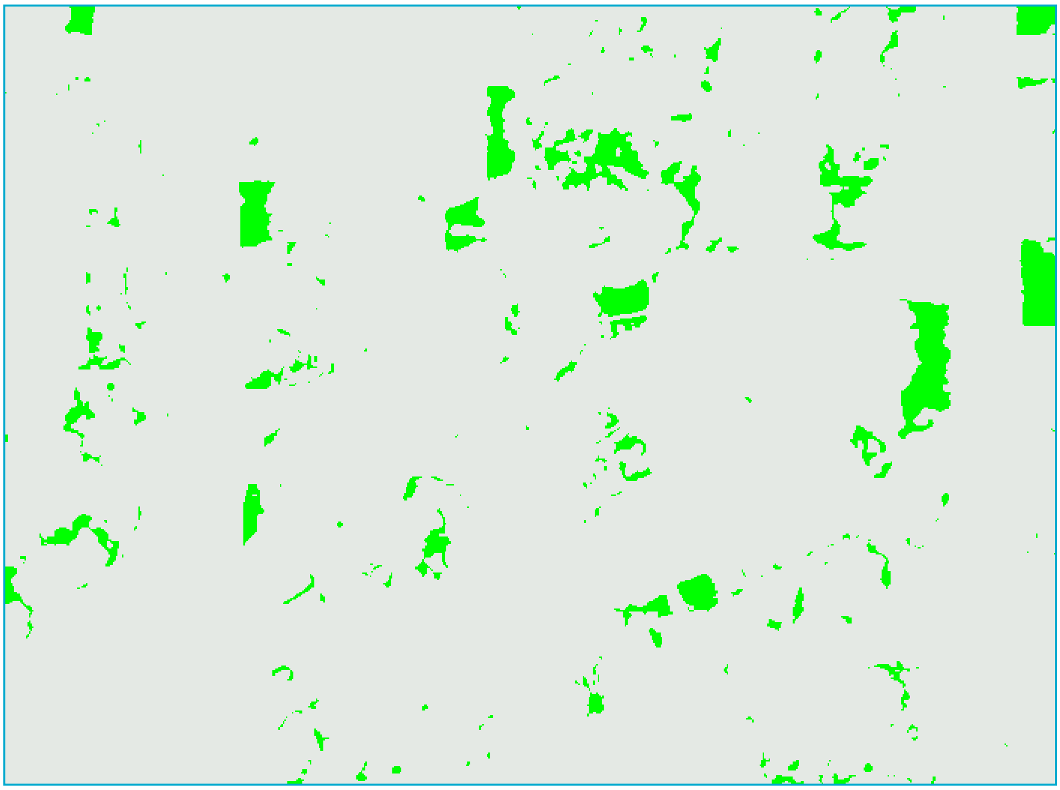


Figure 15: The grass and low bush mask (green = grass, grey = everything else)

3.10.1 FORMAT

This raster data is stored as unsigned 8bit integers. Pixels determined to be vegetation close to the ground have been assigned a value of 1. All other pixels, including missing data are assigned a value of 0 which corresponds to the NULL value of the dataset. File names contain the abbreviation *grs*.

3.10.2 LIMITATIONS

The grass and low bush mask is restricted by the limitations of the vegetation height data. For example sparse-crowned trees can appear as grass. As with the vegetation mask dry heath and brown grass are not included.

3.11 Tree mask

The tree mask is a mask of all the vegetation greater than 0.5m in height and it is best viewed as a bright green layer.

