Can You See That?

Fuzzy viewsheds and realistic models of landscape visibility

Geography 647

Final Project

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25-April-2007
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Viewsheds</td>
<td>2</td>
</tr>
<tr>
<td>Binary Viewsheds</td>
<td>2</td>
</tr>
<tr>
<td>Probable Viewsheds</td>
<td>2</td>
</tr>
<tr>
<td>Fuzzy Viewsheds</td>
<td>3</td>
</tr>
<tr>
<td>Creating a Fuzzy Viewshed</td>
<td>3</td>
</tr>
<tr>
<td>Binary Viewshed Creation</td>
<td>4</td>
</tr>
<tr>
<td>Distance Buffer Creation</td>
<td>5</td>
</tr>
<tr>
<td>Distance Decay Function</td>
<td>6</td>
</tr>
<tr>
<td>Distance Decay Buffer Creation</td>
<td>8</td>
</tr>
<tr>
<td>Fuzzy Viewshed Creation</td>
<td>8</td>
</tr>
<tr>
<td>Fuzzy Viewshed Variations</td>
<td>9</td>
</tr>
<tr>
<td>Modeling Variations in Visibility</td>
<td>10</td>
</tr>
<tr>
<td>Environmental Factors Affecting Visibility</td>
<td>13</td>
</tr>
<tr>
<td>Physical Properties of the Object Affecting Visibility</td>
<td>15</td>
</tr>
<tr>
<td>Observer Imposed Restraints on Visibility</td>
<td>17</td>
</tr>
<tr>
<td>Conclusion</td>
<td>18</td>
</tr>
<tr>
<td>References Cited</td>
<td>20</td>
</tr>
</tbody>
</table>
**Introduction**

Standard viewshed analyses use line of sight algorithms to mathematically determine visibility across landscapes (ESRI 2005). These viewshed analyses, however, assume both perfect clarity within the environment and perfect vision for the observer, neither of which are realistic in the real world. Despite the unrealistic nature of these assumptions, though, viewshed analyses have been used in fields such as archaeology to model real world phenomena for considerable time, and continue to be used today (Lake, Woodman et al. 1998; Jones 2006). Some researchers have cautioned, however, that ignoring such assumptions can lead to unreliable results (Ogburn 2006).

Several factors affect the visibility of the landscape and the objects within it. These factors range from things as diverse as atmospheric or illumination conditions and the visual acuity of the observer to the physical properties of the objects under investigation or even the cognitive state of the observer. Considering the myriad of factors at play, using a GIS to try and accurately model a view of the real world can be a daunting and complicated proposition. This paper will examine the GIS function of viewshed analysis and explore how it can be modified and adapted to account for factors affecting the visibility of landscapes and objects, and thus create more realistic models of landscape visibility.

The first section of this paper will briefly introduce the concept of GIS viewshed analysis and describe several variations of the viewshed before examining one of those viewshed variations, the fuzzy viewshed, in detail. The fuzzy viewshed will be described, and a systematic procedure for creating one in a raster based GIS system will be presented.

The second section of the paper will deal with variations of the fuzzy viewshed which attempt to increase the realism of the fuzzy viewshed model. A significant portion of this section will deal with the distance decay function, the lynch pin of the fuzzy viewshed. The paper will then conclude by briefly
examining two of the more difficult and problematic issues concerning viewshed analysis - creating realistic viewshed models for objects of various sizes and diverse visual characteristics, as well as creating viewshed models that consider observer imposed visibility restraints.

**Viewsheds**

Viewshed analysis is a form of surface spatial examination that attempts to digitally represent the visual landscape of a given area by showing those places visible and not visible from a specified location. The process is usually conducted using a digital elevation model, or DEM. A viewshed analysis is created by producing a line-of-sight analysis from the DEM cell representing the viewing location, to every other cell within the DEM (ESRI 2005). Each cell which falls along a direct and uninterrupted line-of-sight is classified as visible and is assigned a value of 1, while those in which the line-of-sight is blocked by the elevation values of other cells is classed as not visible and is assigned a value of 0. A viewshed, then, is a raster image in which the value of each cell is either 1 or 0.

