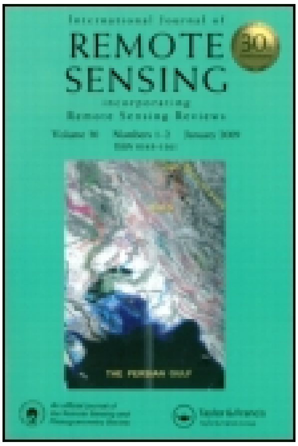

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An approach to regional wetland digital elevation model development using a differential global positioning system and a custom-built helicopter-based surveying system

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Accurate topographic data are critical to restoration science and planning for the Everglades region of South Florida, USA. They are needed to monitor and simulate water level, water depth and hydroperiod and are used in scientific research on hydrologic and biologic processes. Because large wetland environments and data acquisition challenge conventional ground-based and remotely sensed data collection methods, the United States Geological Survey (USGS) adapted a classical data collection instrument to global positioning system (GPS) and geographic information system (GIS) technologies. Data acquired with this instrument were processed using geostatistics to yield sub-water level elevation values with centimetre accuracy (±15 cm). The developed database framework, modelling philosophy and metadata protocol allow for continued, collaborative model revision and expansion, given additional elevation or other ancillary data.

1. Introduction

The Florida Everglades region of South Florida, USA (see figure 1) is a unique and important wetland system that historically stretched from the southern rim of Lake Okeechobee (the second largest freshwater lake in the USA) to the Florida Bay (Steinman *et al.* 2002). Everglades land cover is composed of mosaics of open water and wet prairie, as well as herbaceous, shrub and forested wetlands (Gunderson 1994). The majority of its area is covered by wet prairie and sawgrass marsh (Jones *et al.* 2001), and it has long been referred to as the 'river of grass' (Douglas 1947). Numerous government agencies and non-government organizations are collaborating to restore and protect Everglades resources. Accurate data on topography are critical for Everglades process research and resource management (Department of Interior (DOI) 2005). These data are required to monitor and simulate water levels, water depths and hydroperiods and are used in scientific research on hydrologic and biologic processes. Here, the processes used to collect elevation data region-wide for resource management/research and the approach used for regional digital elevation model (DEM) development, evaluation and refinement are illustrated. First, the inadequacies of existing regional elevation models are described and the impediments to

