

Personalising the Viewshed: Visibility analysis from the human perspective

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Abstract

Viewshed analysis remains one of the most popular GIS tools for assessing visibility, despite the recognition of several limitations when quantifying visibility from a human perspective. The visual significance of terrain is heavily influenced by the vertical dimension (i.e. slope, aspect and elevation) and distance from the observer, neither of which are adjusted for in standard viewshed analyses. Based on these limitations, this study aimed to develop a methodology which extends the standard viewshed to represent visible landscape as more realistically perceived by a human, called the 'Vertical Visibility Index' (VVI). This method was intended to overcome the primary limitations of the standard viewshed by calculating the vertical degrees of visibility between the eye-level of a human and the top and bottom point of each visible cell in a viewshed. Next, the validity of the VVI was assessed using two comparison methods: 1) the known proportion of vegetation visible as assessed through imagery for 10 locations; and 2) standard viewshed analysis for 50 viewpoints in an urban setting. While positive, significant correlations were observed between the VVI values and both comparators, the correlation was strongest between the VVI values and the image verified, known values ($r = 0.863$, $p = 0.001$). The validation results indicate that the VVI is a valid method which can be used as an improvement on standard viewshed analyses for the accurate representation of landscape visibility from a human perspective.

Highlights

- Standard viewshed analysis is a poor measure of visibility from a human perspective.
- A novel method (VVI) was developed to represent visibility from a human perspective.
- The VVI demonstrated predictive validity for known environment visibility ($r = 0.863$, $p = 0.001$).
- The VVI is a valid novel methodology for improving viewshed analyses when visibility from a human perspective is the focus.

Keywords

visibility analysis, viewshed, environment visibility, environment health, GIS

1. Introduction

How many residents will be visually affected by the development of a particular wind farm? Does an increased view of the ocean improve wellbeing? What landmarks were visible from this location a thousand years ago? These are just some of the questions that are often answered using viewshed analysis. As a method for deriving areas of visibility from any given vantage point or area, viewshed analysis is an important tool used to describe the visible spatial structure of an environment. In the field of GIS, viewshed analysis has proven to be the most popular methodology for quantifying visibility (Turner et al., 2001), and its application is now common practice in a range of fields including archaeology (Wheatley & Gillings, 2000), urban planning (Danese et al., 2009), forestry (Domingo-Santos et al., 2011), impact assessment (Howes & Gatrell, 1993) and in the military (VanHorn & Mosurinjohn, 2010).

The term 'viewshed' was first coined by Tandy (1967) who introduced it as an analogy to the watershed, and by 1968 it was implemented in the first computer program designed to automatically quantify visibility across terrain (Amidon & Elsner, 1968). Viewshed analysis quantifies visibility by generating Lines of Sight (LoS) between an observer point and all cells of a gridded elevation surface or Digital Elevation Model (DEM). Every cell is initially treated as visible, unless the LoS detects intervening topography or other obstructions. In its most basic form, this is the basis of the 'binary viewshed' which produces a raster surface indicating visibility by '1' and non-visibility by '0' for all cells (Wheatley & Gillings, 2000). However the viewshed is a poor measure of visibility from a human perspective for two primary reasons. The 'visual significance' of perceived terrain is a term that can be used to describe how influential visible terrain is to one's perception of the environment and this is heavily influenced by two factors; the distance between a perceived object and the observer, and the vertical dimension (i.e. slope and aspect) of terrain. Closer visible objects are perceived as having more significance than distant objects. This is a result of many factors such as relative size of objects and object-background clarity, all which are a function of the distance between the perceived object and the observer. For example, Bishop & Miller (2007) found while lighting and atmospheric conditions affected the visibility of offshore wind farms, distance and background contrast has the most influence. Distance decay functions offer a method for weighting visible cells of the viewshed as a function of their relative distance to the observer's location where nearby cells hold more significance than distant cells. The 'fuzzy viewshed', an adaption of the binary viewshed, harnesses distance decay functions to illustrate the degree to which a cell is visible (Fisher, 1994). Typically, an exponential distance decay function is used which states the visual significance of an object decreases exponentially with increasing distance from the observer (Kumsap et al. 2005). A host of differing distance decay functions can be selected to represent atmospheric conditions such

as fog, haze and rain (Fisher, 1994). An alternative method developed by Higuchi & Terry (1983) called the 'Higuchi Viewshed', well demonstrated by Wheatley & Gillings (2000), accounts for distance by developing a standardized index. Three distance bands are defined which reflect three identified 'visibility zones'. The foreground corresponds to a proximal area centred on the viewer where clarity can be considered perfect. In the middle ground, clarity begins to decay and objects become nearly indistinguishable towards the further edge of the zone. The background zone essentially begins where objects cannot be individually identified, and only broad landscape features are distinguished. These three visibility zones are not fixed distances and can be chosen to reflect the climatic conditions and nature of the visible landscape. For example, the distance between the edge of clarity will decrease with increased atmospheric interference. By identifying these three areas as distinct zones, characteristics of a subjects view can be defined by calculating descriptive statistics e.g. is the view dominated by visible ground within the foreground, or is there a distant mountain range which has a larger influence in the visual scene?

