Chapter 5
Volume Analysis

Coastal landform change is driven by sediment transport and redistribution of sand. In this chapter, we present techniques for mapping volumes of land mass using rectangular segments and analyzing volume evolution and redistribution in absolute and relative terms.

5.1 DEM Differencing

DEMs can be differenced to produce a map that represents the change in the elevation surface between the two time snapshots. These maps are sometimes referred to as DEMs of Difference (DoD) and can be produced in GRASS using `r.mapcalc`. For example, the total change in elevation within the Nag's Head study area from the beginning of the study period (1999) to the end of the study period (2008), which is shown in Fig. 5.1, can be can be computed by running the following GRASS commands:

```
# Purpose: Compute a DEM of Difference (DoD).
r.mapcalc \
   expression='NH_total_change=NH_2008_1m-NH_1999_1m'
r.colors map=NH_total_change \
   rules=color_elevation_diff.txt
```

Volume change per raster cell is then obtained by multiplying the elevation change by the raster cell area.

E. Hardin et al., *GIS-based Analysis of Coastal Lidar Time-Series*, SpringerBriefs
in Computer Science, DOI 10.1007/978-1-4939-1835-5_5

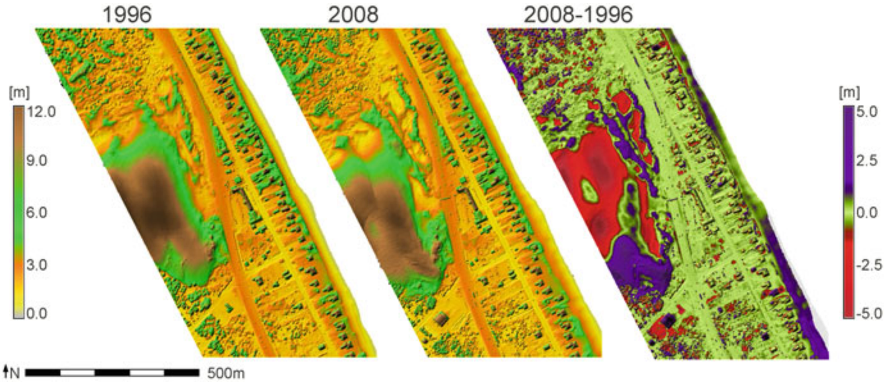

Fig. 5.1 DEMs representing the terrain at the beginning (1999) and end (2008) of the study period, as well as the difference between the two maps, representing the terrain change observed during the student period

5.2 Landscape Segmentation into Bins

To compute volumes and volume change for areas larger than the raster cell (to reduce noise and provide information more indicative of the local coastal state) but still small enough to provide information about spatial redistribution of sand, the beach-foredune area can be partitioned into the rectangular segments. These segments can be generated by combining long-shore partitions with cross-shore transects.

5.2.1 Long-Shore Partitioning

We have already derived the *core* and *envelope* surfaces as the minimum and maximum elevations measured for each raster cell. We have also delineated a shoreface area, called the *shoreline band*, as the area between the MHW contours of the core and envelope surfaces. The area within the shoreline band bounds shoreline evolution over the study period, and the width of the shoreline band measures the shoreline migration range (Mitasova et al. 2012). The shoreline band will be our first long-shore partition.

The second long-shore partition is defined inland of the shoreline band. It is bound by the core (minimum) shoreline and by a horizontal distance of 110 m inland of the core shoreline to bound the upper-beach dune section. The constant inland distance of 110 m was chosen to ensure complete lidar data coverage for each year. The area within the shoreline band and the area that extends inland of the shoreline band (Fig. 5.2) can be extracted using `r.mapcalc` in conjunction with `v.buffer`:

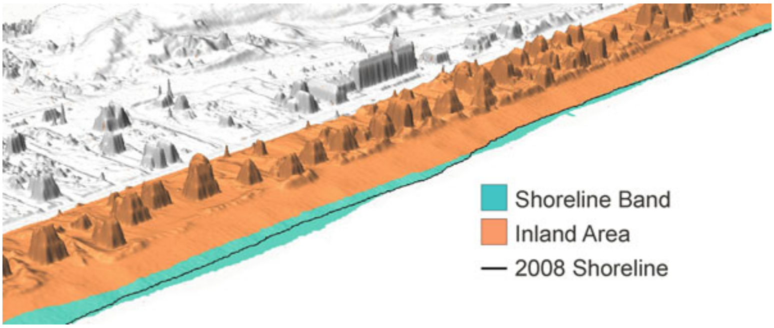

Fig. 5.2 Area within the shoreline band (extracted as the area bounded by the core and envelope shorelines) and the area that extends 110 m inland of the shoreline

```
# Purpose: Extract area within shoreline band.
r.mapcalc \
   expression=’shorelineBand=if(isnull(NH_core) && \
   !isnull(NH_env), 1, null())’
# Extract area landward of the shoreline band.
r.contour input=NH_core output=NH_core_shoreline \
   level=0.8 cut=400
v.buffer input=NH_core_shoreline \
   output=NH_core_shoreline_110mbuff distance=110
v.to.rast input=NH_core_shoreline_110mbuff \
   output=NH_core_shoreline_110mbuff typ=area use=val \
   value=1
r.mapcalc expression=’coreArea=if(!isnull(NH_core) && \
   !isnull(NH_core_shoreline_110mbuff), 1, null())’
```

The area inland of the core shoreline will be referred to as the *area with core* as opposed to the *shoreline band area* which has no core surface in it.

5.2.2 Cross-Shore Segments

In order to quantify along-shore trends, we can further partition the beach foredune system using cross-shore transects perpendicular to a baseline. The baseline can be a selected shoreline (in our example we use the core surface shoreline) or an offshore line approximately parallel with a selected shoreline. Cross-shore segments can be generated using the GRASS add-on module `v.transects`, by setting the `type` parameter to `area`.

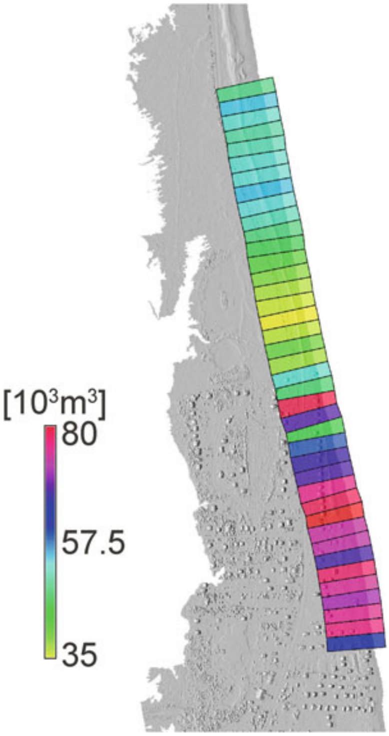

Fig. 5.3 Vector map representing the volumes for each segment area displayed over a shaded relief

```
# Purpose: Segment the DEM into cross-shore areas
# along the shoreline.
r.contour input=NH_core output=NH_core_shoreline\
   level=0.8 cut=400 --o
# v.clean and v.build.polylines were required to keep
# the contour from doubling back
v.clean input=NH_core_shoreline \
   output=NH_core_shoreline_c tool=rmsa --o
v.build.polylines input=NH_core_shoreline_c \
   output=NH_core_shoreline --o
v.transects.py input=NH_core_shoreline \
   output=NH_alongShoreSegments dleft=50 dright=150 \
   type=area transect_spacing=50 --o
```

An overlay of long-shore and cross-shore segments will create partitioning of the beach-foredune system into rectangular segments as shown in Fig. 5.3. These partitions will allow us to map and quantify the volume change along the highly dynamic shoreline band and along the upper beach-foredune segments.

5.3 Volume Estimation for Segments

Volume of mass over a given area can be estimated from a DEM by summing elevations in raster cells defining this area

$$V = A \sum_i \sum_j z(i, j) \tag{5.1}$$

where V is the volume, A is the area of a raster cell, z is the elevation of a surface, and i and j are summed over all raster cells in the area for which volume is computed. In the following example, we estimate the total volume defined by a raster surface and horizontal plane or datum over a given area using the `r.volume` command. We set a MASK to the raster map `coreArea` to limit the volume calculation to the area of interest.

```
# Purpose: Limit volume measurement to 100 m of
# shoreline.
r.mask input=coreArea
r.volume NH_2008_1m
r.mask input=coreArea -r
```