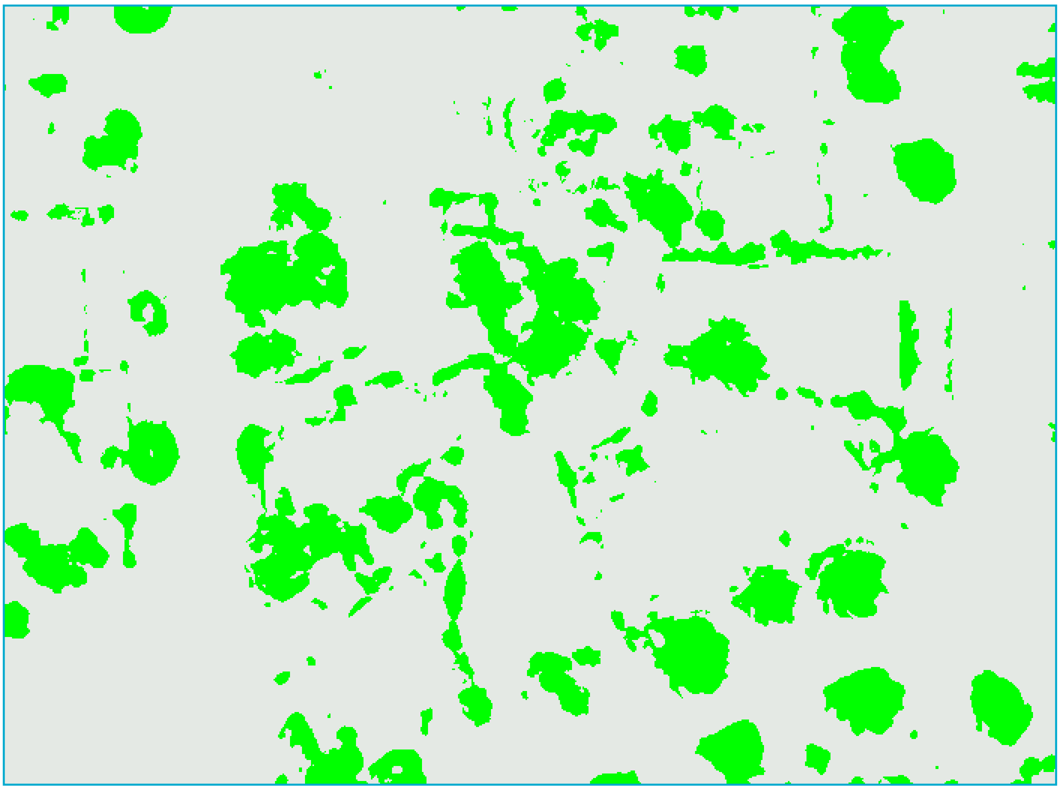


Figure 16: The tree mask (green = tree, grey = everything else)

3.11.1 FORMAT

This raster data is stored as unsigned 8bit integers. Pixels determined to be vegetation above the ground have been assigned a value of 1. All other pixels, including missing data are assigned a value of 0 which corresponds to the NULL value of the dataset. File names contain the abbreviation *tre*.

3.11.2 LIMITATIONS

The tree mask is restricted by the limitations of the vegetation height data. For example sparse-crowned trees will not appear in the tree mask.

3.12 Error unfixed lists and vector files

3.12.1 FORMAT

These vectors are saved as ASCII text files with the format given by ERMapper. Each vector starts with a newline, and some characters denoting the type of vector (e.g. “box”, or “polygon”). It is followed by a name or description of the vector and then a list of points denoting the actual shape.

The name/description of the vectors in these files first refers to an error type and may contain further information such as a unique number, a location description, or a comment about the error.

File names contain the abbreviation *eru*.

3.13 Error fixed lists and vector files

These vectors are saved as ASCII text files with the format given by ERMapper. Each vector starts with a newline, and some characters denoting the type of vector (e.g. “box”, or “polygon”). It is followed by a name or description of the vector and then a list of points denoting the actual shape.

The name/description of the vectors in these files first refers to an error type and may contain further information such as a unique number, a location description, or a comment about the error.

File names contain the abbreviation *erf*.

4 METADATA AND NAMING CONVENTIONS

This section describes how the Urban Monitor area is divided into 73 tiles and the file naming convention used for the products and tiles. The format and the location of the files are also included.

4.1 Extent and Map Sheets of the Perth Urban Monitor Area

The Urban Monitor extents and map tile extents are shown in Figure 17. The Urban Monitor area was divided into 73 tiles with the extent of each tile based on the extent of the 1:25,000 cartographic maps. The map tile coordinates are justified to allow certain overlaps with adjacent map tiles and / or to extend to cover important features such as the coast. The map coordinate system is based on GDA94 (datum) and MGA50 (projection). Except for the Rottnest Island map tile, all the map tile names are based on the national standard map identifications and names. The coordinates for each map tile and map tile names are listed in Table 2.

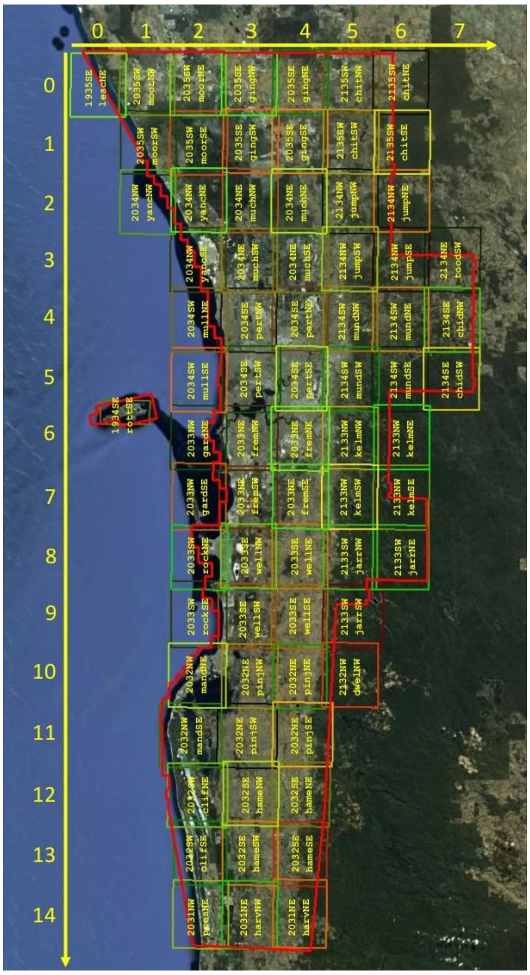


Figure 17 The Urban Monitor Perth region (in red) and the extent of the 73 map tiles (assigned random colours).