While the above adaptations to the viewshed offer partial solutions mitigating the influence distance has on visibility, and are a step closer to portraying visibility from the human perspective, they fail to account for the vertical dimension of visibility. The vast majority of visibility analysis is conducted in either the 2nd dimension such as isovists (for urban and architectural studies) or in 2.5 dimensions with viewshed analysis (Bartie et al. 2011). While the viewshed can be an extremely useful tool, especially in large scale terrain analysis for which it was designed, it takes a God's eye view approach and fails to portray the vertical dimension of terrain, a characteristic of visibility which is particularly important from the human perspective. Slope, aspect, distance and elevation of visible areas all influence the visual significance of observed features, none of which are accounted for in standard viewshed analysis. Figure 1 below shows two DEM's representing two hills. The second DEM is a replicate of the first after applying significant vertical exaggeration. While the vertically exaggerated DEM holds much more visual significance from the human perspective, there is no difference in the resulting viewshed. A realization of this sparked a new generation of visibility analysis called 'viewsapes' which move away from 2.5 dimensional viewsheds and express visibility within a 3D sphere (Bartie et al. 2011).

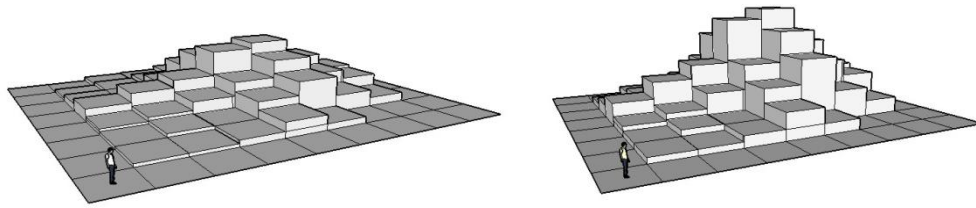


Figure 1: A DEM representation of a hill (on left) and a vertically exaggerated copy (on right). While the second holds much greater visual significance than the first, both return the same viewshed.

Travis et al. (1975) developed the computer model VIEWIT which was the first tool to extend the viewshed and quantify visibility across environments after factoring in the vertical nature of terrain. Each cell considered visible in the viewshed was assigned a maximum of 10 points based on the relative elevations of the observer and visible cell, the visible cell slope and the visible cell aspect, while a distance decay function was conducted independently to weight closer cells as more significant. More recently, Domingo-Santos et al., (2011) made further improvements by developing a visibility tool that calculated the solid angle of each visible cell within a DEM. Solid angles are described as the “surface area covered by a given object on the retina of the observer” (Domingo-Santos et al., 2011 p. 57) and take into account every visible cells relative aspect, relative elevation, slope and distance from observer, all of which influence the visual structure of an environment. The work by Domingo-Santos et al. (2011) represents the beginning of a shift in focus from environment visibility to visibility of the environment from a human perspective.

This study aimed to extend the standard viewshed to represent visible landscape as perceived by a human, by creating a measure termed the 'Vertical Visibility Index' (VVI). The VVI undertakes a similar approach to Domingo-Santos et al. (2011) calculation of the solid angle. Here however, the focus lies in the vertical nature of visible terrain and the method favours highly undulating settings where standard viewshed methods are unable to provide an accurate representation of the view from the human perspective.

2. Methods

The VVI methodology extended the viewshed by recalculating values for each cell deemed visible by LoS analysis in a meaningful way from a human perspective. Firstly, a standard viewshed output from a single observer location was created using the ESRI ArcGIS viewshed tool (Redlands, CA). A two-step process was then used to capture the 'visual significance' of terrain. The calculation of the 'vertical angle' initially improved visibility measures by taking into account i) surface slope, ii) distance between the observer and visible terrain, and iii) elevation difference between the observer and visible terrain. Secondly, the visual significance was adjusted for the aspect of visible terrain (i.e. which direction the surface slopes relative to the observer) giving the 'adjusted visual significance'. This two-step process was developed as an automated python script which iterated through each cell deemed visible from the viewshed tool and summed the adjusted visual significance of each visible raster cell to give an overall measure of visibility from an observer point. The following steps outline the procedure taken to calculate the adjusted visual significance for one individual cell.

