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Modelling of Singapore's topographic transformation based on DEMs

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ABSTRACT

Singapore's topography has been heavily transformed by industrialization and urbanization processes. To investigate topographic changes and evaluate soil mass flows, historical topographic maps of 1924 and 2012 were employed, and basic topographic features were vectorized. Digital elevation models (DEMs) for the two years were reconstructed based on vector features. Corresponding slope maps, a surface difference map and a scatter plot of elevation changes were generated and used to quantify and categorize the nature of the topographic transformation. The surface difference map is aggregated into five main categories of changes: (1) areas without significant height changes, (2) lowered-down areas where hill ranges were cut down, (3) raised-up areas where valleys and swamps were filled in, (4) reclaimed areas from the sea, and (5) new water-covered areas. Considering spatial proximity and configurations of different types of changes, topographic transformation can be differentiated as either creating inland flat areas or reclaiming new land from the sea. Typical topographic changes are discussed in the context of Singapore's urbanization processes. The two slope maps and elevation histograms show that generally, the topographic surface of Singapore has become flatter and lower since 1924. More than 89% of height changes have happened within a range of 20 m and 95% have been below 40 m. Because of differences in land surveying and map drawing methods, uncertainties and inaccuracies inherent in the 1924 topographic maps are discussed in detail. In this work, a modified version of a traditional scatter plot is used to present height transformation patterns intuitively. This method of deriving categorical maps of topographical changes from a surface difference map can be used in similar studies to qualitatively interpret transformation. Slope maps and histograms were also used jointly to reveal additional patterns of topographic change.

1. Introduction

Natural processes and human activity constantly act on the topographic surface. Quantifying topographic changes and investigating natural causes and consequences have been a focus of research in various scientific domains, including studies of coasts (White and Wang, 2003; Mitasova et al., 2012), glaciers (Berthier et al., 2006; Wen et al., 2012), and mountains (Thiery et al., 2004; Maimouni et al., 2012). Beyond prediction and assessment of natural processes, topographic modelling can yield clues about the culture, technology and socio-political organization of past generations if landforms have been mainly affected by anthropogenic processes (Hesse, 2014). The relationships between topographic transformation and anthropogenic activities have also been investigated in landscape archaeology (Verhagen and Dragut, 2012). The underlying observation is that anthropogenic activities make use of and shape land at small and medium scales while topographic features restrain large-scale development, especially in the case of urbanization processes. Hooimeijer (2011) presents the case of Amsterdam and relates movements of silt and digging of drains to urban expansion, planning and institutional change. Evaluating the topography of low-lying coastal regions is extremely important in the context of global climate change and sea-level rise (Nicholls and Cazenave, 2010).

Singapore has experienced remarkable landform transformations in tandem with a rapidly rising economy, especially over the last half-century. In 2014, Singapore was composed of a main island of ca. 630 km^2 and a group of small surrounding islands of less than 100 km^2 in total. Generally the islands are low-lying, and the highest peak is 165 m. The natural landforms of Singapore have been little affected by major natural disasters and instead have been shaped mainly by urban development. The major natural process shaping the landform is landslides and less than 20 were reported greater than 10 m in height (Toll, 2001), which have contributed few to topographic changes in the whole island. Since the end of the 19th century, urbanization and industrialization processes have heavily transformed the island from agricultural areas of original tropical forests and coastal mangrove swamps into a global metropolis with 71% of its area covered by buildings and infrastructure. After Singapore's independence in 1965, large-scale foreshore reclamation and spatial optimization of the original land surface have been implemented to reconcile past and future decades of rapid population growth and related demands including

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housing and other infrastructure. By 2012, land reclamation had thus created approximately 20% of Singapore's land. This purposeful transformation is part of a strategy to build and strengthen Singapore's self-consciousness as a nation and her global and regional role as an economic stronghold and logistic hub (Ooi and Chiang, 1969; Dale, 1999; Yuen, 2011). Changes in the natural and cultural landscapes of Singapore have been a topic for researchers of oceanography, biology, water management, urban planning and regional policy (Chew, et al., 1986; Pui, 1986; Glaser et al., 1991; Teo et al., 2004). A crude mass flow estimation of sand for land reclamation has been made based on assumptions of seashore depth and rough statistics from various sources (Schulz, 2005).

The above-mentioned studies of Singapore focused on specific areas of newly reclaimed land, or the interface between new land and water. At the same time most of the available work has taken a two-dimensional (2D) view on maps and related seaward expansion of the shoreline. Three-dimensional (3D) information of height and related quantitative topographic transformation of Singapore's entire land surface has not been addressed yet in mass-flow research.

This paper proposes a new methodology to quantify topographic transformation and soil mass flows in Singapore over nearly nine decades, using two digital elevation models (DEMs) reconstructed from historical topographic maps of 1924 and 2012. The main objectives of this research are to: 1) generate DEMs based on historical topographic maps and provide the historical DEMs for urban transformation studies; 2) develop height change detection and topographic pattern identification methodologies, which can reveal more information than height change from a classical surface difference map; and 3) identify typical topographic transformation types in Singapore and provide basic mass-flow quantitative statistics.