Table 2 Urban Monitor (Perth) map tile extents (names, sizes and coordinates)

Tile Grid (row,col)	Map ID	Width (Eastings)	Height (Northings)	Top-Left Easting	Top-Left Northing	Bottom-Right Easting	Bottom-Right Northing

0,0	1935SE_lescNE	13000	15000	345000	6542000	358000	6527000
0,1	2035SW_moorNW	13000	15000	356500	6542500	369500	6527500
0,2	2035SW_moorNE	13000	15000	368500	6542500	381500	6527500
0,3	2035SE_gingNW	13000	15000	380500	6542500	393500	6527500
0,4	2035SE_gingNE	13000	15000	392500	6543000	405500	6528000
0,5	2135SW_chitNW	13000	15000	404500	6543000	417500	6528000
0,6	2135SW_chitNE	13000	15000	416000	6543000	429000	6528000
1,1	2035SW_moorSW	13000	15000	357000	6528500	370000	6513500
1,2	2035SW_moorSE	13500	15000	368500	6528500	382000	6513500
1,3	2035SE_gingSW	13000	15000	381000	6529000	394000	6514000
1,4	2035SE_gingSE	13000	15000	392500	6529000	405500	6514000
1,5	2135SW_chitSW	13000	15000	404500	6529000	417500	6514000
1,6	2135SW_chitSE	13000	15000	416500	6529000	429500	6514000
2,1	2034NW_yancNW	13000	15000	357000	6514500	370000	6499500
2,2	2034NW_yancNE	13000	15000	369000	6515000	382000	6500000
2,3	2034NE_muchNW	13000	15000	381000	6515000	394000	6500000
2,4	2034NE_muchNE	13000	15000	392500	6515000	405500	6500000
2,5	2134NW_jumpNW	13000	15000	404500	6515000	417500	6500000
2,6	2134NW_jumpNE	13000	14500	416500	6515000	429500	6500500
3,2	2034NW_yancSE	13000	15000	369000	6501000	382000	6486000
3,3	2034NE_muchSW	13000	15000	381000	6501000	394000	6486000
3,4	2034NE_muchSE	13000	15000	393000	6501000	406000	6486000
3,5	2134NW_jumpSW	13000	15000	404500	6501500	417500	6486500
3,6	2134NW_jumpSE	13000	15000	416500	6501500	429500	6486500
3,7	2134NE_toodSW	13000	15000	428500	6501500	441500	6486500
4,2	2034SW_mullNE	13000	15000	369500	6487000	382500	6472000
4,3	2034SE_pertNW	13000	15000	381000	6487000	394000	6472000
4,4	2034SE_pertNE	13000	15000	393000	6487500	406000	6472500
4,5	2134SW_mundNW	12500	15000	405000	6487500	417500	6472500
4,6	2134SW_mundNE	13000	15000	416500	6487500	429500	6472500
4,7	2134SE_chidNW	13000	15000	428500	6487500	441500	6472500
5,2	2034SW_mullSE	13000	15000	369500	6473000	382500	6458000
5,3	2034SE_pertSW	13500	15500	381500	6473500	395000	6458000
5,4	2034SE_pertSE	12000	15000	394000	6473500	406000	6458500
5,5	2134SW_mundSW	13000	15000	405000	6473500	418000	6458500
5,6	2134SW_mundSE	13000	15000	416500	6473500	429500	6458500
5,7	2134SE_chidSW	13000	14500	428500	6473500	441500	6459000
6,2	2033NW_gardNE	13000	15000	369500	6459500	382500	6444500
6,3	2033NE_fremNW	13000	15000	381500	6459500	394500	6444500
6,4	2033NE_fremNE	13500	15000	393000	6459500	406500	6444500
6,5	2133NW_kelmNW	13000	14500	405000	6459500	418000	6445000
6,6	2133NW_kelmNE	13000	15000	417000	6460000	430000	6445000
7,2	2033NW_gardSE	12500	15500	370000	6446000	382500	6430500
7,3	2033NE_fremSW	13500	14500	381000	6445500	394500	6431000
7,4	2033NE_fremSE	13000	15000	393500	6446000	406500	6431000
7,5	2133NW_kelmSW	13000	15000	405000	6446000	418000	6431000