Beyond the simple binary viewshed described above, there are two other viewshed variations that bear mentioning, the probable viewshed, and the primary topic of this paper, the fuzzy viewshed.

**Binary Viewsheds**

A binary viewshed is the simplest of the viewshed models. It assumes perfect clarity and perfect visibility and, as explained above, consists solely of 1s and 0s, representing cells which are either visible from the viewing location or not visible from the viewing location.

**Probable Viewsheds**

There has been some confusion in the literature over the difference between fuzzy and probable viewsheds (Fisher 1994). Fuzzy viewsheds indicate the *degree* of visibility of a cell while probable viewsheds indicate the *probability*
of a cell being visible. A Monte Carlo simulation of error approach is followed when creating a probable viewshed. The process of creating a probable viewshed consists of adding together several binary viewsheds with the same viewpoint. The differences between each of the component binary viewsheds results from the elevation values of the cells in the DEM used to create the viewsheds, which are randomly varied based on the stated error the DEM prior to creating each component binary viewshed. The resulting viewshed, then, consists of a raster with cells containing values ranging from 0 to \( n \), with \( n \) being the number of times the simulation was run. The higher the cell value in a probable viewshed, the more likely that cell is to be visible from the specified viewpoint (Fisher 1992)

**Fuzzy Viewsheds**

The fuzzy viewshed was first proposed by Fisher (1994), and was later expanded upon by Ogburn (Ogburn 2006). The purpose of the fuzzy viewshed is to more accurately model the real world view afforded by various environmental conditions within a GIS. In order to achieve this, fuzzy viewsheds introduce a distance decay function into the standard binary viewshed. Unlike a binary viewshed, in which each cell is classed as either visible or not visible, or a probable viewshed, in which the viewshed cell values represent the probability of the cell being visible, each cell within a fuzzy viewshed is assigned a value from 0 to 1 representing the degree of visibility of the cell from the viewpoint. The closer to 1 the cell value is, the easier it is to see that location from the designated viewpoint.

**Creating a Fuzzy Viewshed**

There are several steps to creating a fuzzy viewshed, involving three primary components. The primary components necessary for the creation of a fuzzy viewshed are, a binary viewshed, a distance buffer and a distance decay function. The following explanation will assume a single viewpoint, but several viewpoints may be chosen if desired.
**Binary Viewshed Creation**

The initial step in creating a fuzzy viewshed is to create a binary viewshed. This is a relatively simple process utilizing a digital elevation model. First, a viewpoint is selected, and then options such as viewpoint, or viewed point, elevation offsets and earth curvature compensation are set. Finally, the standard viewshed analysis function is run. In ArcMap this function can be found under either 3D Analyst or Spatial Analyst (ESRI 2005). A binary viewshed example can be seen in Figure 1.

The raster layer resulting from the creation of a binary viewshed consists of cells classed as either visible or not visible from the viewpoint. It is informative, however, to regard the cells of the binary viewshed in a slightly different manner. The viewshed cells classified as visible should be regarded as *possibly* visible, until a fuzzy viewshed is created and can be used to determine if the *possibly* visible cells remain visible and if so, their degree of visibility.

*Figure 1*: Binary Viewshed of the City of Calgary from a viewpoint (red dot) in Nose Hill Park. The black areas are not visible from the viewpoint and the white areas are *possibly* visible from the viewpoint. The city boundary is shown in red.
Distance Buffer Creation

Since the creation of a fuzzy viewshed depends a great deal on each cell’s distance from the viewpoint, a layer must be created containing that distance information. This is accomplished by creating a raster layer in which the value of each cell equals the distance from that cell to the viewpoint. The Euclidian distance function found under Spatial Analyst is a simple way to create this layer in ArcMap (ESRI 2005). See Figure 2 for an example of a distance buffer.