2.1 Calculating the visual significance: The vertical angle

The vertical angle is defined as the angle between an observer's eye level and the up-slope point and down-slope point of the visible cell (Figure 2).

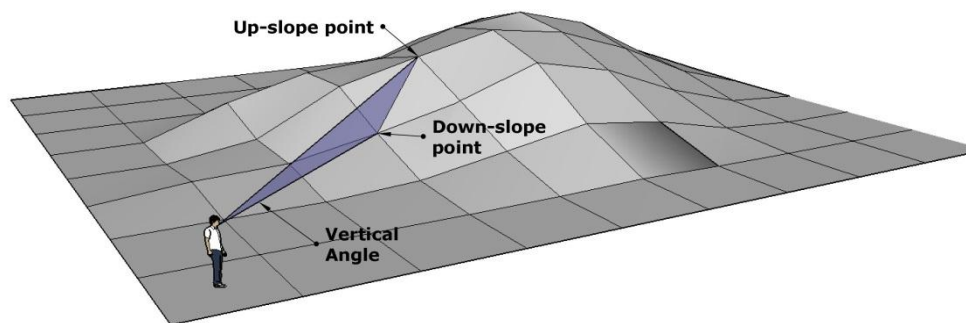


Figure 2: The vertical angle between the eye level of a viewer and the up-slope and down-slope points of a visible raster cell on a DEM surface.

In order to calculate the vertical angle, three sides of a theoretical non-right angled triangle are required (see Figure 3):

- i) Distance between the observer's eye level and the up-slope point of the sloped cell.
- ii) Distance between the observer's eye level and the down-slope point of the sloped cell.
- iii) Distance between the up-slope and down-slope points of the cell.

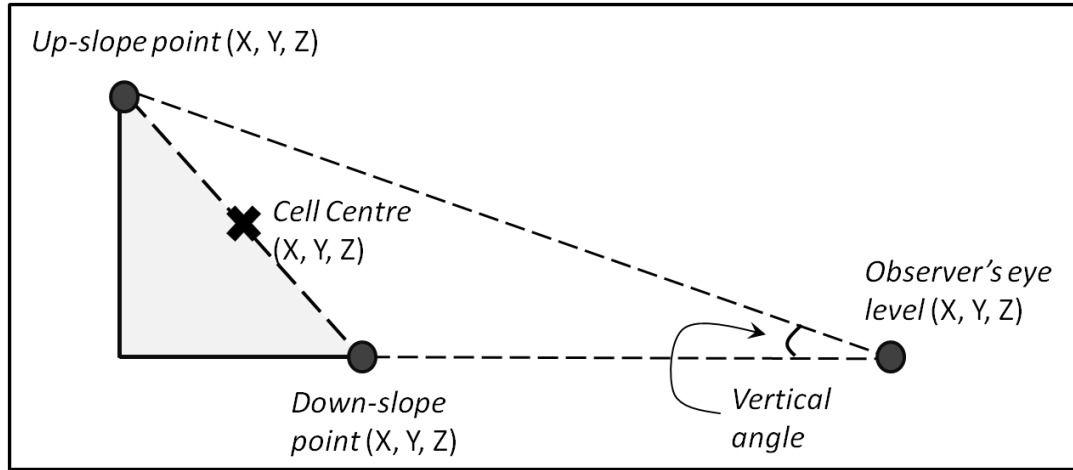


Figure 3: A cross-sectional view of one visible cell from an observer point. The X, Y, Z coordinates for the three points are required to calculate the vertical angle between the observer's eye level and the up-slope and down-slope points of the cell.

Given all three side lengths, the interior vertical angle of a non-right angled triangle can be calculated using the trigonometry law of cosines. However, before these three distances can be calculated, the positioning of the up-slope and down-slope points must be known within 3D space (i.e. their X, Y, Z coordinates). As only the location of the raster cell geometric centroid is stored within the GIS, these points must be estimated relative to the cell centre. Trigonometry can be used to derive the elevation change within the cell once the cell slope (or gradient) is known by multiplying the cell width (cell resolution) by the tangent of the cell slope. In turn, the up and down-slope Z coordinate is calculated by adding/subtracting half the elevation change to/from the cell centre's elevation. Cell slope was estimated based on the elevation values of its neighbouring cells using the ESRI ArcGIS slope tool (Redlands, CA). The calculation of the XY coordinates for the up-slope and down-slope points were also derived relative to the cell centre XY , however unlike the calculation of the Z coordinate, they are influenced by the bearing of the visible cell relative to the observer's position. The bearing between the visible cell and the observer's location dictates which of eight formulas should be used to calculate the up-slope and down-slope points, each covering a range of 45° . One limitation of this process is the assumption of orthogonality of a sloping surface to the observer however, this error is mitigated by weighting the vertical angle by cell aspect (see below).