7,6	2133NW_kelmSE	13000	15000	417000	6446000	430000	6431000
8,2	2033SW_rockNE	13000	15000	370000	6431500	383000	6416500
8,3	2033SE_wellNW	13000	15000	381500	6432000	394500	6417000
8,4	2033SE_wellNE	13000	15000	393500	6432000	406500	6417000
8,5	2133SW_jarrNW	12500	15000	405500	6432000	418000	6417000
8,6	2133SW_jarrNE	13000	15000	417000	6432000	430000	6417000
9,2	2033SW_rockSE	13000	15500	370000	6418500	383000	6403000
9,3	2033SE_wellSW	13500	15000	381000	6418000	394500	6403000
9,4	2033SE_wellSE	13000	15000	393500	6418000	406500	6403000
9,5	2133SW_jarrSW	14000	15000	405500	6418000	419500	6403000
10,2	2032NW_mandNE	13500	15000	369500	6404000	383000	6389000
10,3	2032NE_pinjNW	13000	15000	382000	6404000	395000	6389000
10,4	2032NE_pinjNE	12500	15000	394000	6404000	406500	6389000
10,5	2132NW_dwelNW	13000	15000	405500	6404500	418500	6389500
11,2	2032NW_mandSE	14500	15000	367500	6390000	382000	6375000
11,3	2032NE_pinjSW	14000	15000	381000	6390000	395000	6375000
11,4	2032NE_pinjSE	14000	15000	394000	6390500	408000	6375500
12,2	2032SW_clifNE	14000	15000	369500	6376000	383500	6361000
12,3	2032SE_hameNW	13000	15000	382500	6376500	395500	6361500
12,4	2032SE_hameNE	13500	15000	394000	6376500	407500	6361500
13,2	2032SW_clifSE	12500	15000	371000	6362500	383500	6347500
13,3	2032SE_hameSW	13000	15000	382500	6362500	395500	6347500
13,4	2032SE_hameSE	12500	15000	394500	6362500	407000	6347500
14,2	2031NW_presNE	13000	16000	371000	6348500	384000	6332500
14,3	2031NE_harvNW	13000	16000	382500	6348500	395500	6332500
14,4	2031NE_harvNE	12500	16000	394500	6349000	407000	6333000
Rottnest	1934SE_rottSE	11500	5500	353000	6460500	364500	6455000

4.2 File naming conventions

The raster products are formed and stored in band-interleaved-by-line format (BIL), and each BIL file is accompanied by an ERMapper raster header file (with extension .ers). The vector products are formed and stored in a text file in ERMapper format, each accompanied by an ERMapper vector header (with extension .erv). The following basic naming convention applies for the Urban Monitor products (letters are case insensitive):

year_mon_UM_snrID_mapsID_nameID_ geoid_mproj_xxx_yyy_client_timeTag_state

where:

- year: 4 digits for the year the majority of the images were captured
- mon: 3 letters for the month the majority of the images were captured
- UM: 2 letters to identify the products derived using the CSIRO Urban Monitor technology
- snrID: data capturing sensor ID. 3 letters followed by 2 digits, e.g. ucd00, ads40, ads80 etc.
- mapsID: 4 digits of the 1:100,000 map ID followed by two letters of quadrant ID, e.g. 2033NE
- nameID: 4 letters of the 1:50,000 map name followed by two letters of quadrant ID, e.g. fremNW

- geoid: 5 letters to specify the geodetic datum e.g. gda94
- mproj: 5 letters to specify the map projection e.g. mga50
- xxx: 3 letters to name the nature of the product, e.g. dsm, msp, dem, gem, nsm, msk etc.
- yyy: 3 letters to specify special processing applied e.g. non-edited (raw), radiometric calibration (cal), terrain illumination correction (ter) etc.
- client: 5 letters used to indicate the client/custom of this product
- timeTag: 10 digits to stamp the date/hour the file was produced with format YYYYMMDDHH, e.g. 2012053110
- state: 5 letters to specify the production state/version e.g. ver01, final etc.

Current xxx options in use are:

- dsm: **d**igital **s**urface **m**odel. 32bit signed integer, units are in millimetres
- dom: multispectral **d**igital **o**rthorectified **m**osaic. 16bit unsigned integer
- gem: **g**round **e**levation **m**odel. 32bit signed integer, units are in millimetre
- nsm: relative elevation model, also known as the **n**ormalised digital **s**urface **m**odel. 32bit signed integer, units are in millimetre
- msk: **mask** layer. 8bit unsigned integer. The type of mask is specified in yyy or its corresponding .hst file. Currently the only data set using this name is the no data product which has yyy=nod.
- eru: will be an ERMapper vector file containing ***u***nfixed ***er***rors. (date stamp not necessarily reflective of the last change)
- erf: an ERMapper vector file containing **f**ixed **er**rors
- veg: a **veg**etation/non-vegetation classification. 8bit unsigned integer, with vegetation a value of 1
- vht: **h**eigh**t**s of **v**egetation, 32bit signed integer, units are in millimetres
- vin: **v**egetation **in**dex. The ndvi of vegetation pixels. In floating point data type (IEEE 4byte real)
- grs: ground height vegetation (**gr**a**s**s). 8bit unsigned integer, 1=vegetation close to the ground
- tre: vegetation above the ground (ie. **tre**es). 8bit unsigned integer, 1=vegetation above the ground

Current yyy options in use are:

- raw: non-edited data
- cal: radiometric **cal**ibration
- ter: **ter**rain illumination correction
- non: not applicable (for some types of products)
- nod: for **no d**ata mask

edt: for data that has manually **edit**ed. This doesn't extend to products derived from edited versions. For example a manually fixed gem would have a *gem_edt* file name, whilst the ndsm generated using this gem would have a *nsm_raw* file name because ndsm itself hasn't been manually corrected.

4.3 Format of Products

The raster products are formed and stored in band-interleaved-by-line format (BIL), and each BIL file is accompanied by an ERMapper raster header file (with extension .ers). The ground sampling distance (GSD) of all the raster products is 0.2m. The vector products are formed and stored in a text file in ERMapper format, each accompanied by an ERMapper vector header (with extension .erv).

4.4 Location of Data

The data is stored in directories first according to year and then according to tile name (mapsID_nameID). For delivery, the data has been spread across multiple drives.