Figure 2: A distance buffer for a viewpoint in Nose Hill Park created in ArcMap using spatial analyst. The viewpoint is represented by the red dot, and the city boundary is the red line. The darker the area, the farther away from the viewpoint it lies.
Distance Decay Function

The distance decay function is the key to the creation of the fuzzy viewshed. It is this function that models the drop in visual clarity that occurs with increasing distance from the viewpoint. Building on earlier work in fuzzy math and soil profile modeling, Fisher (1994) derived and applied the following distance decay function to viewshed analysis.

\[
\mu(x_{ij}) = \frac{1}{1 + \left( \frac{d_{vp-ij} - b_1}{b_2} \right)^2} \quad \text{for} \quad d_{vp-ij} \leq b_1
\]

\[
\mu(x_{ij}) = \frac{1}{1 + \left( \frac{d_{vp-ij} - b_1}{b_2} \right)^2} \quad \text{for} \quad d_{vp-ij} > b_1
\]

where:
\( \mu = \) fuzzy membership
\( d = \) distance from viewpoint
\( b_1 = \) maximum distance from viewpoint of clear visibility
\( b_2 = \) distance from viewpoint at which visibility drops to 50%

The top line in the equation accounts for the zone around the viewpoint in which there is no discernable drop in visibility - the zone of clear visibility. The value of \( b_1 \) is the maximum distance from the viewpoint of this zone. Distance does not affect the visibility of any cell whose distance \( (d) \) from the viewpoint is \( \leq b_1 \), therefore all these cells are assigned a fuzzy membership value of one, the maximum value that can be assigned.

The bottom portion of the equation calculates the fuzzy membership values for all cells lying beyond the zone of clear visibility. The visibility of these cells, those whose distance \( (d) \) from the viewpoint is \( > b_1 \), is reduced, and their fuzzy membership values therefore also decay. The fuzzy membership values for all these cells are less than one.

The variable \( b_2 \), in the bottom portion of the equation, represents the distance from \( b_1 \) to the point at which visibility from the viewpoint drops to 50%. This point is has been called the crossover point (Ogburn 2006) and is the point...
at which the fuzzy membership value is 0.5. The distance from the viewer to the crossover point, then, is $b_1 + b_2$, as illustrated in Figure 3.

Figure 3 Visibility from the viewpoint (red dot) to anywhere within the inner circle ($d \leq b_1$) is not affected by distance (fuzzy membership =1). Visibility begins dropping off beyond the inner circle ($d > b_1$). At the crossover point, the large circle ($d = b_1 + b_2$), visibility drops to 50% (fuzzy membership =0.5). Beyond the crossover point (outside the large circle) visibility decays continuously to zero (fuzzy membership <0.5).

The user can set the values of the variables $b_1$ and $b_2$ as necessary to model the conditions the viewshed is meant to represent. Fisher (1994) suggested values of 1 km for $b_1$, and 2 km for $b_2$, as good starting points for modeling visibility under ideal conditions. One thing to remember when selecting values for these variables, however, is that the units of the variables must match the units of the distance buffer created earlier. A graph of the decay function, equation 1, with Fisher’s suggested $b_1$ and $b_2$ values, is illustrated in Figure 4.
Figure 4: Decay function graph using Fisher’s (1994) suggested values of 1 km for $b_1$ and 3 km for $b_2$. Note the position of the crossover point, the value of which along the horizontal axis is 4 km, which equals $b_1 + b_2$.

Distance Decay Buffer Creation

Once the decay function distance variables have been selected, and the equation finalized, a distance decay buffer must be created. The distance decay buffer is a raster layer created by applying the distance decay function to the distance buffer layer (see Figure 5). In ArcMap, this is accomplished using the raster calculator function of the program (ESRI 2005).