Following the computation of the three sets of XYZ coordinates identified in Figure 3, the distance between them was calculated using the 3D point's distance formula given in equation 1:

$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (1)$$

Once all three distances, or side lengths of the theoretical triangle in Figure 3 are known, the law of cosines is used to calculate the interior vertical angle shown in equation 2 where a, b and c correspond to the length of a triangle edge.

$$\text{Vertical Angle} = \cos^{-1} \left(\frac{a^2 + b^2 - c^2}{2ab} \right) \quad (2)$$

The vertical angle adjusts for three factors that influence the visual significance of terrain from the human perspective; cell slope, distance between the observer and the visible cell and finally, the elevation difference between observer and visible cell. Visible cells that are closer to the observer result in larger vertical angles indicating increased visual significance while distant cells result in a smaller vertical angle reducing the visual significance. Sloped cells may increase or decrease the vertical angle depending on whether the visible cell is at a higher or lower elevation than the observer (see Figure 4 and Figure 5 for illustration).

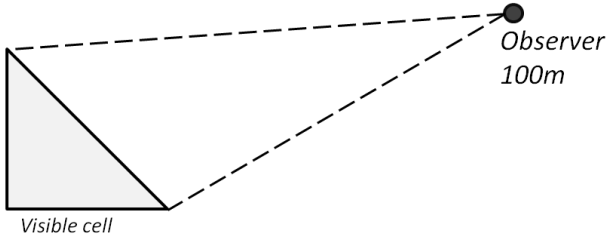
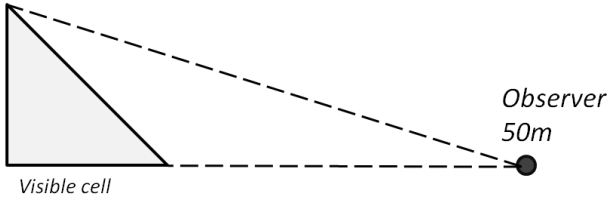
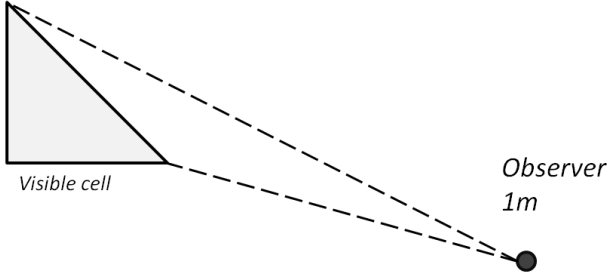
 <p>Observer 100m</p> <p>Visible cell</p>	<p>Observer above visible cell</p> <p>VA increases as direct view of slope increases VA = 25°</p>
 <p>Observer 50m</p> <p>Visible cell</p>	<p>Observer level with visible cell</p> <p>VA = 20°</p>
 <p>Observer 1m</p> <p>Visible cell</p>	<p>Observer below visible cell</p> <p>VA decreases as direct view of slope decreases VA = 5°</p>

Figure 4: Cross-sectional view showing the influence of observer elevation relative to the elevation of a visible cell on the vertical angle (VA).

