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Automated extraction of tidal creeks from airborne laser altimetry data

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SUMMARY

Tidal creeks (TCs) are transitional waterways between terrestrial and marine environments. Extracting geometric information for tidal creek networks (TCN) geometry from remote sensing is essential to understanding their characteristics, formation, and evolution. Currently, the major obstacles to automated recognition using digital elevation models (DEMs) derived from airborne light detection and ranging (LiDAR) data are low relief, varying widths, high density, strong anisotropy, and complicated patterns. Conventional methods, such as the optimal-elevation threshold method, the optimal-curvature threshold method, and the D8 method, cannot achieve satisfactory performance under these conditions. We propose an automated method for extracting tidal creeks (AMETC) using topographic features detected from LiDAR. Specifically, a multi-window median neighborhood analysis was designed to enhance depressions both in mudflat and marsh environments; a multi-scale and multi-directional Gaussian-matched filtering method was incorporated to enhance width-variant TCs; and a two-stage adaptive thresholding algorithm was implemented to segment low-contrast TCs. The AMETC was tested on two large LiDAR datasets of the Jiangsu coast with different resolutions. The quantitative assessments show that AMETC successfully extracted both small and large TCs from our study areas. The true positive extraction rate reached 95%, outperforming conventional methods. The AMETC is robust and weakly dependent on scale, and rarely requires manual intervention. Further applications suggests that the AMETC has potential for extraction of other types of channel features (e.g., badland networks and ravines).

1. Introduction

Tidal creeks (TCs) are linear/striped depressions embedded in the tidally dominated coastal landscapes. They consist of intricate systems of bifurcated channels, ultimately resulting in patterns that are among the most striking observed in natural environments. Functioning as channels for exchange sediments, nutrients, and pollutants (Pestrong, 1965; French and Stoddart, 1992), TCs propagate tidal waves, support fragile habitats (Kirwan and Mudd, 2012), and maintain delicate balances between sedimentary processes and hydrodynamics (Rinaldo et al., 1999; Allen, 2000; Lanzoni and Seminara, 2002; D'Alpaos et al., 2005; Marani et al., 2007; Mudd et al., 2010; Coco et al., 2013). Centuries of overexploitation and habitat transformation along coastal zones (Lotze et al., 2006), have jeopardized this equilibrium, resulting in a dramatically morphological adaptations of TCs. It is estimated that a total area of 13,380 km^2 of coastal zones in China have been reclaimed between 1950 and 2008, and a further 2469 km^2 of coastal reclamation is planned for 2012–2020 (Wang et al., 2014). As a consequence, salt marshes and upper intertidal zone are absence in many tidally dominated coastal zones. The morphological responses of TCs to intensifying anthropogenic disturbances, including reactivation, lateral migration, headward erosion, and bank erosion, may rework deposits, obliterating records of past environments, and posing more vulnerability to the coastal defense from waves and storms (Gabet, 1998; Hughes et al., 2009). To record changes in morphology, quantify network expansion and reduction rates, and understand future evolution trends, it is of critical importance to delineate tidal creeks precisely and objectively.

Field measurements and visual interpretation of aerial images are the two conventional methods of mapping tidal creek networks (TCNs). However, the former is greatly restricted by poor accessibility and limited tidal exposure and is limited to local coverage;

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while the latter is cumbersome, subjective, and rather impractical for repetitive observations or inspection of large areas (Mason et al., 2006). In contrast, airborne laser altimetry (Light Detection And Ranging, LiDAR) can represent TC geometry more accurately by providing high-resolution topography data (Klemas, 2011). Recent advances in LiDAR mapping have improved the efficiency of channel feature extraction. This technique has been applied to interdisciplinary research, including detection of typical channel-like TCs (Lohani and Mason, 2001; Lohani et al., 2006; Mason et al., 2006). Other applications include the recognition of channel heads (Clubb et al., 2014), moraines (Rutzinger et al., 2006), gullies (James et al., 2007; Baruch and Filin, 2011), channel-bed morphology (Cavalli et al., 2008), streams (Cho et al., 2011), coastal structural lines (Brzank et al., 2008), and surface fissures (Stumpf et al., 2013).

The methods developed in interdisciplinary studies are all pertinent to the extraction of TCs, so we considered methods designed for both TCs and other channel-like features. In general, the relevant methods can be divided into the following four categories: (1) Flow-routing models. River networks can be extracted from digital elevation models (DEMs) according to their flow accumulation grids, calculated using by the classic D8 method (Ocallaghan and Mark, 1984), the Rho8 method (Fairfield and Leymarie, 1991), the FD8 method (Freeman, 1991), or the D-infinity method (Tarboton, 1997). (2) Thresholding methods. Fagherazzi et al. (1999) extracted tidal creeks from low-resolution DEMs based on combined elevation and curvature thresholds. Lohani and Mason (2001) introduced an adaptive elevation threshold method to locate TC fragments. Rutzinger et al. (2006) used predefined windows and thresholds on curve segments for moraine extraction. (3) Methods based on mathematical morphology operations. Cho et al. (2011) detected forested streams using a bottom-hat operation. (4) High-level image processing (HLIP) methods. Mason et al. (2006) presented a semi-automatic multi-level knowledge-based approach. High-gradient pixels were found using edge detectors, and this was followed by edge association, centerline generation, network repair, and channel expansion. Brzank et al. (2008) extracted structural lines in the Wadden Sea by fitting a pre-defined surface model—a two-dimensional (2D) hyperbolic tangent curve). Stumpf et al. (2013) detected surface fissures with a combination of Gaussian filters, mathematical morphology and object-oriented image analysis.

