Assessment of Spatial Analysis Techniques for Estimating Impervious Cover

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Abstract: Impervious cover proportion is recognised as an important parameter in hydrologic modelling. Recent advances in the spatial sciences provide new capabilities for estimation of this value. This paper describes an assessment of seven estimation techniques, including human and computer based methods requiring a range of different input data and skill levels. In order to quantify the value of any gain in accuracy, the results from each method were applied to a real catchment using event based (WBNM) and continuous simulation (MUSIC) hydrologic models. The results showed that use of high resolution satellite imagery enabled the most accurate measurements of impervious cover proportion to be made, however in general human and computer based methods are comparable in terms of accuracy. Also it was found that in some circumstances the sensitivity of peak discharge and runoff volume estimates to error in impervious cover proportion can be very high, confirming the need for accurate measurement.

Keywords: Hydrology, Impervious Surfaces, Image Classification, Spatial Analysis

1. INTRODUCTION

Estimation of impervious cover proportion within a catchment is fundamental to hydrologic prediction. Despite being a physically measurable characteristic of a catchment, impervious cover estimates are often based on a desktop assessment. This is because direct field measurement is generally time consuming and impractical. Whilst this approach may be acceptable in some circumstances, these same estimates are often applied less appropriately.

Over recent years an increase in computing power and data availability has occurred in addition to the rapid advancement of spatial technologies, e.g. Geographic Information Systems (GIS) and remote sensing, providing new tools for assessment of impervious cover. Currently the skills necessary to apply these spatial tools are outside the core skill set of many engineers, presenting an opportunity to explore the use of such technologies for impervious cover estimation.

This paper outlines several of the most relevant spatial methodologies available for impervious cover estimation and evaluates the performance of each method from an engineering perspective. Impervious cover is estimated for a real catchment to construct an event based and a continuous simulation hydrologic model. Sensitivity using varying rainfall and soil infiltration is reported. This hydrologic modelling component of the research allows the hydrologic value of new technologies to be critically assessed.

2. TEST CATCHMENT

The test catchment selected is Horsley Creek, located near the City of Shellharbour, NSW, Australia. The catchment is 925 hectares in area and comprises six main arms all draining in a radial fashion north towards Lake Illawarra. The catchment is ideally suited to this study having a broad range of component land uses as well as a wealth of available mapping data.

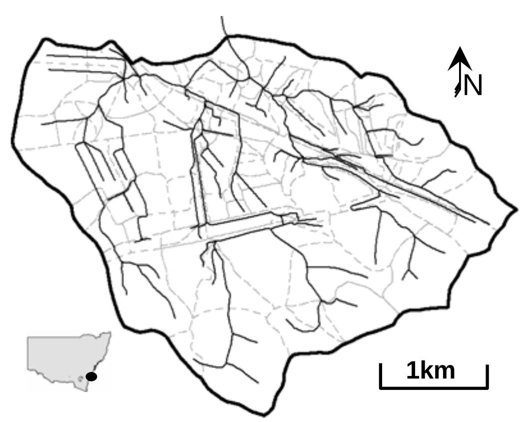

Figure 1: Horsley Creek Catchment Plan

Approximately half the catchment can be classified as urban, which includes low and medium density residential, industrial, commercial and open space land uses as well as large regional transport corridors. The southern and western half of the catchment includes a mixture of dense and sparse forest types, open grassland and large hard rock quarries.

For the purpose of hydrologic modelling, the catchment has been split into 145 component subareas of various sizes as dictated by drainage patterns and hydrologic modelling needs. These subareas and the estimation of their impervious cover are the focus of the methods described in Section 3.

3. IMPERVIOUS COVER ESTIMATION

Seven methods were selected for estimation of impervious surfaces. The methods were chosen to ensure a broad coverage of available technologies and input data requirements, including some of those currently employed by engineers for hydrologic analysis. Inclusion of these current methods facilitates a comparison of their performance against the more leading edge spatial technologies.

3.1 Method 1 – Manual Digitization

Method 1 utilised on-screen digitization of all impervious surfaces within the catchment using high spatial resolution (0.2m pixel) ortho-rectified aerial photography within a MAPINFO GIS environment.

Whilst Method 1 is conceptually simple, highly accurate and often used in practice for very small catchments (generally lot scale), it is considered impractical for large catchments due to excessive and tedious input requirements. However for this research it was necessary as a ground reference against which the other methods could be compared as it renders the most accurate depiction of impervious cover.