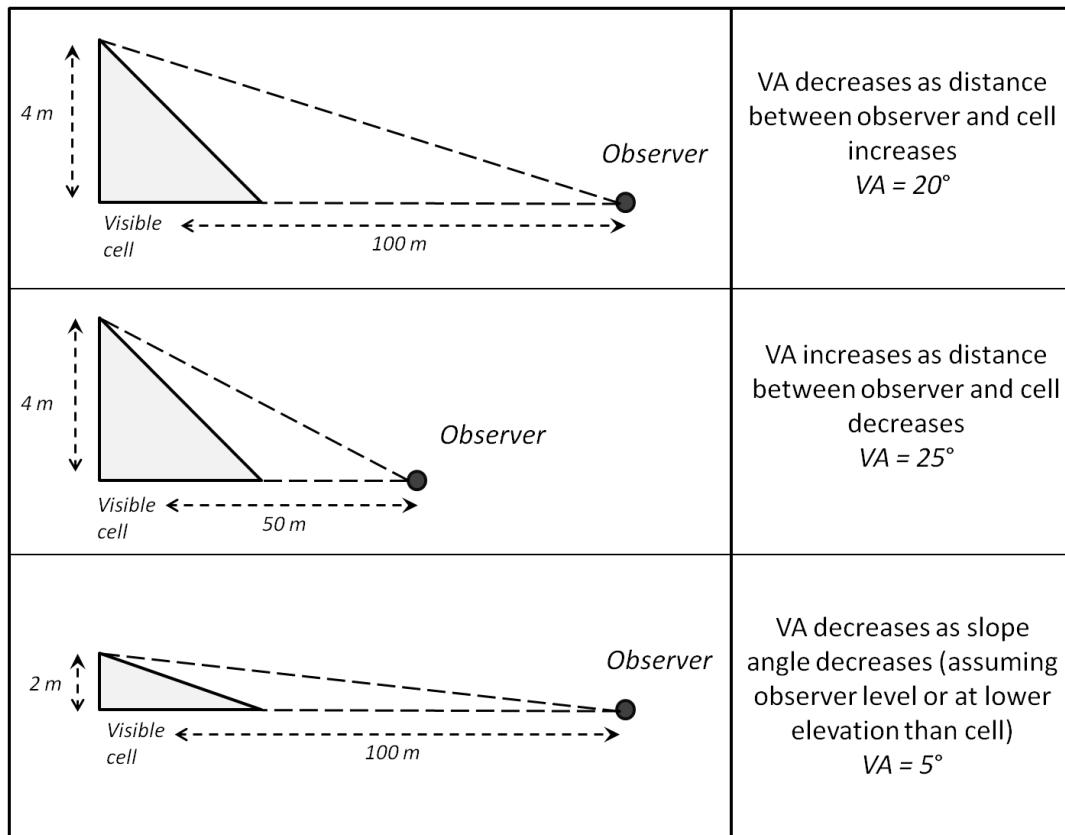


Figure 5: Cross-sectional view showing i) the influence distance between observer location and visible cells has on the Vertical Angle (VA) and ii) the influence cell slope has on the VA.

2.2 Calculating the visual significance: Adjusting for aspect

The influence of terrain aspect is the last factor to be accounted for and can potentially have a significant influence. For example, a slope that is facing 45° relative to the observer has less visual significance than a slope directly facing the observer. Furthermore, a slope facing 90° relative to an observer is theoretically not visible. The adjusted measure of the visual significance is defined as:

$$\text{Adjusted Visual Significance} = \text{Vertical Angle} \left(1 - \frac{\text{Relative Aspect}}{90.0} \right) \quad (3)$$

where relative aspect is the difference between cell aspect and cell bearing (i.e. amount of the cell slope facing the observer). All cells with a slope greater than 3° were weighted by the aspect factor.

Finally, the adjusted visual significance value for each cell visible from an observer is totalled, giving the total adjusted visual significance which we have termed the Vertical Visibility Index.

2.3 Assessing validity of the VVI

In order to assess the validity of the VVI measure, we calculated measures of visible vegetation from selected observer locations in Wellington, New Zealand using two comparison methods. These locations were selected to represent areas with low, mid and high levels of visible vegetation. For the first comparison, for each selected location, we collected Google Earth Street Map imagery and created 360° panoramic images (Google Inc, 2005). The visible vegetation within these images was then programmatically classified using a python script. The RGB values for each pixel in the Google Earth Images were analysed. “Green” pixels were kept while all other pixels were removed. Figure 6, below, is a section of one such image which expresses visible green space as a proportion of the street view image. As shown in Figure 6, street view imagery was not completely representative of an entire visual space. For example, overhead sky is not included which is consistent with the VVI interpretation of visibility which expresses green space as a proportion of visibility within 360° rotational degrees and 90° vertical degrees. These image verified values are considered to be the known amount of green space within a scene.