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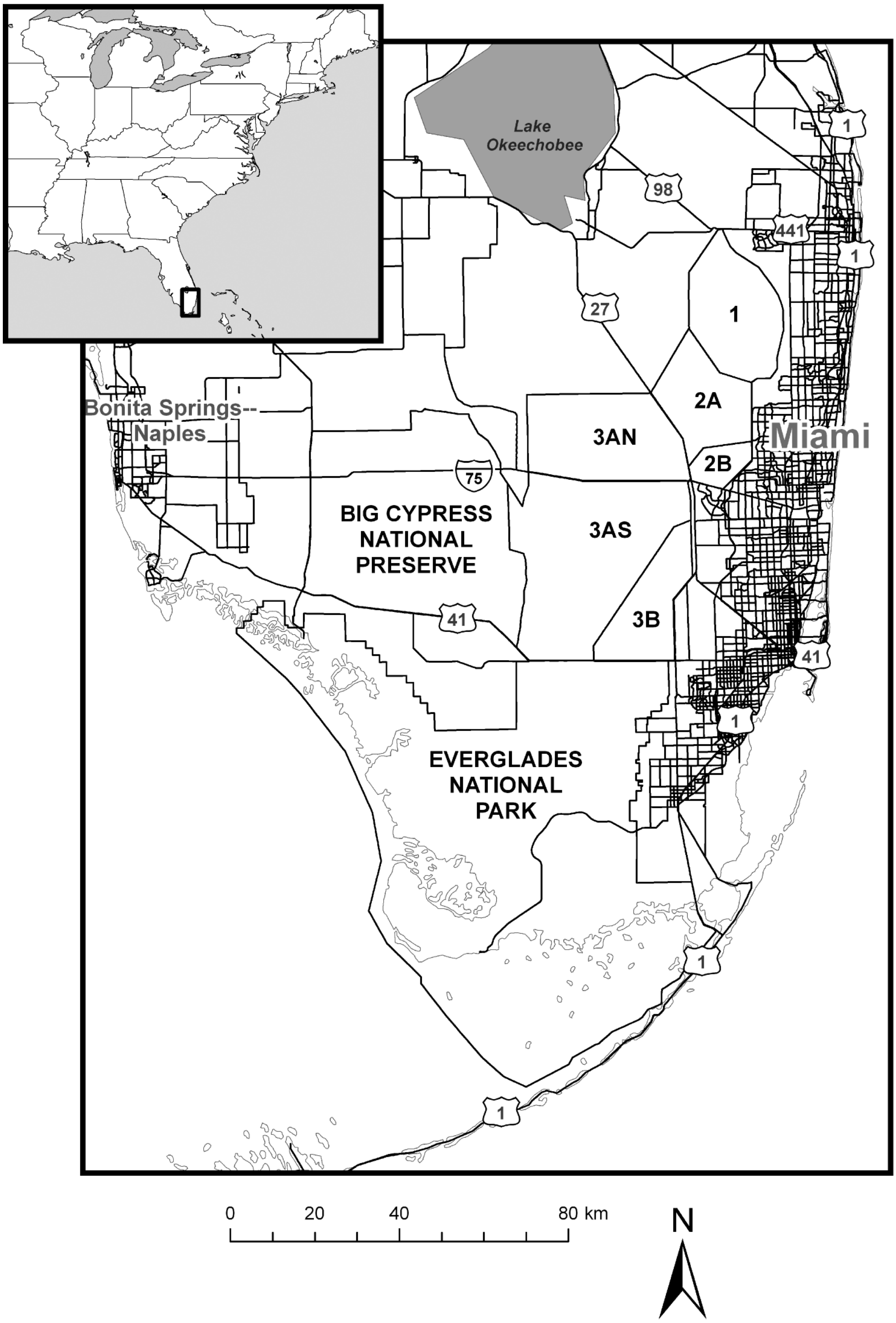

Figure 1. Study area location (inset) and the major resource management sub-areas (e.g. '1' for Water Conservation Area 1 or WCA1) within which individual elevation models are developed. Sub-areas are divided by levees and canals that cause abrupt changes in elevation. Segmentation by these sub-areas accounts for these changes as well as differences in sub-area geomorphology.

conventional remote-sensing approaches are discussed. Then, specifics regarding the United States Geological Survey (USGS) solution to sub-water surface ground elevation data collection are provided. Next, the approach developed for DEM research, evaluation and revision is outlined, followed by an example of its use. Finally, conclusions and future research directions are indicated.

2. Data requirements

Existing regional elevation models, such as the National Elevation Database (NED) and the Shuttle Radar Topography Mission (SRTM), have relatively fine horizontal resolution (30 m). However, their target vertical accuracies (root mean square errors (RMSEs) of 7.5 and 16 m, respectively) and readily observable differences (figure 2, table 1) show that they are insufficient for restoration requirements. Furthermore, while high-resolution digital elevation data have been collected for limited areas of