Fuzzy Viewshed Creation

The final step in creating a fuzzy viewshed is to combine the layer representing the distance decay function, and the layer classifying all cells as either not visible or possibly visible from the viewpoint based on the topography of the region. This is accomplished by multiplying the distance decay buffer by the binary viewshed. This is a simple process involving the use of the raster calculator function in ArcMap (ESRI 2005). The resulting raster layer will consist of cells with values ranging from 0-1 (see Figure 6). Cells with a value of zero are not visible from the viewpoint, cells with a value of 1 are 100% visible from
the viewpoint, with the remainder of the cells having a visibility state somewhere between these two extremes.

![A decay buffer for a viewpoint in Nose Hill Park created in ArcMap by applying Fisher’s (1994) distance decay function to a distance buffer using spatial analyst. The viewpoint is represented by the red dot, and the city boundary is the red line](image)

Figure 5: A decay buffer for a viewpoint in Nose Hill Park created in ArcMap by applying Fisher’s (1994) distance decay function to a distance buffer using spatial analyst. The viewpoint is represented by the red dot, and the city boundary is the red line

**Fuzzy Viewshed Variations**

The purpose of the fuzzy viewshed is to model visibility with a GIS under diverse visual conditions. For a fuzzy viewshed function to be successful, then, it must be flexible enough to accommodate various conditions affecting visibility. The primary factors affecting visibility can be grouped into three categories: environmental factors affecting conditions between the observer and the object under view, the physical properties of the object being viewed and constraints imposed on visibility by the observer (Ogburn 2006).
Figure 6: A fuzzy viewshed created by multiplying the decay buffer (Figure 5) by the binary viewshed (Figure 1). The black areas are regions not visible from the viewpoint (red dot). Pure white areas are 100% visible from the viewpoint. Remaining regions vary in their degree of visibility from the viewpoint, the darker the area the less visible it is. Fisher’s (1994) distance decay function (Equation 1) was used to create this fuzzy viewshed.

Examples of environmental factors affecting visibility are the presence or absence of atmospheric particulates and varying levels and directions of illumination. The physical properties of the object being viewed refers to the size of an object, as well as its colour, reflectivity and texture as it relates to its surrounding area, all of which have an impact visibility. The constraints imposed by the observer on visibility refer to such things as the visual acuity of the observer and the observer’s culturally influenced concepts of landscape and cognition.

**Modeling Variations in Visibility**

The key to modeling these conditions is the ability to adjust the distance decay function. Ogburn (2006) noted Fisher’s distance decay function may not accurately represent the conditions for which it was intended. Indeed,
Fisher (1994) himself stated the drop off in visibility his equation modeled may be too steep. While it may be true the visual drop off is too steep under ideal conditions, it is likely there are other conditions under which Fisher’s original equation is accurate.

In an effort to create a distance decay function with a more gradual drop off, and thus a more accurate model of human visibility under ideal conditions, Ogburn (2006) made several modifications to Fisher’s original model. His first modifications consisted simply of changing the value of one of the variables within the equation. He left the \( b_1 \) variable value at 1 km, but succeeded in altering Fisher’s model by changing the value of the \( b_2 \) variable to 4.75 km, 7.6 km and 16.2 km. He also tried modifying the equation itself by adding a multiplier to the denominator. Ogburn’s modification to Fisher’s original distance decay function is shown as equation 2. A graph showing the distance decay function curves resulting from Ogburn’s modifications is illustrated in Figure 7, and a fuzzy viewshed created with Ogburn’s distance decay function in which he modified Fisher’s original equation by adding a multiplier to the denominator (equation 2) and using a \( b_2 \) value of 16.2 km is shown in Figure 8.