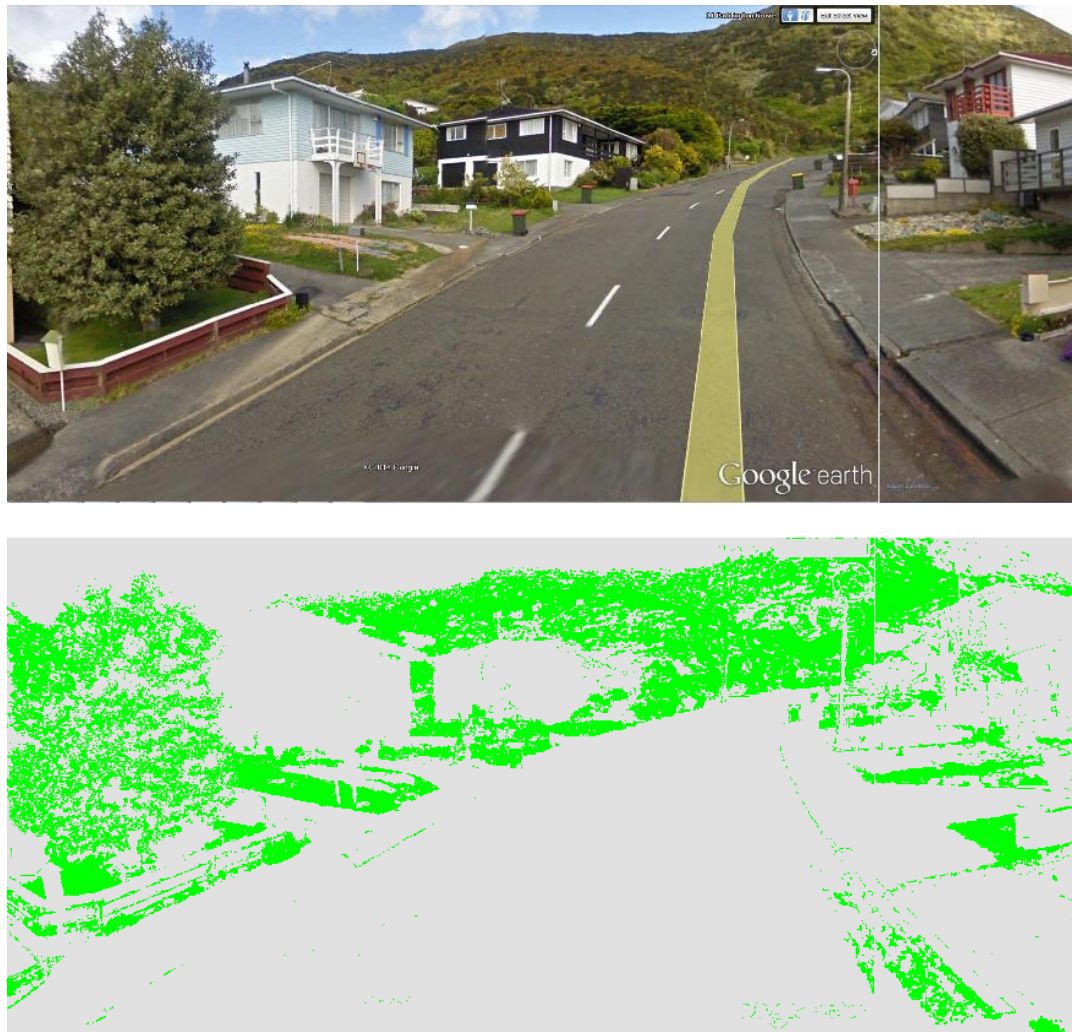


Figure 6: A section of a panoramic Google Earth Street Map image and the results of the python script used to calculate the proportion of “green” pixels in an image.

For further comparison, we also calculated standard viewshed scores (in ArcGIS v10.2) using a 5m resolution raster provided by the Wellington City Council, which had building heights burnt into it at 1m resolution. Using a land cover dataset to represent vegetation, all areas which intersected with ‘visible’ cells were extracted. The number of visible cells that intersected vegetated areas was multiplied by 25 (the area of one cell) to give the area of visible vegetation in m².

Pearson’s correlation coefficients were calculated to assess the relationship between: 1) the VVI scores and the calculated proportion of visible vegetation using Google Earth Street Map imagery for 10 locations; and 2) the VVI scores and standard viewshed analyses. All correlation tests were conducted using STATAv12 (College Station, TX, USA).

3. Results of validation

Calculation of the VVI for the 10 locations in Wellington City took approximately 15 minutes. Values for these locations ranged from 324 to 4368 (mean = 1720 , sd = 1322), where 32400 represents the highest theoretical level of vegetation visibility (i.e. complete immersion in vegetation). All locations were within the urban core of this capital city. Due to time costs, assessment of Google Earth Street Map imagery was done at 10 locations taking approximately four hours, not including manual image sourcing. Values for these locations ranged from 0.5 to 21 (mean = 6.58 , sd = 6.51), where 100 represents the highest possible level of vegetation visibility. We found a strong, positive association between the image verified level of green space and the novel VVI method ($r = 0.863$, $p = 0.001$) (see Figure 7).