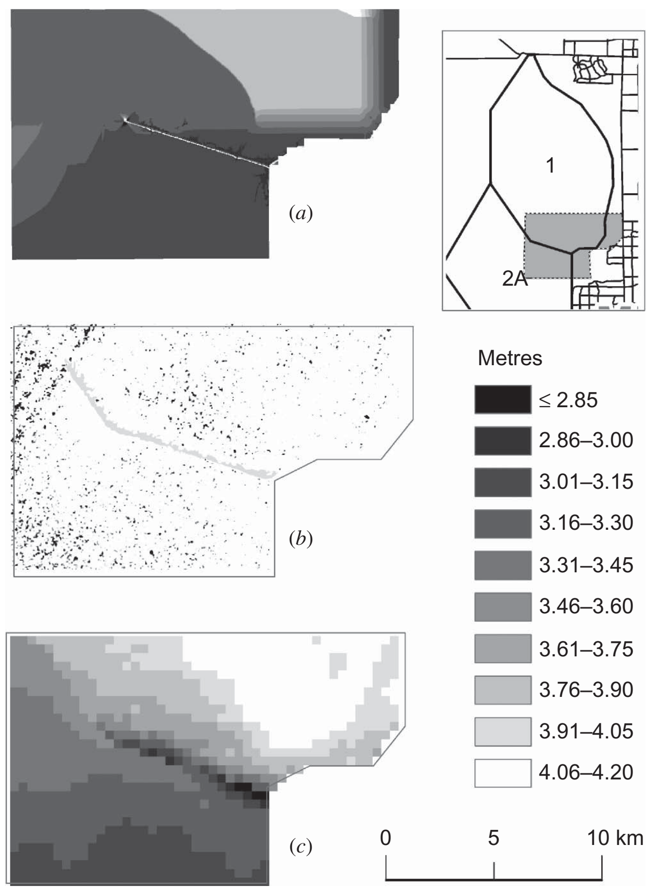

Figure 2. Excerpts from three digital elevation models (DEMs) for the boundary area between Water Conservation Area 1 (WCA1) and WCA2A show that standard DEM products lack sufficient vertical accuracy for Everglades restoration science. (*a*) National Elevation Dataset data (NED), (*b*) the Shuttle Radar Topography Mission (SRTM) and (*c*) the DEM developed through the method described here (Everglades Depth Estimation Network (EDEN)). The DEM statistics are in table 1.

Table 1. Statistics for the same geographic subset of the three publicly available Everglades regional DEMs shown in figure 2.

DEM product	Min (m)	Max (m)	Mean (m)	Std Dev (m)
NED	1.05	8.49	3.32	0.29
SRTM	−9.00	23.00	6.70	1.86
EDEN	2.57	4.26	3.59	0.40

Note: DEM, digital elevation model; NED, National Elevation Dataset; SRTM, Shuttle Radar Topography Mission; EDEN, Everglades Depth Estimation Network; Min, minimum; Max, maximum; Std Dev, standard deviation.

the Everglades (Houle *et al.* 2006), there are no representative, high-resolution data sets that would allow for direct and rigorous landscape-scale geostatistical analysis of elevation across the various Everglades landscapes and for the dominant ridge and slough landscape in particular. If one assumes that the primary determinant of Everglades vegetation is elevation, geostatistical analysis of remotely sensed indices of vegetation density in ridge and slough areas (Jones 2001) and other multi-scale analyses of vegetation associations based on visually interpreted aerial photography (Obeysekera and Rutchey 1997) suggest that sampling resolutions of 30 to 100 m are necessary to describe variations in Everglades elevation at the landscape scale. However, the primary uses envisioned for the highly accurate elevation data described here are regional-scale hydrodynamic and aquatic modelling. Previously, Everglades hydrodynamic models were based on elevation data with a horizontal spacing of 3.22 km (MacVicar *et al.* 1984, South Florida Water Management District (SFWMD) 1997). Given discussions with the Everglades hydrologic modelling community and considering the need to balance hydrodynamic modelling plans against data collection costs, a horizontal distance between collected elevation points of approximately 400 m and a sub-water surface ground elevation vertical accuracy of ±15 cm for each point were specified as minimum requirements for the elevation data.