\[
\mu(x_{ij}) = \begin{cases} 
\frac{1}{1 + 2\left( \frac{d_{vp_{ij}} - b_1}{b_2} \right)^2} & \text{for } d_{vp_{ij}} \leq b_1 \\
\frac{1}{1 + 2\left( \frac{d_{vp_{ij}} - b_1}{b_2} \right)^2} & \text{for } d_{vp_{ij}} > b_1 
\end{cases}
\]

where:
\( \mu = \) fuzzy membership
\( d = \) distance from viewpoint
\( b_1 = \) maximum distance from viewpoint of clear visibility
\( b_2 = \) distance from viewpoint at which visibility drops to 50%
Figure 7: Distance decay function graphs modeling different conditions of visibility. The green line is Fisher's (1994) original equation (identical to that shown in Figure 1). The remaining lines are variations of Fisher's model created by Ogburn (2006). The magenta line (Ogburn 1) uses a $h_2$ value of 4.75 km and the yellow line (Ogburn 2) uses a $h_2$ value of 7.6 km. The cyan line (Ogburn 3) is Ogburn’s variation on Fisher's equation (equation 2) with a multiplier added to the denominator, and a $h_2$ value of 16.2 km.

Figure 8: A fuzzy viewshed created using Ogburn’s (2006) distance decay function (equation 2, and Ogburn 3 in Figure 7), a modification of Fisher’s (1994) original distance decay function. Note the much more gradual drop off in visibility of this viewshed compared to one created using Fisher’s original equation (see Figure 6).
Environmental Factors Affecting Visibility

As mentioned above, two examples of environmental factors affecting visibility are the presence or absence of atmospheric particulates and the level and direction of illumination.

Atmospheric Particulates

For the purposes of this paper, the category of Atmospheric Particulates refers to both aerosols and large particulate matter, meaning any airborne item that absorbs, reflects or scatters light. Three causes of atmospheric particulates affecting visibility are human induced particulates, human/natural particulates and naturally occurring particulates. Human induced particulates are substances such as pollution or smog, which can occur in almost any location in which humans are active, but are particularly prevalent over large cities. Human/natural particulates are things like smoke or dust, and may be the result of human activity, or may simply be naturally occurring phenomena resulting from something like a forest fire. Examples of naturally occurring atmospheric particulates are water in the form of fog or rain, sand from a sandstorm or swarms of insects.

All forms of atmospheric particulates negatively affect visibility, and figure 9 illustrates some of these phenomena. Visibility in the foreground area is clear and unaffected by airborne particulates, but as the distance from the viewpoint increases, so does the affect of smog and water vapour, resulting in a decrease in the level of visibility. Also of note is the visibility level beneath the thunderstorm in the background, an extreme example of decreased visibility caused by airborne water. The area beneath the thunderstorm is not visible, while areas neighbouring it still show a degree of visibility. Fisher (1994) attempted to create a viewshed model for a similar atmospheric condition, fog, but other than this, very little has been done to model the affects on visibility of atmospheric particulates with viewshed analysis.
**Varying Illumination Affects**

Another factor affecting visibility is the amount, and direction, of illumination. It seems obvious that the greater the amount of light available, the more favourable will be the viewing conditions. There does not appear, however, to have been much research conducted using viewshed analysis to model varying levels of illumination and the affects it has on visibility.

Another light related factor affecting visibility is the direction of illumination. If a light source is of sufficient brightness, it may be that the degree of visibility is greater when looking away from the light source than when looking toward it. Examples of this phenomenon would be bright sunrises or sunsets. In both cases, the degree of visibility afforded the observer will be greater when looking away from the sun than when looking toward it. As with the affect of the amount of illumination on visibility, there has been very little research using viewshed analysis to model directional illumination affects on visibility. Fisher (1994) has attempted to use viewshed analysis to model the affects directional sunlight on a landscape has on visibility, but the description of his method to account for the angle of the sun was somewhat vague, and further investigation is required to adequately illustrate the process.