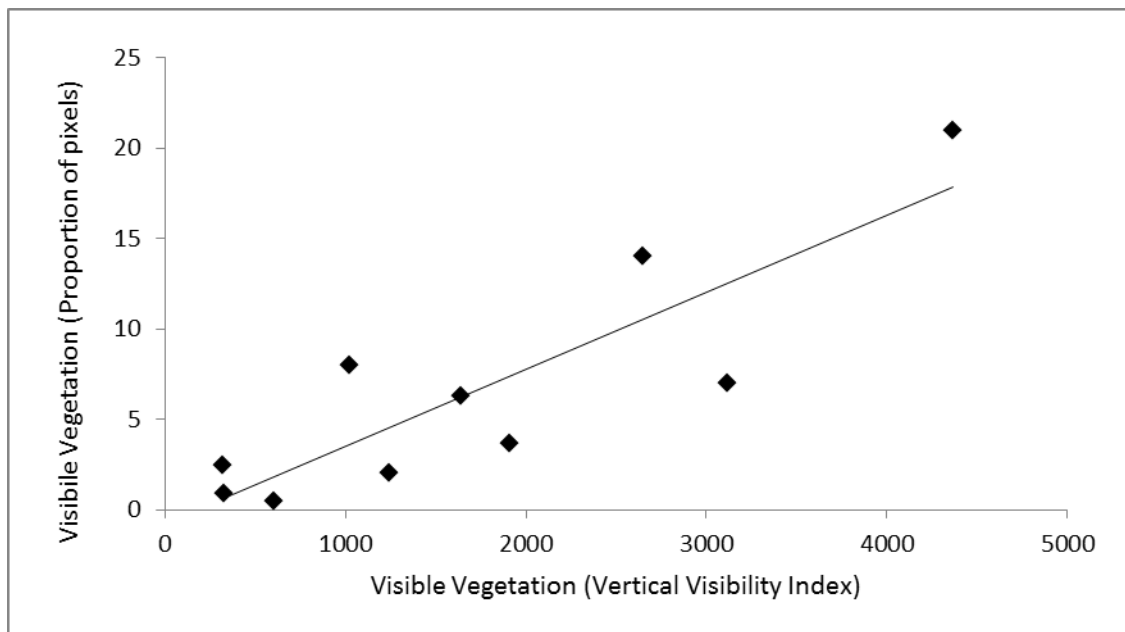


Figure 7: Correlation ($r = 0.863$, $p = 0.001$) between VVI scores of visible vegetation and known proportion of visible vegetation.

Next, we found a positive and significant correlation between the VVI index and standard viewshed analysis results for 50 sample points ($r = 0.581$, $p = 0.001$) (Figure 8). While the two measures of visibility were associated, as we would expect, a high VVI score does not reflect a respectively large viewshed output. This is expected due to the VVI accounting for the influence of slope, aspect and distance while standard viewshed analysis does not. It is likely that while large viewsheds result in a large amount of *visible area*, the visual significance of these distant areas are very small, thereby giving a large viewshed result a relatively smaller VVI value. For example, Viewpoint A in Figure 8 yielded high values using viewshed analysis. However, this viewpoint primarily involves distant green

space, so Viewpoint A yielded a lower VVI score. By contrast, Viewpoint B yielded a low score using the standard viewshed analysis and a high VVI due to the green space being in close proximity and sloping towards the viewpoint.

Importantly, the novel VVI method yielded a stronger correlation with the image verified level of green space than to standard viewshed analysis values.