In addition to the quantitative data, “quick look” versions of the data (see Section 4.5) have also been included on a drive in directories named UM_07QuickViews and UM_09QuickViews representing 2007 and 2009 data repectively.

4.5 Compressed images for quick viewing

All products have quick viewing versions saved in compressed jpeg2000 format. The vegetation mask, grass mask and tree mask are saved as single band images (0 corresponds to vegetation, grass or trees in each of the images) with a NULL mask. All other compressed images are in stored as RGB images with a NULL mask.

All of the 2007 and most of the 2009 compressed images are stored on the NAS drive. The remainder of the 2009 compressed images are stored on one of the other commodity hard drives.

4.6 Lists of known errors, and fixed errors

For each tile, for each year, there is a list of known errors saved in ERMapper vector format (the files use abbreviations *eru_non* - see the naming conventions for more information). In this format the vectors are in an easily human readable ASCII text file (with no extension) and have an associated ERMapper header (.erv extension). Each vector has been named with a specific code denoting the type of error; often it also includes unique numbers, or location descriptions or further information about the error. The codes and the error types are described in

Table , Table and Table .

The errors are also easily viewable by opening the vector file in ERMapper.

When fixes have occurred on an overlap it may not be in the error fixed vector file (erf) of all the involved tiles.

When an error fixed file doesn’t exist it means either the only fixes occurred in overlaps with neighbouring tiles, or no fixes have occurred. Similarly no unfixed error file (eru), or an empty error file means no errors were noted.