To calculate the volume for each cross-shore segment (which is a vector area), we connect a table to the vector map. Then we populate the table with statistics derived from the DEM using the `v.rast.stats` command as in the following GRASS code:

```
# Purpose: Calculate the volume in each segment.
v.db.addtable map=NH_alongShoreSegments
v.rast.stats vector=alongShoreSegments \
   raster=NH_2008_1m column_prefix=NH2008
v.db.addcolumn map=NH_alongShoreSegments \
   column='volume DOUBLE PRECISION'
# volume = raster cell area (which is 1) * sum of
# elevations
v.db.update map=NH_alongShoreSegments col=volume \
   qcol="1*NH2008_sum"
v.db.select map=NH_alongShoreSegments \
   columns="cat,volume"
```

We can then display the volumes as colored vector areas using the module `d.vect.thematic` (Fig. 5.3).

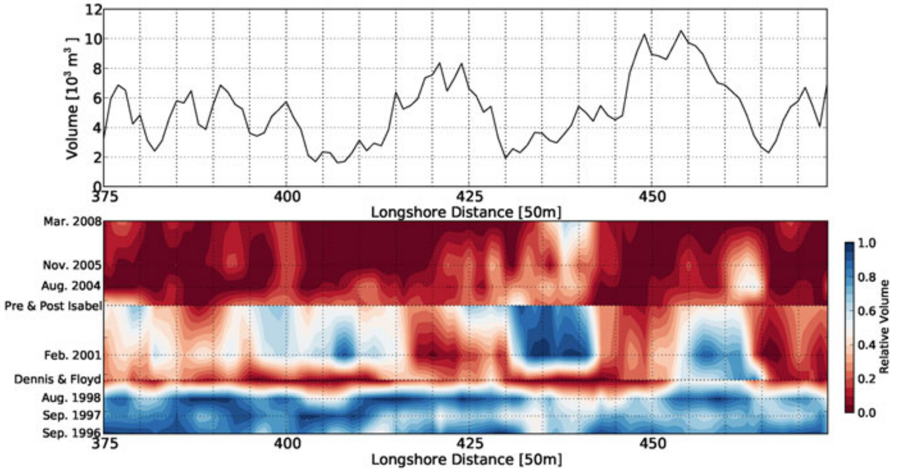

Fig. 5.4 Graph showing volumes in the shoreline band and a heat map showing volume evolution

5.4 Volume Change Metrics

Given the volume maps computed for each time snapshot, we can analyze the pattern of volume change. In addition to a standard graph showing volumes along the segments for each year (Fig. 5.4), we can compute the volume differences between any given time snapshots for all segments using vector attributes database operations or by converting the vector volumes map to raster representation and using map algebra. Evolution of volumes over time can be represented using a heat map (Tateosian et al. 2013) (Fig. 5.4).

Relative volumes, normalized according to the volume of the dynamic layer, allow us to analyze the volume of each segment relative to the minimum (core) and maximum (envelope) volume and how this pattern has changed over time. Relative volume in the upper beach—foredune area (area with core, inland from the core shoreline) is defined for each time snapshot and for each segment j as follows:

$$\hat{V}_{ij} = \frac{V_{ij} - V_{cj}}{V_{ej} - V_{cj}}, \tag{5.2}$$

where $\hat{V}_{ij}$ is the relative volume for the ith survey in the time series, V_{ij} is the volume under the ith elevation surface, V_{ej} is the volume under the envelope surface, and V_{cj} is the volume under the core surface. Volumes were calculated relative to MHW. This relative volume can then be calculated by running the following GRASS commands:

```
# Purpose: Calculate relative volume.
r.mask input=coreArea
r.mapcalc\
  expression="NH_2008_volRel_inland=\
  (NH_2008_1m-NH_core)/(NH_env-NH_core)"
r.univar NH_2008_volRel_inland
 [..]
 mean: 0.442037
 [..]
r.mask input=coreArea -r
```