![Figure 9: A photograph looking to the southeast from the viewpoint used for all analyses in this paper. Note the clear visibility in the area in the immediate vicinity of the viewpoint, and the decreasing visibility as distance from the viewpoint increases. Also note the thunderstorm in the right background of the photo, and the affect on visibility it has on the area beneath it.](image-url)
Physical Properties of the Object Affecting Visibility

Since the goal of viewshed analysis is to model visibility, it is important to remember the purpose of the viewshed and take into account the properties of the objects within it that are of interest. Due to its size and colour characteristics, for example, a rabbit will disappear from view at a much closer distance than a larger animal such as a bison. If a viewshed is attempting to model visibility for the purpose of spotting rabbits, then, the viewshed should indicate as visible only those cells in which an object with the size and characteristics of a rabbit could be seen. Although other locations within the landscape may be visible, if the goal is to indicate the degree of visibility for the purposes of rabbit hunting, these locations must be classed as not visible. A few researchers have addressed this issue, some specifically with viewshed analysis (Wheatley and Gillings 2000; Ogburn 2006).

Higuchi Viewsheds

In the early 1980s, Tadahiko Higuchi, a Japanese landscape planner, attempted to address the issue of the visibility of objects in the landscape with relation to their size and background (Higuchi 1983). Higuchi developed the concept of three levels of perceptive visibility based upon the visual characteristics of a tree as they related to the distance of that tree from an observer. At short range, he stated trees could be individually identified and features of the tree could be discerned. At a middle range distance, he stated treetops could be seen, and though individual trees were no longer discernable, the forest was still visible. At long range, Higuchi wrote that only major topographic features could be seen, and the forest was no longer visible to the human observer (Higuchi 1983). Researchers such as Wheatley and Gillings (2000) have suggested incorporating Higuchi’s ideas into viewshed analyses, and Ogburn (2006) has attempted to do just that.

To create his version of the Higuchi viewshed, Ogburn modified Fisher’s (1994) fuzzy viewshed to incorporate information about the size of an object. Ogburn’s variation of Fisher’s model consisted of adjusting the value of
the $b_2$ variable of the equation based on the size of the object being viewed, and adding a multiplier to the denominator (see equation 2).

An object’s size, and its distance from the viewer, determines the limit at which human vision can accurately detect it. This limit can be determined by measuring the visual angle occupied by the object in the viewer’s field of vision. The limit of normal human vision is reached when an object subtends 1’ of visual arc (Ogburn 2006). Ogburn used this trait to determine a value for the $b_2$ variable in the distance decay function. To accomplish this, he calculated a multiplier ($a$), based on the visual angle occupied by an object, using equation 3.

$$a = \frac{1}{2 \tan \left( \frac{\beta}{2} \right)}$$

(3)

Where:

- $a$=distance multiplier to determine value of $b_2$ based on object size
- $\beta$=visual angle occupied by the object being viewed

Since the goal was to determine the limit of human vision, an angle ($\beta$) of 1’ was used. When the resulting value of $a$ was then multiplied by the size of the object in question, the maximum distance of visibility of that object was determined. Ogburn then used this value for the variable $b_2$. However, since $b_2$ is meant to be the crossover point (distance, when added to $b_1$, at which visibility drops to 50%) and not the point of visual extinction, Ogburn added a multiplier to the denominator to compensate (Ogburn 2006). The result of these operations, when creating a model for an object of 5 m in size, is the curve, Ogburn 3, in Figure 7, and the fuzzy viewshed illustrated in Figure 8.

Ogburn’s procedure does not appear to be an ideal solution to the difficulty of using viewshed analysis to model visibility as it relates to human visual acuity and object size. His use of $a$, which is the distance of visual extinction of an object, as a value for $b_2$, which is the crossover point and not the point of visual extinction, for instance, may produce a viewshed that overestimates the degree of visibility within a landscape. Also, he is not able to
take into account the reflective nature of the object in question, or its relationship
to its background. A green object in front of a blue background, for example, will
be visible at a much greater distance than the same object in front of a green
background. Still, his method is the first attempt at incorporating Higuchi’s theory
into viewshed analysis, and does provide a basis upon which to build.