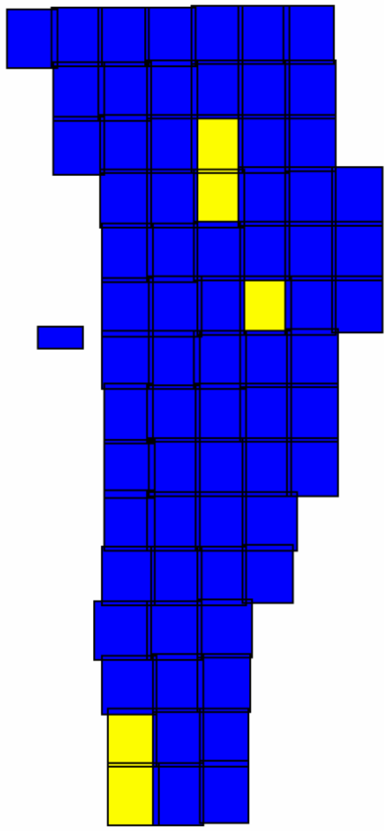


Figure 18: 2007 DSM Processing

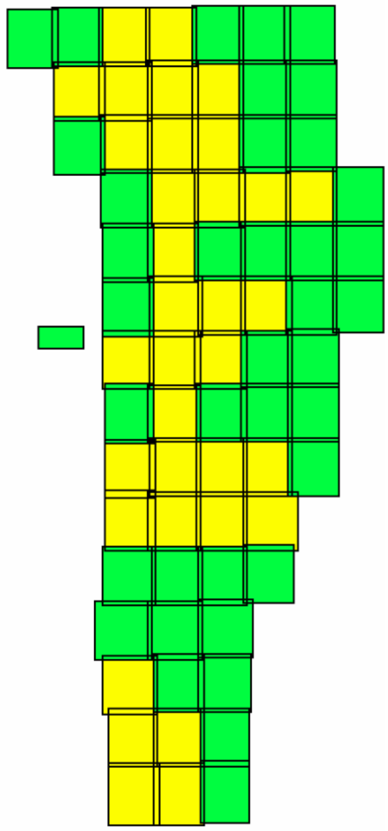


Figure 19: 2007 GEM Processing

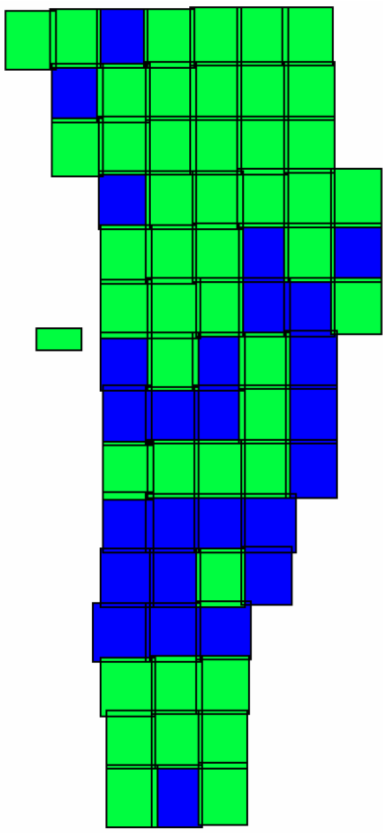


Figure 20: 2007 rem Processing

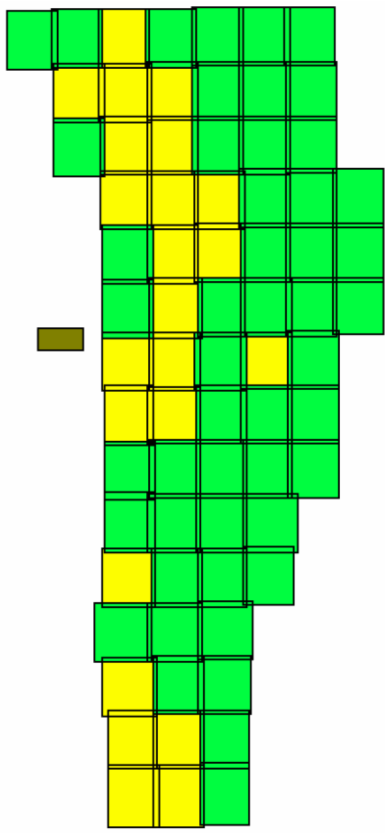


Figure 21: 2007 Vegetation Processing

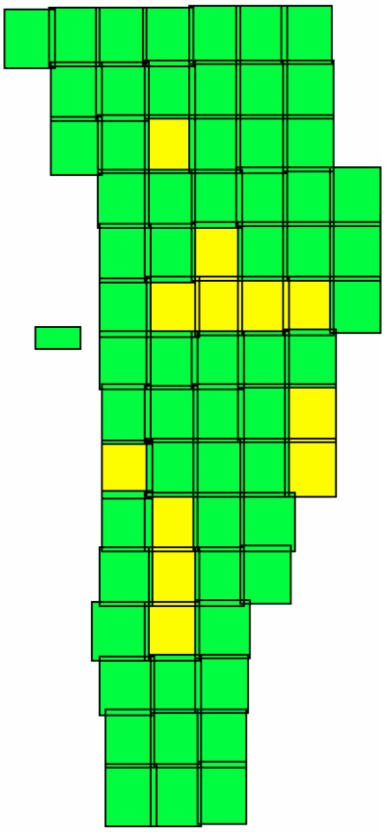


Figure 22: 2009 DSM Processing

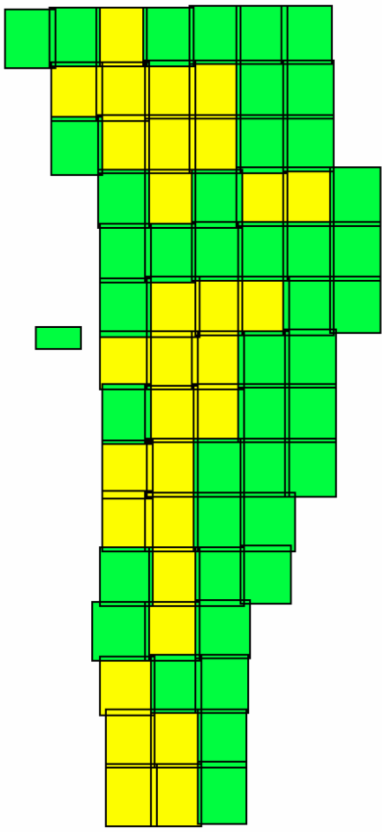


Figure 23: 2009 GEM Processing

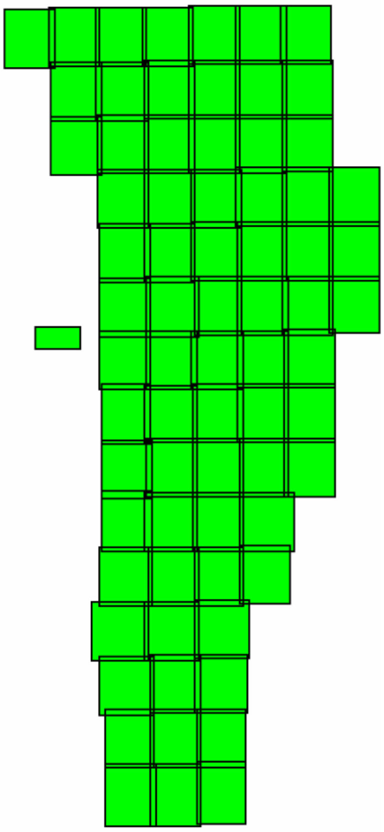


Figure 24: 2009 rem Processing

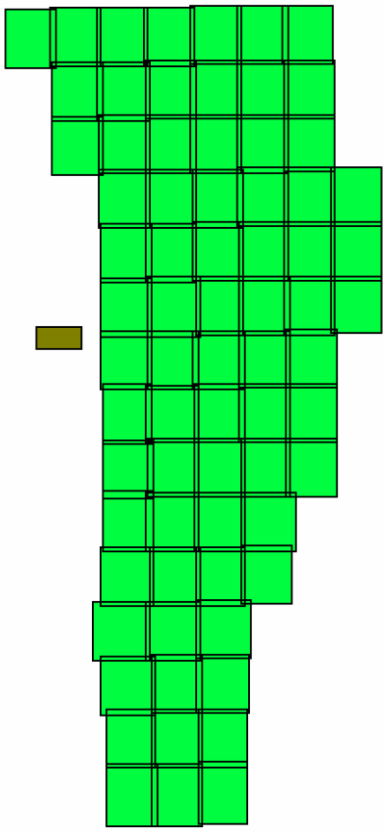


Figure 25: 2009 Vegetation Processing

Table 3: Error codes for height data with descriptions

Error Code	Description of Error	Cause of Error
rfInGEM	A roof that is in the GEM	The roof has multiple levels, or its edges are close to the ground
indRfsGEM	A large cluster of roofs in the GEM, in an industrial/commercial area	Industrial/commercial roofs tends to be more complicated with various levels, faces (such as saw-toothed shaped) and with air conditioners and other things on the roof. Thus an industrial/commercial area is likely to have many roofs in the GEM
stitchGEM	The GEM has creases in it not associated with any real features	The GEM was created on many small tiles and then stitched together. If a tile edge coincides with a large area of obscured ground then a small crease may be visible in the surface.
spikeDSM	A tall spike in the DSM. This is quite similar to the cloudDSM error	Two possible causes: (1) A moving object has confused the pixel matching or (2) the area is homogenous which sometimes confuses the pixel matching.
triangErr	Appears as erroneous North-to-South, or East-to-West terraces in the DSM and GEM, of length greater than 500m	The triangulation of a frame (calculation of the camera direction and location) must have been incorrect. This has caused pixels using this frame to be at a different height to neighbouring frames.
cloudDSM	Clumps/small regions of extreme height values, even over areas with lots of texture	Cloud in the raw data has caused difficulty in matching pixels for the DSM. Note the cloud itself may not be visible in the final digital orthomosaic.
peaksMissedGmkGEM	The GEM completely misses medium-large hills that have clearly visible ground.	The hill has been excluded from the set of candidate ground points.
belGrdGEM	An erroneous drop in the GEM	Caused by a few erroneously low pixels in the DSM. If the error persists to the GEM then the outlier removal of the GEM process will have expanded the size of the error.
corruptDSM	Appears as lots of East-West striations in the DSM	Caused by an i/o error in the DSM process.
treeDSM	Where there is a tree in the spectral data however the DSM is the same height as the ground.	When the tree's crown is sparse or very small then the ground beneath the tree is visible in the raw images. The pixel matching then matches ground level pixels, rather than the leafy pixels.

Table 4: Error codes for vegetation data with descriptions

Error Code	Description of Error	Cause of Error
frmBndInVeg	Straight North-South or East-West boundaries separating differing amounts of vegetation not corresponding to any true features on the ground. Doesn't include other errors such as cldShadow.	One of the frames involved has had calibration issues.