3.2 Method 2 – Human Visual Estimation

The method involved visual estimation by nine ‘spatially aware’ practitioners (GIS Analysts and Engineers) of the proportion of different landuse within each subarea (e.g. residential, open-space, industrial) from high resolution aerial photography. Samples of these landuse types were then accurately measured to calculate their typical impervious cover proportion. For each subarea the component land use proportions (estimated by each respondent) were multiplied by their respective typical impervious cover proportions to derive an estimate of the impervious cover proportion of the overall subarea.

To reflect the reality that some individuals may consistently make poor estimates, the average of the nine responses was used, along with one standard deviation below and above this average. For ease of presentation these have been subsequently referred to in this paper as Methods 2A, 2B and 2C respectively.

3.3 Method 3 – Landuse Zoning Based

Method 3 involved the use of Local Government landuse zoning information to derive the proportion of each landuse within each subarea. As per Method 2, samples of these landuse types were then accurately measured using the Method 1 ground reference dataset. For each subarea the component land uses were multiplied by their respective typical impervious cover proportions to derive an estimate of the impervious cover proportion of the overall subarea.

3.4 Method 4 – Medium Spatial Resolution Satellite Imagery

Method 4 involved a sub-pixel analysis of a multi-spectral Landsat 7 ETM (Enhanced Thematic Mapper) satellite image of the catchment. The satellite image was first pan-sharpened from 30m pixel size down to 12.5m pixel size using Landsat 7 ETM panchromatic band data. A maximum likelihood image classification was then carried out using the remote sensing software package ENVI v4.2 developed by Research Systems Incorporated. This classification process categorised each pixel as either urban (building, road, paved etc) or non-urban (grassland or forest).

The relatively coarse spatial resolution of Landsat imagery, produces pixels that contain several surface cover types e.g. “mixed pixels”, creating the need to estimate the proportion of cover types within each pixel. The mixture of impervious and pervious surfaces within each mixed pixel was calculated using a Tasselled Cap Analysis (TCA) applied to the pan-sharpened Landsat multi-spectral image to derive a relationship between TCA “greenness” (a standard TCA output) and imperviousness. This methodology is similar to that described by Bauer [2002]. Using the derived relationship, all urban pixels identified using the maximum likelihood classifier were then assigned a proportion of impervious cover. These were then summed to calculate the impervious cover proportion of each subarea.

3.5 Method 5 – High Resolution Aerial Photography

Method 5 utilised pattern recognition capabilities of the Feature Analyst software package (ArcGIS extension produced by Visual Learning Systems) to extract impervious features. Operating on high resolution (0.2m pixel) ortho-rectified aerial photography of the catchment, Feature Analyst's machine learning algorithms were used to recognise patterns and texture (e.g. road and roof patterns), thus improving the classification process.

3.6 Method 6 – LIDAR

Method 6 involved a decision tree classification of two LIDAR (also known as Air-borne Laser Scanning) derived datasets:

1) A 1m cell size Digital Elevation Model (DEM) of the height of objects above their local ground level.
2) LIDAR Intensity Images (1m pixel size), these being a grey-scale image showing the intensity of laser pulse returns.

A grid query was carried out using Vertical Mapper v3.0, an extension of the MAPINFO suite of GIS software. Vertical Mapper was used to categorise each 1m cell according to its height and intensity values. This classified grid was then used to calculate the impervious cover proportion of each subarea using standard grid query techniques within Vertical Mapper.

3.7 Method 7 – High Spatial Resolution Satellite Imagery

A high spatial resolution multi-spectral Quickbird satellite image (2.4m pixel) was used to calculate a Normalised Difference Vegetation Index (NDVI), attempting to classify the image into vegetated (pervious), non-vegetated (impervious) and mixed (combination of pervious and impervious) surfaces. Mixed pixels were assigned a 50% impervious proportion. A GIS query within a MAPINFO GIS environment was then used to calculate the impervious cover proportion of each subarea.

4. HYDROLOGIC MODELLING

4.1 Event Based

The results of the seven impervious cover estimation techniques described in Section 3 were applied to the catchment using the event based hydrologic model WBNM, developed by Boyd, Rigby and Van Drie [2005]. The model constructed is highly detailed reflecting the full complexity of the catchment including 145 subareas, basins, diversions and explicit modelling of non-natural storage.

To test for rainfall sensitivity, three different Average Recurrence Interval (ARI) events were considered; 5yr, 100yr and Probable Maximum Flood (PMF), each associated storm being of 120 minutes in duration which is the calculated critical duration of the catchment at its outlet.