Observer Imposed Restraints on Visibility

The final category affecting visibility, observer imposed restraints, can
be divided into physiological restraints and psychological restraints.
Physiological restraints are those which physically limit the visual acuity of the
observer, while psychological restraints are cognitive limitations imposed by the
observers background or culture.

Human Visual Acuity

This category primarily deals with how well the observer can see. A
viewshed analysis is intended to show the area visible from any given viewpoint,
yet there is no easy way to incorporate into the model the level of the observer’s
eyesight. As noted near the beginning of this paper, binary viewshed analysis
assumes the ability of unlimited vision. Human vision, however, has limits.
Observers may suffer from near sightedness, far sightedness, have cataracts,
astigmatism, or suffer any of a myriad of other visual impairments that can affect
their ability to see a landscape. Despite this, there has been very little, if any,
work published regarding GIS viewshed analysis as it relates to the varying ability
of humans to see.

Culturally Influenced Concepts of Landscape and Cognition

What people see is often limited as much by their cultural background
as by the physical background in which they reside. Many times people having
different cultural experiences see different things when looking at the same
landscape. After conducting research in Sicily, in which he examined how
different people perceive their landscape, Fitzjohn (2007) concluded:
“how something is viewed is not necessarily dependent on how visible it is or how much can be seen from the location, [and] what is significant in a region is not simply what is visible or visually stimulating. In fact, even those who live in the vicinity of the most prominent and highly visible feature in a region do not necessarily perceive it.”

These findings support the view of philosophers such as Gibson (1979), who feel that what we see in the world is dependant upon both the environment and perceiver, and that material objects only afford properties of visibility in the correct context. Sartre (Sartre and Cumming 1965) has gone even further, stating that our understanding of space resides within us, only manifesting itself when we encounter that place, with the result it can become “impossible to distinguish between what is felt and what is perceived.”

Much research has been conducted trying to identify and quantify how humans see and perceive space (Llobera 1996; Ayala and Fitzjohn 2002; Fitzjohn 2007; Llobera 2007). Some researchers have even attempted to use GIS to model the cognitively limited human perceptions of space and landscape (Gaffney, Stancic et al. 1996; Germino, Reiners et al. 2001; Llobera 2001; Llobera 2003). The ability to model this complex phenomenon with viewshed analysis, however, has yet to meet with much success.

**Conclusion**

Viewshed analysis is a powerful analytical instrument within the GIS toolbox, and has great potential for landscape visibility modeling. Unfortunately, it needs further development before realizing its full potential, and the fuzzy viewshed can help with that realization. Before that will happen, however, there needs to be further refinement of fuzzy viewshed analysis. The intricacies of the distance decay function, for example, need to be explored, and real world tests of the various modeling functions need to be conducted. The inclusion of visually related information from other fields is one area of investigation that has received very little attention, and should be explored prior, even, to further experimentation with current distance decay functions.
The level at which the incorporation of Higuchi’s visual theories into viewshed analyses for the purposes of creating object specific viewshed models is, at present, less than ideal, but does show promise and should be pursued. The successful viewshed modeling of observer imposed restraints on visibility, on the other hand, appears a long way off. One of the prime difficulties with this aspect of viewshed analysis is there is no general agreement on what constitutes human perception of the landscape. Until there is agreement on just what should be modeled, it is difficult to see any resolution on just how to model it.

The primary focus of this paper was modeling environmental limitations on visibility with fuzzy viewshed analysis. Another viewshed procedure deserves mention, though, that of probable viewshed analysis . While little attention was paid to the probable viewshed in this paper, it does appear to be important for dealing with error, and DEM uncertainty. The combination of fuzzy viewsheds and probable viewsheds will be a powerful analytical tool for anyone conducting landscape visibility analysis with digital elevation models.
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