These accuracy requirements could be met by surveyors using differential global positioning systems (GPSs) and airboats. However, a pilot study in which approximately 11 000 elevation points were collected by contractors demonstrated the disadvantages of such an approach for region-wide coverage. First and foremost, a grid-based pattern of airboat use throughout the entire Everglades system could have significant negative impacts on Everglades ecosystems. The airboat traffic required for a conventional ground-based survey would create a grid pattern of impacted herbaceous vegetation that could affect water flow as well as habitat conditions in this low-gradient environment where vegetation resistance is a primary determinant of flow velocity and pattern. Second, some areas are still not accessible via airboat or easily surveyed on foot. (Tree islands in the area of the ground-based experiment were not surveyed for this reason.) This leads to unwanted gaps in data coverage. Third, the current protected land area of the Greater Everglades is more than 561 000 ha. It would be too time consuming and expensive to cover such a large and difficult region as the Everglades using field surveying methods. With regard to remote-sensing techniques, expansive areas of the Everglades surface are typically inundated (some with water of high tannin content), have dark peat soils and are obscured by periphyton and/or vegetation. These characteristics make the consistent use of conventional remote-sensing methods for collecting elevation data with ±15 cm accuracy, such as photogrammetry, light detection and ranging (LiDAR) and interferometric synthetic aperture radar (InSAR) problematic. For example, in 1999, airborne LiDAR data were collected over the entirety of Water Conservation Area 3 (noted by a '3' in figure 1) under optimal conditions: during a drought and following an extensive and intense fire when water and vegetation coverage were at their absolute minimum. Because of a dark peat substrate, some standing water, unburned vegetation and systematic errors in the LiDAR instrument, the resulting DEM failed to meet study accuracy requirements (unpublished data). In addition, while InSAR techniques have been used to estimate Everglades water-level changes (Wdowinski *et al.* 2008) and vegetation heights (Simard *et al*. 2006), sub-water surface ground elevations were not available through InSAR. An alternative solution was needed.

3. Elevation data collection

To meet the accuracy requirements given the challenging Everglades environment, the USGS adapted a helicopter-based system known as the Airborne Control System, originally developed in the 1960s (Loving 1963, American Society for Photogrammetry and Remote Sensing (ASPRS) 1980), to differential GPS technology (figure 3). This adaptation, named the Airborne Height Finder (AHF), measures sub-water, terrain surface elevation in a non-invasive and non-destructive manner. Using a 1.4 kg bob, the system automatically collected an observation when resistance on the plumb line reached a prescribed amount that testing has shown results in appropriate penetration of surface and submerged herbaceous vegetation cover. Reliance on this set resistance value also ensured that the instrument consistently compressed flocculant materials and mud that might lead other techniques to provide false 'ground' returns (e.g. assuming sufficient LiDAR laser energy can penetrate vegetation and water cover and return to the sensor). Finally, as the helicopter typically hovered between 3 and 6 m above the surface for Everglades data collection, the operator ensured that the plumb bob did not hang up on hardwood (such as mangrove root) and always made contact with the ground surface.

Tests were conducted to assess how well the AHF measured elevation relative to the ±15 cm vertical accuracy specification. For example, all (17) available National Geodetic Survey (NGS) first-order benchmarks in the Everglades National Park (ENP) were measured at two different helicopter hover heights. The average difference between the AHF measured elevations and the NGS data across the two hover heights was approximately 3.3 cm, with an RMSE of 4.1 cm (summary statistics for both AHF hover heights are provided in table 2). To ensure sufficient accuracy throughout the ENP, the USGS created a geodetic control network that allowed the AHF to be within 20 km of two reference stations while in operation. Using the AHF and this network, a series of survey campaigns collected sub-water surface elevations at an approximate spacing of 400 m across the ENP, the water conservation areas (WCAs) and a portion of the Big Cypress National Preserve (BCNP). In some cases, AHF data have replaced elevation values measured through airboat, ground-based surveys and LiDAR. The AHF has also been deployed to address specific terrain-related questions identified by Everglades hydrologic and biologic research. For example, the replacement of the existing DEM with AHF data in SFWMD hydrodynamic models resulted in 'pooling' on the downstream side of Highway 41 (see figure 1) that was not previously simulated

Figure 3. The Airborne Height Finder (AHF) installation. The AHF is positioned on the left-hand side of the helicopter in front of the AHF operator and the global positioning system (GPS) containing the flight line information is positioned on top of the instrument console where it is visible to both the pilot and the AHF operator. The AHF plumb-bob and calibration plate are mounted outside the helicopter door.