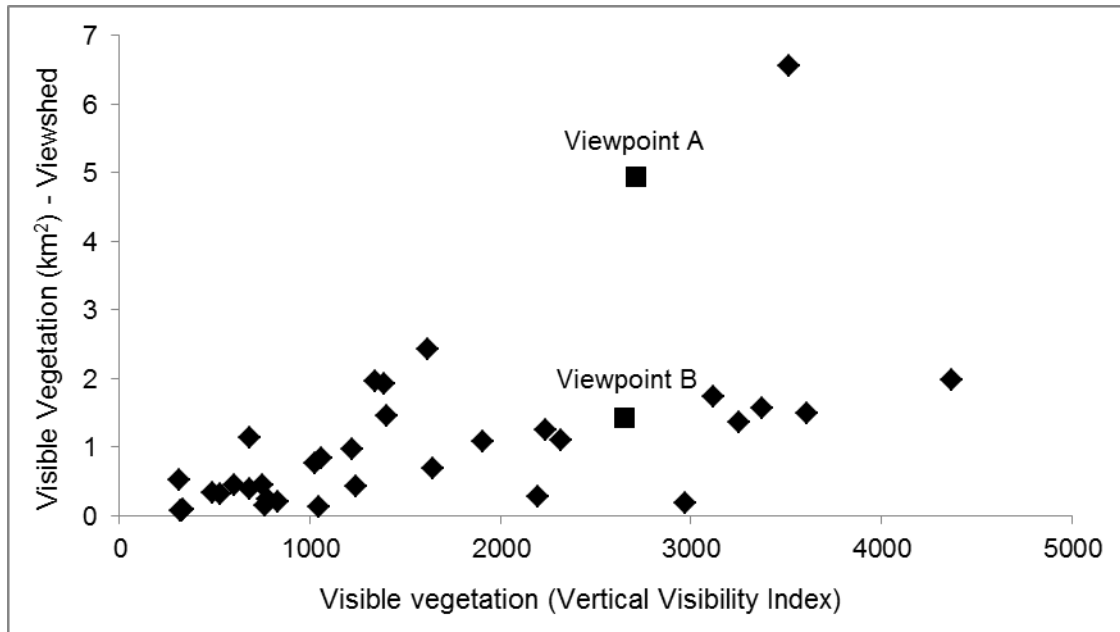


Figure 8: Correlation ($r = 0.581$, $p = 0.001$) between VVI scores of visible vegetation and standard viewshed analysis results at 50 urban locations.

4. Discussion

Numerous limitations of standard viewshed practice are well documented. Despite the development of a number of alternative approaches (Domingo-Santos et al., 2011; Higuchi & Terry, 1983; Travis et al., 1975), they remain the most common and standard visibility technique across most GIS systems (Turner et al., 2001). Of particular significance is the failure of standard viewsheds to account for the vertical nature of terrain. The VVI is a measure of visibility designed to overcome this primary limitation. By incorporating measures of slope, aspect, proximity and elevation of visible terrain relative to observer locations, the VVI was found to be an accurate measure of visibility from the human perspective, as validated through comparisons with image verified visibility and standard viewshed analysis. In particular, a stronger correlation was observed between the image verified visibility measures and the VVI values, compared to the observed correlation between standard viewshed values and the VVI values. It is, therefore, recommended that visibility measures such as the VVI should be employed in favour over the viewshed in scenarios where visibility from the human perspective is a focus.

Nonetheless, there are limitations specific to the VVI methodology worth noting. In order to reduce the impact of nearby cells having a disproportionate vertical angle due to their close proximity, nearby visible vegetation (<300m) was not included in analysis. The resulting repercussion is that VVI measures of green space visibility are likely to be slightly under representative at close ranges while very distant visible cells are likely to be slightly over represented. We therefore recommend that the VVI methodology is best suited for assessing visibility in the middle ground (as described by Higuchi & Terry (1983)). Due to additional computational steps in the calculation of the VVI, particularly the derivation of terrain slope and aspect, considerably more processing power is required in comparison to standard viewshed analysis and increased calculation time should be expected by users. However, the calculation of the VVI was observed to be much faster than image classification methods. While the VVI overcomes a number of the shortcomings of standard viewshed analysis, limitations common to all visibility analyses remain and are also worth discussing in the context of the VVI. Accurately incorporating vegetation proves to be the most difficult challenge due to its semi-transparent and often non-uniform distribution across terrain (Bartie et al., 2011; Kumsap et al. 2013; Wheatley & Gillings, 2000). Partial solutions have been developed (Bartie et al., 2011; Llobera, 2007; Murgoitio et al., 2013; Tomko et al, 2009), however are not based on the viewshed approach and therefore are not applicable to the VVI methodology. While not an ideal solution, the most common approach is to add a raster vegetation layer to digital terrain models, where new elevation values represent ground height plus the average height of the dominant

vegetation type (Wheatley & Gillings, 2000). Similarly, by merging spatially accurate rasterized building footprints with a terrain model, a DEM can be created to represent both natural terrain and surface features (Sander & Manson, 2007; VanHorn & Mosurinjohn, 2010). Resulting viewsheds therefore account for buildings and their influence is preserved in the resulting VVI.

5. Conclusion

Standard viewshed measures fail to accurately capture visibility from the human perspective, as they do not account for the visual significance of terrain. By developing a new method which extends the capabilities of the standard viewshed to account for the vertical dimension of terrain and the relative distance of visible areas, this study was able to represent visibility in a way that is more realistic from a human perspective. It is therefore recommended that new visibility methods such as the VVI be used as alternative measures of visibility where the research focus is the human perspective, for example when assessing the impact of visual space on human well-being or behaviour.

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- A novel method (VVI) was developed to represent visibility from a human perspective.
- The VVI demonstrated predictive validity for known environment visibility ($r = 0.863$, $p = 0.001$).
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