brVeg	Trees or bushes that are brown and have not been included in the vegetation mask	There are various causes for brown vegetation. This doesn't include brown grass/heath, only brown trees and bushes that are living.
blRfVeg	A blue roof that has been labelled vegetation	Blue surfaces often have an unusually high near-infrared reflectance causing them to appear like vegetation when using just the red and near-infrared bands. Not all blues roofs are included because of the morphological rules in the vegetation classification algorithm.
rfInVeg	Any non-blue roof that has been labelled vegetation	Unusual roof surfaces can have an unexpectedly high near-infrared reflectance causing them to be labelled vegetation.
shInVeg	Dark shadows that have been labelled vegetation	The vegetation classification has a shadow exclusion rule. Dark shadows that are labelled vegetation must have unusual spectral values.
cldShadow	A dark patch in the digital orthomosaic with a fairly distinct boundary, *and* the vegetation mask is poor quality inside.	Ground that has been shadowed by clouds gives unusual spectral values. Sometimes it has resulted in an obvious under commission of vegetation have been noted.
waterInVeg	Water that has been labelled vegetation	Spectral values in water are not reliable, occasionally resulting in water pixels having a relatively high near-infrared value.
cld	A cloud that is visible in the digital orthomosaic	This is caused by the aircraft flying over a cloud whilst collecting data.
forestSpec	Large patches of high density green trees that have skewed the spectral values and caused over commission errors in the vegetation mask.	This issue was only seen in the 2007 data and was an artefact of the calibration method.
dirtVeg	A large area of dirt that has been labelled vegetation	Caused by spectral calibration issues, and is often contained in only one frame.
wetlandVeg	Dark green wetland vegetation that hasn't been marked as vegetation.	This is caused by the high moisture content absorbing the near-infrared radiation.
blSynthVeg	Synthetic blue surfaces that are labelled vegetation (not including blue roofs)	For the same reason as blue roof errors: Blue surfaces often have an unusually high near-infrared reflectance causing them to appear like vegetation when using just the red and near-infrared bands.
grSynthVeg	Synthetic green surfaces that	Similar to blSynthVeg. Synthetic green surfaces

	are labelled vegetation	often have an unusually high near-infrared reflectance.
noiseVeg	Noise in the spectral data has caused erroneous vegetation labelling.	Occasional random noise in the raw photography causes erroneous spectral values in the orthomosaick
terrainIlluminationVeg	Steep slopes where the accuracy of the vegetation mask is poorer than normal	Steep terrain can cause inaccuracies in the spectral calibration due to assumptions about illumination, causing the vegetation mask to be incorrect.
isVeg	Green growing vegetation that hasn't been included in the vegetation mask, and can't be attributed to one of the errors above.	