Relative volume within the shoreline band (between the core and envelope shorelines) is defined for each time snapshot and for each segment j as follows:

$$\hat{W}_{ij} = \frac{W_{ij}}{W_{ej}}, \tag{5.3}$$

where $\hat{W}_{ij}$ is the relative volume for the ith survey in the time series, W_{ij}, is the volume under the ith elevation surface, and W_{ej} is the volume under the envelope surface within the shoreline band. By definition, the core surface does not exist within the shoreline band above MHW and therefore the core volume W_{cj} is equal to zero. Relative volume in the shoreline band can be calculated by running the following commands:

```
# Purpose: Calculate relative volume in the shoreline
# band.
r.mask input=shorelineBandr
r. mapcalcexpression=\
 "NH_2008_volRel_shoreband=NH_2008_1m/NH_env"
r.univar NH_2008_volRel_shoreband
 [..]
 mean: 0.863858
 [..]
r.mask input=shorelineBand -r
```

Although it is typical to report volumetric analysis in absolute values in units of m^3 (Burroughs and Tebbens 2008; White and Wang 2003), analyzing and visualizing relative volume offers some advantages: First, the core surface gives a lower bound on terrain evolution, and for this reason, the core is a logical datum. Removal of the core values from the analysis highlights changes, (e.g., in areas where the volume of transported sediment is much less than the volume of the stable sediment under the core surface). Second, because the core represents a minimum bound on volume evolution, volumes near the core volume represent worst case scenarios observed in the time-series. Finally, because the terrain evolved exclusively within the dynamic layer, visualizing volume as a percent of the dynamic layer volume allows for an

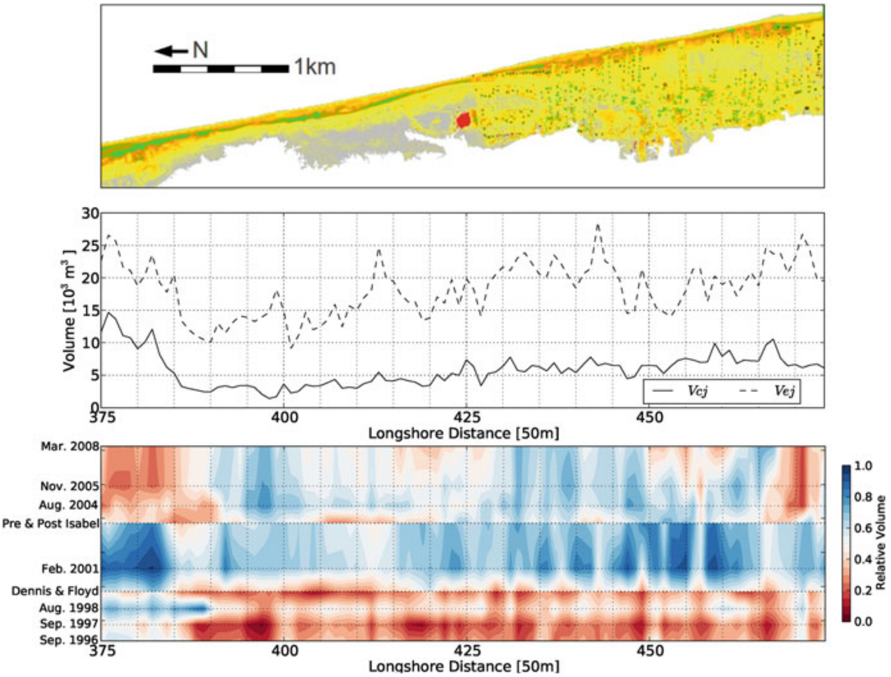

Fig. 5.5 Graph showing core and envelope volumes, and heat map showing relative volume evolution

at-a-glance determination of the present state relative to the minimum and maximum observed over the study period. Evolution of the relative volumes can be visualized using a heat map (Fig. 5.5).

References

Burroughs, S. and Tebbens, S. (2008). Dune retreat and shoreline change on the Outer Banks of North Carolina. *Journal of Coastal Research*, 24:104–112. DOI: 10.2112/05-0583.1.

Mitasova, H., Overton, M., Oliver, R., and Hardin, E. (2012). Ocean shoreline migration. Technical report, Albemarle-Pamlico National Estuary Program.

Tateosian, L., Mitasova, M., Thakur, S., Hardin, E., Russ, E., and Bruce, B. (2013). Visualizations of coastal terrain time-series. *Information Visualization*, 13:266–282.

White, S. and Wang, Y. (2003). Utilizing DEMs derived from LIDAR data to analyze morphologic change in the North Carolina coastline. *Remote Sensing of Environment*, 85(1):39–47. DOI: 10.1016/S0034-4257(02)00185-2.