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Research Paper

Visibility analysis of oceanic blue space using digital elevation models

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ABSTRACT

Published evidence shows that views to blue spaces (e.g. ocean, lake, and river) have positive effects on humans' health and mental well-beings. However, quantitative assessment of blue space visibility is challenging for large spatial areas with complex terrain or built environment. The assessment approach introduced in this study applied an innovative sampling strategy which generalizes blue space as a lattice of points and calculate visibility of all the points within a continuous area. Compared to traditional viewpoint-based visibility analyses, this approach can assess blue space visibility over a large area at a fine spatial resolution. The raster output can be overlaid with data recorded at different spatial units to study the associations between blue space visibility and socio-economic and health disparities. Additionally, this approach can be applied to assess impact of buildings to blue space visibility over space by comparing outputs generated from different digital elevation models (DEM). The utility of this approach was demonstrated in a case study in the island of O'ahu, Hawaii, which finds that: (1) wealthier and older people possess higher share of ocean visibility; (2) man-made buildings have caused large shrink and redistribution of ocean visibility; (3) high-rise buildings have particularly high and extensive impact to ocean visibility. The findings suggest that improved environmental assessment processes and planning policies are needed to mitigate the inequality of visible blue space in different population groups and preserve the shrinking visible blue space in the process of urban development.

1. Introduction

The belief that viewing natural environment (such as water and vegetation) can ameliorate stress and illness dates back to the early ages, which influenced the landscaping of early cities in Persia, China and Greece (Marcus & Barnes, 1999). Contemporary psychological studies confirmed the positive effects of viewing natural scenes on stress reduction compared with viewing scenes of built environment (Ulrich, 1981, 1999; Velarde, Fry, & Tveit, 2007). Particularly, views to the aquatic elements (e.g. ocean, lake, and river) in the natural environment are often perceived with higher restorativeness (Laumann, Gärling, & Stormark, 2001), positive influence on psychophysiological states (Ulrich, 1981, Laumann, Gärling, & Stormark, 2003), and stress-reducing and mood-enhancing effects (Karmanov & Hamel, 2008). Such restorative and healing aquatic environments are referred to as blue space. The emotional, healing and restorative effects of visible blue space are systematically reviewed in (Völker & Kistemann, 2011). Considering the increasing threat of stress-related diseases to our society, more attention should be paid to the benefits of visible blue space on the public mental well-being and environmental injustice associated with unequal share of visible blue space in different population groups. Investigations to these issues can be facilitated by a quantitative assessment of visible blue space in people's living environment.

The economic value of views to blue space has been widely recognized. Environmental scenes containing water are associated with higher perceived attractiveness and higher willingness to pay or/and visit than those without water (White et al., 2010). For instance, hotel rooms and residential homes with a view of blue space are higher priced (Luttik, 2000; Lange & Schaeffer, 2001). In the city of Honolulu, Hawaii, around 81% of serious inquiries for home purchase express a desire for ocean views (Krischke, 2017). In the meantime, views to blue space are dynamically changing in the process of urban development. Waterfront buildings may create views of blue space for residents in the buildings, but interrupt views in other areas. The importance of preserving scenic landscape (including blue space) has been recognized at the policy level. The National Environmental Policy Act (1969) has determined preserving the aesthetic aspect of the environment as one of the Federal responsibilities (Council on Environmental Quality, 1969). At the state level, Hawaii Environmental Policy Act of 1969 has listed 'affecting on scenic vistas and view planes' as one of the thirteen administrative criteria to assess potential environment impact of an action (Office of Environmental Quality Control, 2012). Despite the recognized importance of scenic landscape in planning documents, there is a general lack of practical methods and tools to quantify impact of man-made building to visible blue space, which is a major element of scenic landscape in many coastal cities. The social and economic implications of the change of visible blue space deserve further investigation.

Views of blue space are unevenly distributed in space. In geographical information systems (GIS), visibility analysis (also called

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viewshed analysis) can be performed in digital terrain models to determine areas visible from one or multiple specified observation locations (viewpoints). However, viewshed analysis in current GIS cannot be directly applied to assess visibility of blue space for two main reasons. First, analyzing the amount of visible blue space in an area can be computing-intensive. The computation of viewshed from a viewing area (e.g. a coastal area) to a target area (the ocean surface) includes a huge number of line-of-sight (LOS) analyses, which would result in a long processing time. Second, the output of viewshed analysis is a binary raster in which 0 stands for invisible from the observation point(s) and 1 means visible, which, however, does not consider visual significance from a human perspective. The visual significance of an object decays as its distance to a human observer increases due to the shrinking size of the object in the observer's vision, the aspect of the object (e.g. standing, laying or siding), and atmospheric interference.

This study introduced an innovative approach to assess visibility of aquatic blue space with a flat surface (e.g. ocean, lake, and calm rivers). This approach applies a reverse sampling strategy which generalizes blue space as a lattice of points and aggregates visibility of all the points within a continuous area. The computed visibility takes into account the distance and vertical aspect of blue space to observers. Compared to traditional visibility analyses based on viewpoints, this approach can calculate blue space visibility within a spatial large area at a fine resolution. The utility of the approach was demonstrated in a case study of analyzing ocean visibility on the island of O'ahu, Hawaii, which led to 5 m-resolution rasters of ocean visibility for the entire island. The derived ocean visibility rasters were then overlaid with other spatial data to analyze the relations between ocean visibility and a number of socio-economic and mental health variables. Furthermore, we demonstrated the utility of this approach in assessing the impact of man-made buildings to ocean visibility by comparing outputs generated using different digital elevation models (DEMs). The introduced approach can be potentially applied as a planning tool to assess building impacts to visible blue space in the environment. It can also benefit scientific research about the health, social disparities and environmental justice issues associated with blue space visibility.