Other methods beyond those designed for TCs may also be suitable for use. TCs are characterized by low relief, variable widths, strong anisotropy of waterway directions, and widespread distribution in inter-tidal zones. TCs are often of high density near tidal estuaries. All of the aforementioned characteristics present challenges to accurate extraction. Flow-routing models only achieve moderate performance in low-relief intertidal zones (Lohani and Mason, 2001). Thresholding and mathematical morphology methods use pre-defined threshold/mask/structure-element that reduce their adaptability and may limit them to use with low-resolution data (Baruch and Filin, 2011). HLIP methods use the geometry and geomorphology of linear features and yield reasonably good results for uncomplicated areas (Cho et al., 2011). Although HLIP is relatively promising, its automation and application require further improvements (Lohani et al., 2006).

An automated method for extracting tidal creeks (AMETC) from LiDAR DEMs based on HLIP techniques is proposed in this paper. The method will help coastal geomorphologists detect and map TCs and better understand their formation and evolution. The AMETC was developed to be weakly dependent on scale, robust, and automatic. Weak dependence on scale helps in the detection of TCs of different widths across DEMs of different resolutions. The efficient detection of high-density TCs at any orientation across vast tidal flats makes the method robust. Automation is improved because the parameters used in the AMETC should be stable enough to minimize the need for manual intervention.

2. Study area and datasets

2.1. Study area

The Jiangsu coast is located in the west side of the Southern Yellow Sea (SYS) (Fig. 1a). Its offshore area is characterized by the Southern Yellow Sea Radial Sand Ridges (SYSRSR)—the largest offshore tidal ridges on the Chinese continental shelf. Over the last few centuries, the Jiangsu coast has received large sediment loads from both the Yellow River and the Yangtze River (Wang et al., 2012), resulting in broad tidal flats (>5000 km^2 above the lowest normal low water). These tidal flats are located in a macro-tidal environment, with an average tidal range of 3.9–5.5 m (Xing et al., 2012). Two tidal wave systems, i.e., a progressive Poincaré wave from the East China Sea and an amphidromic system in the Yellow Sea, converge near the center part of Jiangsu coast, i.e., Jianggang (Ni et al., 2014). Under these hydrodynamic conditions, the mean tidal range reaches a maximum in the Jianggang area (up to 9.28 m), decreasing southward and northward (Gong et al., 2012).

In the broad Jiangsu coastal zone, intricate TCNs (Fig. 1b–c) have been sculpted by the tidal currents (especially ebb currents from tidal flats). The mean tidal creek density of the Jiangsu coast is approximately 3.61 km/km^2, and can reach a density of 13.27 km/km^2 in some tidal estuaries (e.g., Fig. 1b). A variety of drainage patterns occur in the region, including dendritic, parallel, radial, deranged, and pinnate pattern. During the past 40 years, over 2000 km^2 of tidelands along the Jiangsu coast (including 1444 km^2 of native salt marshes and 229.2 km^2 of *Spartina alterniflora* salt marshes) have been reclaimed (Zhang et al., 2004; Zhao et al., 2015). The remaining salt marshes are no more than 213.21 km^2 in total area, according to our interpretation from synchronous Landsat images (Fig. 1b–c). The mean intertidal flat width has decreased from 7.3 km to 2.9 km, and the mean elevation of the tidal flats has decreased from 1.54 to 0.31 m. As a consequence, these intricate networks are undergoing dramatic morphological changes in response to the changing physical conditions.

2.2. Datasets

Two Airborne LiDAR DEM datasets of different spatial resolutions were used for our study. Both sets were acquired at low tide.

2.2.1. Dataset A (5400 × 6700 pixels, 2.5-m resolution

The dataset covers the southern section of Jiangsu (Region A in Fig. 1a, enlarged in Fig. 1b), and the study area is approximately 226 km^2. On July 17, 2009, the LiDAR data were acquired in first-return mode by an Optech ALTM 3100 at an altitude of 1500 m and a speed of 240 km h^{-1}. The laser wavelength was 1064 nm, the laser pulse rate was 85 kHz, the scan rate was 70 Hz, and the laser footprint at nadir was approximately 30 cm. The spacing of the LiDAR points was 2 m, resulting in a gridded DEM with a cell size of 2.5 m. The root mean square error (RMSE) of the DEMs was approximately 13.5 cm (GPS-RTK synchronous validation).

2.2.2. Dataset B (11,000 × 19,300 pixels, 5-m resolution)

The dataset covers the central region of the Jiangsu coast (Region B in Fig. 1a, enlarged in Fig. 1c), and the study area is approximately 5300 km^2. The LiDAR datasets were produced by the Jiangsu Provincial Bureau of Surveying, Mapping and