Three different rainfall loss scenarios were also considered for each method; low, medium and high, with loss parameters as tabulated below. It is noted that these loss scenarios are not necessarily representative of the test catchment, but have been chosen to provide results for a range of catchment conditions so that the results obtained are of wider relevance.

Table 1: Event Based Model Loss Scenarios

Loss Scenario	Initial Loss (mm)	Continuing Loss (mm/hr)
Low	*0*	*2.5*
Medium	*15*	*2.5*
High	*35*	*4.0*

For each, impervious estimation method, storm and loss scenario combination, estimated in-stream peak discharges at the downstream boundaries of all subareas were collated, along with the associated cumulative impervious cover proportion used as input to the model. This enabled an assessment of the effect of differences in impervious cover estimates on peak discharge as described in Section 5.

4.2 Continuous Simulation

Results from each method were also applied to the catchment using the continuous simulation hydrologic module of the water quality model MUSICv3.0 developed by the CRC for Catchment Hydrology [2005]. The model utilised a simplified subareal layout comprising 27 subareas each of which was an accumulation of several of the 145 subareas used for the event based hydrologic model. The model comprised source nodes and drainage links only, with no routing, treatment nodes, diversions and only a single outlet. To test for rainfall sensitivity, three characteristically different rainfall decades were applied to each method.

Table 2: Continuous Simulation - Modelled Rainfall Decades

Rainfall Condition	10 Year Period	Total Rainfall (mm)
Dry	*1935 to 1944*	*8,054*
Average	*1909 to 1918*	*11,082*
Wet	*1950 to 1959*	*14,813*

These decades were selected based on an analysis of approximately 100 years of daily rainfall data collected at a nearby gauge. It is noted that the study area is in a high rainfall zone and that even the dry decade modelled may be relatively wet compared to other regions. The implications of this observation need to be considered when extrapolating study results outside the immediate area.

Three different rainfall loss scenarios were also applied for each method. This was carried out by application of three pairs of soil Moisture Store Capacity and Field Capacity values, selected from Appendix A.5 of the MUSIC v3.0 software user guide, CRC for Catchment Hydrology [2005]. The selected pairs represent soil types with low, medium and high moisture store capacities (i.e. losses). All other model parameters were based on default values.

Table 3: Continuous Simulation Loss Scenarios

Loss Scenario	Moisture Store Capacity (mm)	Field Cap' (mm)	Example City (as per MUSIC v3.0 manual)
Low	*30*	*20*	*Melbourne*
Medium	*120*	*80*	*Brisbane*
High	*250*	*230*	*Perth*

For each impervious estimation method, rainfall decade and loss scenario combination, total runoff volume from the catchment outlet was calculated, along with the associated cumulative impervious cover proportion. This enabled an assessment of the effect of differences in impervious cover estimates on runoff volume as described in Section 5.

5. RESULTS AND DISCUSSION

5.1 Comparison of Impervious Surface Cover Estimates

Table 4 provides a summary of the impervious surface cover estimates obtained using the 7 methods applied to the test catchment. The grey shaded cells in the left hand column show the average impervious surface cover percentage calculated using Method 1, weighted by the area of each subarea. The remaining columns to the right present average and standard deviation differences in impervious surface cover percentage for each of the other methods when compared to Method 1 (e.g. if Method 1 gave an average of 28% impervious and Method 2A gave an average of 27% impervious then the difference is -1 percentage points).

If a method gave approximately equal numbers of over and under estimates, then the average differences (**Av**), would be near to zero. Values of **Av** significantly greater than zero indicate that on average the method over-estimated impervious cover relative to Method 1 and vice versa. The standard deviations (**Sd**) of the differences are also provided immediately below the relevant weighted averages. A low value of **Sd** indicates that differences in impervious estimates did not have large scatter.

As well as average and standard deviation values for all subareas, values are provided for a series of landuse categories. A subarea was classified into a particular landuse category when greater than approximately 75% of the subarea was comprised of that landuse.