2. Related work

Viewshed analysis (also known as visibility analysis) is a common terrain analysis function in GIS. Conventional viewshed analysis generates a binary output including visible areas (denoted as 1 s) and nonvisible areas (0 s). Viewsheds of multiple observation points can be combined to a cumulative viewshed representing the number of times a location can be seen from the observation points (Wheatley, 1995). Viewshed analysis has been widely used in terrain-based spatial modeling, such as locating the best site for an observation tower for forest fire or diseases (Lee, 1991), planning a scenic path planning in a national park (Stucky, 1998), and selecting locations for telecommunication towers (De Floriani, Marzano, & Puppo, 1994) and radar antenna (Lubczonek et al., 2011). The binary viewshed and cumulative viewshed become standard terrain analysis tools in prevalent GIS packages such as ArcGIS® and QGIS®.

However, the binary output of conventional viewshed analysis does not express the degree of visibility from a human perspective, which is termed Visual Magnitude (VM) in the field of graphic design. Iverson (1985) defined VM as a measure of visible landscape combining the distance, aspect of a land plane or object from the observer and times seen. Iverson (1985) cited the VIEWIT program developed by Travis et al. (1975) for calculating visual perception sensitivity (a similar concept to VM) based on manually digitized terrain data. Later, efforts have been made to incorporate VM into GIS-based viewshed analysis. For instance, Fisher (1994) applied fuzzy set theory to model the decreasing clarity of the view of objects in different distances due to atmospheric conditions. Similarly, Kumsap, Borne, and Moss (2005) modelled the effect of distance decay in visibility analysis for 3D forest landscape, utilizing viewshed analysis in GIS. However, these methods only consider distance decay of visual magnitude but do not take into account the relative aspect of the object to a viewer.

More recently, Domingo-Santos et al. (2011) proposed an algorithm to quantify visual exposure (a similar concept of VM) of terrain within a viewshed. Instead of a binary output, the visual exposure is described by numerical scores, according to the angle or covered surface area on the retina of an observer. Chamberlain and Meitner (2013) conducted a route-based visibility analysis that compares standard viewshed (binary output), cumulative viewshed (times seen), and VM which is evaluated by slope, aspect, and distance of a terrain to a viewer. The VM-based analysis can identify areas in landscape that are potentially more apparent and attention-grabbing seeing along a route. Nutsford's approach (2015, 2016) incorporates both distance decay and aspect of terrain surface to provide personalized visibility analysis for green and blue space. This approach was applied to estimate the visibility of blue and green spaces at centroids of meshblocks (the finest geographic division in New Zealand) as viewpoints, which is then health and social variables. However, the uncertainty of the analysis needs further evaluation, especially in a complex terrain or built environment where the visibility changes dramatically within a short distance and visibility at a viewpoint may not represent entire spatial unit (e.g. meshblock).

Computational efficiency is a long-standing challenge for viewshed analysis. s direct viewshed algorithm consists of numerous line-of-sight (LOS) analyses projected from a viewing point to all other points in the terrain. The direct algorithm (also called R3 algorithm) is inefficient as the algorithm repeats the visibility calculations of points closer to the viewing points when estimating the visibility at a farther point. Thus, the computation of R3 is proportion to not only the size of the grid, but also the distance from the viewing point (Izraelevitz, 2003). Alternatively, the R2 and XDraw algorithm make an approximation of the visibility at a point based on previously calculated visibility of points closer to the viewing point (Franklin & Ray, 1994). R2 and XDraw are substantially more efficient than R3 but are criticized for their lower accuracies (Franklin & Ray, 1994; Kaučič & Zalik, 2002). Variants of these viewshed algorithms with different optimization techniques have been developed (Izraelevitz, 2003; Andrade, Magalhães, Magalhães, Randolph Franklin, & Cutler, 2011; Feng et al., 2015). Please refer to Chamberlain and Meitner (2013) for a more extensive review of viewshed algorithms and applications.

3. Method

3.1. Digital elevation models

The DEM used for this study are processed from point cloud captured by airborne Light Detection and Ranging (LiDAR) systems. LiDAR is an active remote sensing technique that uses laser light to sample the surface of the earth, producing highly accurate x, y, z measurements which are called point cloud. Laser pulses emitted from a LiDAR system reflect from objects both on and above the ground surface. One emitted laser pulse can generate one or many returns. Digital Surface Model (DSM, such as Fig. 1, left) is generated using the highest returns from different cells of a raster. Digital Terrain Model (DTM, such as Fig. 1, right) is generated using the last returns reflected from the ground. Both DSM and DTM share a generic term digital elevation model (DEM). The specific methods of deriving DSM and DTM are documented in (Dong & Chen, 2017).

LiDAR point cloud data used to create the DEMs are publicly available in the online archive of NOAA Digital Coast (https://coast.noaa.gov/htdata/lidar1_z/). The LiDAR data were acquired from June to August 2013 and cover most low-lying coastal areas on the island of O'ahu (Fig. 2). In this study, the LiDAR point cloud data were processed into three DEMs at a 5-meter resolution. This resolution is sufficient to portray outlines of buildings on the ground and can control the data size and computational workload at a moderate level. First, a DTM was