Table 2. Statistics of residuals of National Geodetic Survey first-order benchmarks minus AHF measured elevation.

Hover height (m)	*N*	Min (m)	Max (m)	Mean (m)	Std Dev (m)
3	15	−0.065	0.086	−0.0062	0.0402
6	16	−0.059	0.072	0.0006	0.0423

Note: AHF, Airborne Height Finder; *N*, number of samples; Min, minimum; Max, maximum; Std Dev, standard deviation.

or expected. To test whether AHF data were in error, a special campaign for additional data along six north–south transects across Highway 41 between the WCAs and the Park showed that a measurable 'ridge' existed south of the Highway (unpublished data). As these campaigns progressed and AHF data were applied, the importance of collecting land-cover information associated with each AHF data posting was recognized. For the northernmost WCAs, the system and procedure was modified so that the operator could attribute each collected point with a land-cover value based on

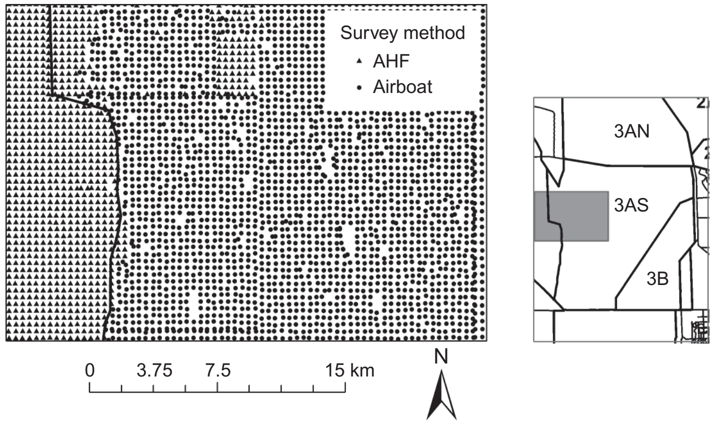

Figure 4. A subset of the High-Accuracy Elevation Database (HAED) along the Big Cypress National Preserve (BCNP)/Water Conservation Area 3 (WCA3) boundary. Circular symbols mark points collected via airboat. Note that data gaps occur where upland/tree island areas were inaccessible via airboat. Triangular symbols mark points collected using the Airborne Height Finder (AHF). Upland and highly vegetated areas do not pose the problems for the AHF that they present for ground- and LiDAR-based surveys, respectively.

categories developed by US Fish and Wildlife and National Park Service collaborators. The total number of points collected by the AHF was approximately 43 000. When combined with ground survey data, the resulting database was referred to as the High-Accuracy Elevation Database (HAED). The data (a very small subset is shown in figure 4) and associated metadata are distributed publicly without fee to the user via the Internet (sofia.usgs.gov). Summary statistics calculated from the entire HAED illustrate the low relief environment of the Everglades region (minimum: −3.43 m, maximum: 5.19 m, mean: 1.38 m and standard deviation: 1.31 m).

4. Elevation model development

The first Everglades region-wide DEM derived from the HAED was produced using the ESRI ArcGIS TOPOGRID algorithm. (Please note, use of product and trade names is for illustrative purposes only and does not represent an endorsement by the US government.) TOPOGRID relies on spline interpolation modified to produce a 'hydrologically correct' DEM (Hutchinson 1989). TOPOGRID is an exact interpolator, meaning elevation values at the locations of input points exactly match those of the input points themselves. However, away from input points and in the absence of break lines and other information, it can generate false peaks and pits along regions where drastic changes in measured elevations occur or where there are long distances and large spaces between input data points. While TOPOGRID produced an aesthetically pleasing regional elevation map and represented general trends in Everglades topography, closer visual inspection uncovered unacceptable errors. A multistage and iterative approach was therefore devised (table 3) to yield more realistic and useful regional elevation models for the Everglades.