2. Material and methods

2.1. Topographic maps and their pre-processing

Digital elevation models (DEMs) are the most common data format for topographic change detection and terrain analysis. There are many ways to efficiently generate DEMs, but remote sensing technologies are the most common one now. However, for reasons of cost, data availability and data policy, remote sensing was not feasible in our case study. Hence two series of paper-based topographic maps of Singapore were used to extract basic information including contour lines, spot heights, hydrological features and coastlines.

Singapore's topographic changes began in the 1820s, shortly after the arrival of the British who used the island as a trading post. Large-scale topographic changes only took place after a remarkable population increase during the 20th century. Based on coverage and the completeness of map content, the topographic maps of Singapore published by the Surveyor General of the Federated Malay States and Straits Settlements in 1924 were selected. The geographic situation represented in this series of maps is taken as the starting point of Singapore's landform in this paper. There are 16 map sheets and three of them have multiple insets. The primary scale of the 1924 maps is specified as “20 chains to an inch” (or “4 inches to a mile”), which is approximately 1:15 840. The elevation interval of contour lines is 25 ft, or 7.62 m. The maps were acquired from the National Archives of Singapore in the format of high-resolution digital raster images. The original maps have suffered from the tropical climate and the paper sheets show irregular distortions. Information about datum and projection is not available. Geographic grid lines are only available on one map sheet. The maps were first rectified by a second-order polynomial transformation (Brovelli and Minghini, 2012) to make the boundaries of the map frames vertically or horizontally straight. Then, topographic maps of Singapore published in 1958 and 1969 at a scale of 1:50 000 were used as references. Unchanged features, including hill peaks and road junctions and other unchanged characteristic points on roads were identified as control points. On average, 20–30 points were carefully pinpointed and used for geo-referencing on each image map, which achieved a residual error smaller than 1 mm on the paper map dimension.

Topographic maps produced in 2012 by the Mapping Unit of the Ministry of Defence of Singapore at a scale of 1:25 000 were taken as representation of the latest situation of Singapore's topographic surface. The contour interval of the 2012 topographic maps is 10 m, with 5 m supplementary in relatively flat areas. This map series was compiled and produced with newer surveying techniques under precise datum information. Because there are no reference grid lines on the maps, a second-order polynomial transformation was used to geo-reference the maps to StreetDirectory, a dataset from the Singapore Land Authority. The control points were mainly identified at street junctions and were well distributed on each map sheet. Because the quality of the original 2012 topographic maps is much better than the quality of the 1924 maps, only four to six points were pinpointed for geo-referencing each map sheet to reach a residual error less than 0.5 mm on the paper dimension.

2.2. Generation of DEMs

For both map series, contour lines, spot heights, hydrological features and coastlines were digitized. Because the ink on some of the map sheets in the 1924 series has worn away and some sheets were ragged because of folding over a long time, topographic maps from 1958 to 1969 were used as supplements to add some missing content. ESRI® ArcToolbox was used to generate hydrologically correct DEMs by enforcing water bodies into the model during interpolation. For this purpose, the streamlines must be directional lines pointing to the downstream direction (Hutchinson, 1989). The determination of the resolution of an interpolated DEM depends on the landform characteristics of the research area, and the base maps' scale and contour intervals of base maps. In this work, resolutions of 5, 10 and 20 m were tried. Visual inspection revealed that 5-m resolution generates over-interpolation (local irregular undulations) artefacts in contour-sparse areas, especially for the 2012 maps. The 20-m resolution misses many terrain details in both series of maps. Therefore a resolution of 10 m was used to generate the raster DEMs.

Because the map sheets were digitized by multiple operators at the same time, a Visual Basic Application (VBA) routine in ArcGIS was developed to merge streamlines passing through the sheets' boundaries and adjust the streamline directions wherever they are not pointing in the downstream direction. For each streamline, the routine retrieves the sequential intersection points with the contour lines it intersects, and sorts them in ascending order according to their distance to the start point. If the elevation values of the intersection points are in ascending order, the routine flips the direction of the streamline. This routine was also used to check the correctness of elevation labels of vectorized contour lines. A rule was specified that the elevation difference of two neighbouring intersection points should be equal to one elevation interval, or one supplementary elevation interval. Only contour lines intersecting streamlines were validated automatically. The remaining contour lines were checked visually according to symbols and elevation annotations.

Contour lines and spot heights on the 1924 maps are well distributed over Singapore's territory, except for the deltas of the Singapore River and the Kallang River, where many artefacts were produced during the interpolation of the DEM. The landform of these areas has been little changed, according to the series of later topographic maps and other historic sources. Height points have been introduced from 2012 topographic maps by pinpointing selected unchanged places.

2.3. Construction of surface difference map

Visual inspection of the two DEMs leads to a quick and intuitive identification of general change patterns. However, this rough assessment is