Table 4: Comparison of Area Weighted Average Impervious Cover Estimates

Imp%	Percentage Point Difference in Imp% when Compared to M1								
M1	M2A	2B	2C	M3	M4	M5	M6	M7	
All Subareas:									
28	-1	-5	3	8	-4	-2	9	-2	**Av**
-	14	14	15	16	15	13	17	10	**Sd**
Dominant Landuse:									
Forest									
7	5	4	7	18	2	1	24	1	**Av**
-	25	25	26	28	27	34	31	27	**Sd**
Grass									
10	6	4	9	20	0	5	12	2	**Av**
-	8	9	10	7	16	6	21	8	**Sd**
Residential									
49	-2	-8	4	0	-2	-7	4	-7	**Av**
-	6	8	5	6	5	4	5	3	**Sd**
Residential Low Density									
27	-1	-8	6	6	-1	2	10	-2	**Av**
-	4	9	7	5	7	5	7	3	**Sd**
Industrial									
65	11	4	17	8	-19	-16	-7	-4	**Av**
-	9	7	11	7	15	9	8	5	**Sd**
Roadway									
66	-19	-23	-15	-21	-9	-6	8	-1	**Av**
-	15	15	15	14	10	7	8	10	**Sd**
Quarry									
37	-26	-27	-25	-12	-15	-11	10	-4	**Av**
-	28	27	29	28	15	17	15	9	**Sd**

The following broad observations can be made with respect to the impervious cover estimates:

- Method 7 provided the best overall accuracy for the test catchment (2% under-estimate with standard deviation of 10 percentage points).
- Method 6 was the least accurate method (9% over-estimate with standard deviation of 17 percentage points).
- All methods performed well within subareas dominated by residential landuse, and poorly within subareas dominated by forest and quarry.
- A typical range of absolute difference (error range) of between 10 and 20 percentage points can be expected for most methods.
- For large subareas (>5ha) best estimates are made using computerised Methods 4, 5, 6 & 7, while for small subareas (<5ha) best estimates are made using human based Methods 2 & 3. This is demonstrated in Table 5 where standard deviation error has been listed for these two size ranges.

Table 5: Std Deviation of Error vs Subarea Size

Sub size	2A	2B	2C	3	4	5	6	7
<5ha	*12*	*13*	*13*	*16*	*16*	*14*	*20*	*12*
>5ha	*16*	*15*	*17*	*16*	*12*	*10*	*10*	*6*

5.2 Comparison of Hydrologic Estimates

5.2.1 Event Based

Figure 2 provides a comparison of error in peak discharge estimates at the downstream boundary of each subarea versus the difference in cumulative impervious cover to the same point. The x-axis gives the difference between the impervious percentage estimated by the various methods and the impervious percentage estimated by Method 1 (e.g. if Method 1 estimated a value of 30% and another method a value of 45%, the difference is 15 percentage points). The results from all 7 methods and all three ARI storms are plotted together to give an overall relationship between hydrologic error and difference in impervious cover estimate. The three loss scenarios (low, medium and high) are presented as three separate graphs. Linear trendline equations are also provided on each graph.

Note that, Figure 2 gives discharges at many points on the catchment each one representing a different accumulation of land use, impervious cover and catchment shape factors. This accounts for the scatter in some data, but nevertheless there is a strong underlying linear relation in all cases.
The linear trendlines demonstrate that as rainfall loss increases from low to high there is increasing potential for discharge error associated with difference in impervious estimates. Also as storm size increases there is a decreasing potential for discharge error associated with difference in impervious estimates.