Table 5: Other error codes with descriptions

Error Code	Description of Error	Cause of Error
specErr	Spectral values that are wildly incorrect and/or corrupted	There are many potential causes.

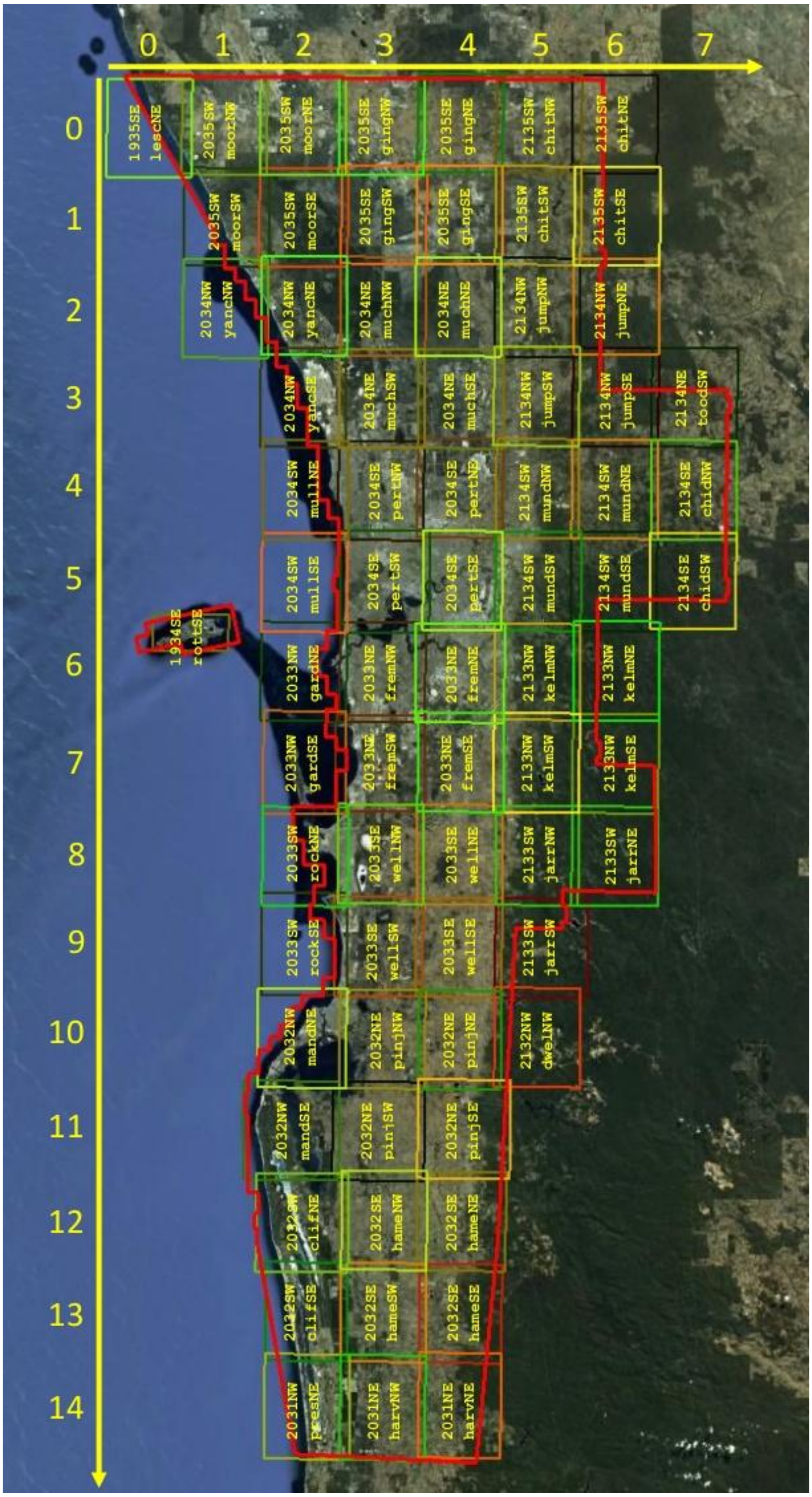
5 Future considerations for monitoring

In this report we have described the generation of spatial information products derived from data and methodology drawn from the Urban Monitor project. This project resulted from collaboration between various Western Australian state government and other agencies involved in natural resource management and CSIRO. It includes scientists and agencies with responsibility for land, water and vegetation management, image processing scientists with experience in environmental monitoring systems, and the agency responsible for state photographic programs. Under this collaboration, standards, processing and products are being developed to maximise uses for environmental monitoring and resource management and planning.

As described in this report, spatial information products derived from 2007 and 2009 were generated. The dates were chosen as prior processing had been performed on these data and the tight timing requirements for the production of the results presented here. Digital aerial photographs after 2009 were acquired as part of the annual capture program by Landgate and have different license conditions.

As a result of this project, new information about the urban environment is being distributed to agencies at a scale that has not been available before. We envisage that, when used in conjunction with other datasets and ground truth information, many questions beyond what may be addressed in this report will emerge. Ideally monitoring will be a routine, on-going activity providing information updated with the view to continuously improving the processes and adapting the process to have the ability to respond to new questions.

Appendix A Enlarged Map of Sheet Extents



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