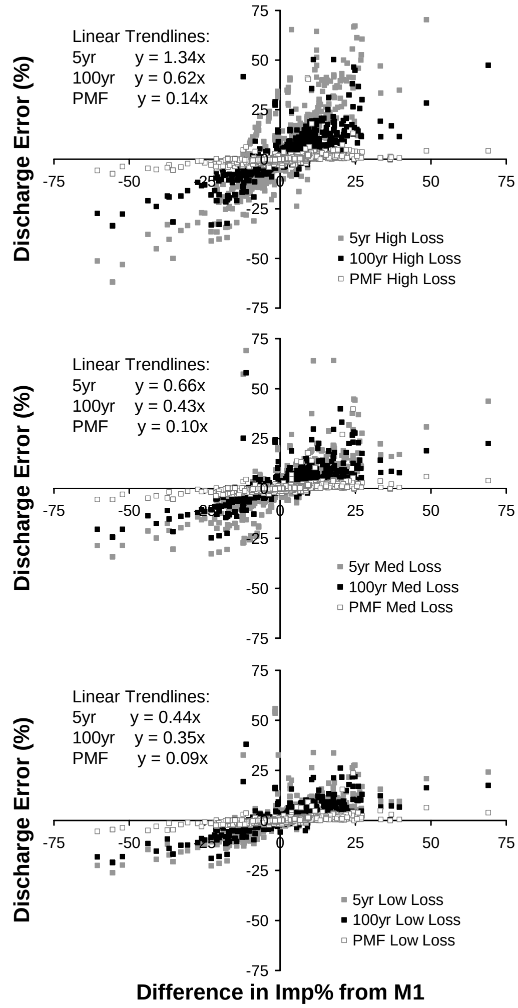

Figure 2: Error in Peak Discharge versus Difference in Impervious Cover Estimate

Figure 2 shows that based on the modelled catchment, the error trend for PMF is subject to minimal scatter and that (based on strong linear trend) for every +/- 10 percentage point difference in impervious cover the error in peak discharge is between 0.9% (low loss) and 1.4% (high loss). For the 100 year event the discharge error for every +/- 10 percentage point difference will typically range between 3.5% and 6.2%. For the 5 year event the difference can range between 4.4% and 13.4%. However there is more scatter in the results for the two smaller ARI events, particularly for high loss catchments. It is therefore possible that some locations will perform considerably better or worse than the values shown above.

5.2.2 Continuous Simulation

Figure 3 shows the error in predicted runoff volumes at the catchment outlet for each method, rainfall condition and loss combination.

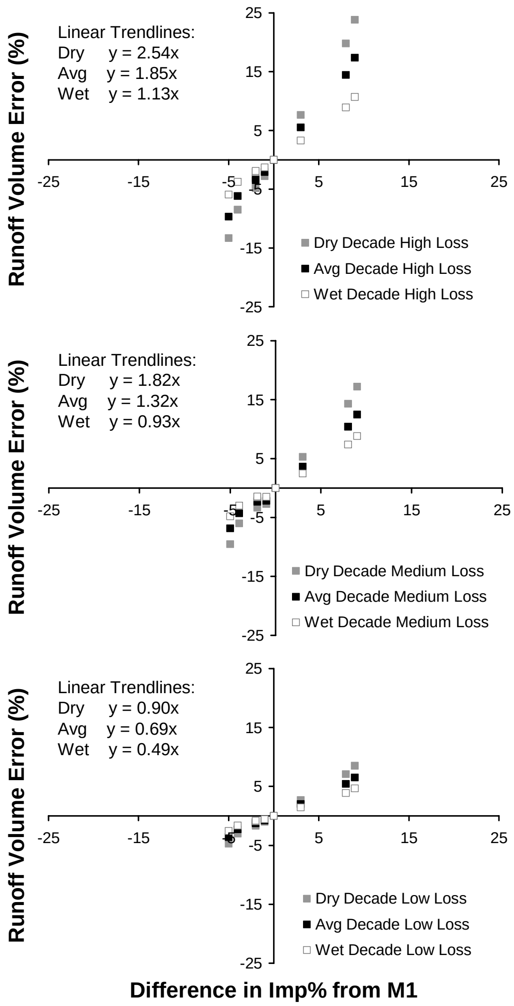

Figure 3: Error in Runoff Volume versus Difference in Impervious Cover Estimate

Figure 3 indicates that for simulation of a wet rainfall period, every +/- 10 percentage points difference in estimated impervious cover can yield a runoff volume error of between 4.9% (low loss) and 11.3% (high loss). This increases to 9.0% and 25.4% respectively for simulation of a dry rainfall period. Note that for low rainfall and high losses, most runoff is generated on impervious surfaces. Thus a difference of 10 percentage points in impervious cover (say from 40 to 50%) can result in a volume error near to 25%, as shown above.

6. CONCLUSIONS

With respect to the estimation of impervious cover proportion of catchments:

- Most techniques trialled (human and computer based) will typically under or over estimate actual impervious cover by between 10 and 20 percentage points.
- Computer based methods (Methods 4, 5, 6, 7) will under or over-estimate small subareas (less than 5 ha) to a greater extent than larger subareas.
- The most accurate method (aside from Method 1) was Method 7 involving the use of high spatial resolution satellite imagery with typical standard deviation of 10 percentage point difference from Method 1.
- Human-based methods (Methods 2 and 3) performed well compared to computer based methods suggesting that, on accuracy measures alone, there is not a strong case for using computer based methods. Other factors may however alter this argument for example when considering much larger catchments, where reduced time inputs could be expected.

With respect to impervious cover estimates and hydrologic error:

- Predicted peak discharges and runoff volumes are sensitive to error in impervious cover when modelling low rainfall events with both event based and continuous simulation models. For the modelled conditions, an impervious cover difference of +/- 10 percentage points from actual, can result in up to approximately 13% error in peak discharge (5yr ARI with an event based model) and 25% error in runoff volume (using a continuous simulation model).
- This high degree of hydrologic sensitivity to impervious cover confirms the need for accurate impervious cover estimates, particularly for low rainfall events.

7. REFERENCES

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