The first step in the approach may include filtering of the HAED to create application-specific input data (an example will be illustrated in §5). Before the Everglades were developed for agriculture and industry, water flowed from Lake

Table 3. The iterative approach used to explore, select, produce and revise a regional digital elevation model (DEM) from multiple models developed at subregional scale.

Step	Procedure
1	**FILTERING.** Filter input elevation data to remove outliers or customize input set for specific application.
2	**SEGMENTATION.** Segment input elevation data by management, ecological or landscape unit sub-areas.
3	**RANDOM EXTRACTION.** Randomly select some portion (e.g. 15%) of each sub-area's input points for withholding from model development/use in true validation (Step 6).
4	**INTERPOLATION.** Interpolate model elevation for each sub-area using various techniques.
5	**CROSS VALIDATION.** Cross validate within each modelling technique to assess interpolator sensitivity to model parameters. Best performing parameters are selected.
6	**TRUE VALIDATION.** Compare elevations produced using 'best' interpolation parameters for each modelling technique against elevation values withheld during model development (i.e. the result of Step 3).
7	**MODEL SELECTION.** Choose the best model for each sub-area based on true validation assessments.
8	**SUB-AREA DEM PRODUCTION.** Generate DEMs using all available input points in each set of selected sub-area model (interpolation technique) and associated parameters.
9	**REGIONAL MODEL CREATION.** Merge sub-area models to produce a single, region-wide result.
10	**DEM PERFORMANCE EVALUATION.** Assess model utility within the context of particular applications such as depth and hydroperiod modelling, hydrodynamic modelling, and/or comparison against other ancillary data (e.g. field data and personal expertise).
11	**DEM DOCUMENTATION AND DISTRIBUTION.** Produce standardized metadata, develop visualizations and provide Internet access.
12	**DEM REVISION.** Improve models at the sub-area scale (i.e. return to Step 1) as new input data or improved segmentation templates become available or as problem areas are identified through performance evaluation/applications of the DEM.

Okeechobee southwestwards towards the Florida Bay and Gulf of Mexico. Now, the Greater Everglades are composed of numerous subdivisions that are separated by canals, roads and levees (figure 1) that obviously affect water flow and depth. In addition, feedbacks among hydroperiod, vegetation production and sediment accretion influence the development of Everglades topography (Ogden 2005). It is therefore most appropriate to segment the HAED and develop elevation models for subunits of the Everglades. The second step is therefore segmentation of the input HAED.

In preparation for what is termed split-sample (Declercq 1996) or true validation (Voltz and Webster 1990), potential input points are randomly selected and withheld from model development. This technique has often been applied iteratively, each time withholding an increasingly greater number of points to assess model dependence on elevation data density (Smith *et al.* 2005). In the case of the HAED, point density is already relatively sparse, but true validation allows rigorous and standardized comparison of a wide variety of interpolation techniques (e.g. both exact and inexact) in the absence of any other independent validation data. These validation data are therefore kept aside, while in the next step, various surfacing algorithms are applied to each sub-area, while individual model parameter sets are evaluated through cross validation. That is, all points not randomly extracted in step 3 of table 3 are used in model parameterization. Individual points are iteratively removed, a given model is applied and differences between modelled and measured values are calculated. Results of all iterations are aggregated to produce error statistics. Then, in step 6 of table 3 (the simple or true-validation process), interpolation approaches that perform best can be compared against withheld data. At this point, a 'best performing technique' is selected for each sub-area and applied to all available data including previously randomly selected points. During this process, cross validation remains a valuable tool to assess model stability and performance given the added input data. Resulting sub-area models are merged to form a regional one.

While statistics provide part of the information needed for model comparison, model utility is best assessed through application. The next step in the approach is to evaluate DEM performance in an applications framework. Since this step typically relies on collaboration across scientific disciplines and institutions, DEM documentation, visualization and distribution are important components of the approach. Geographic information system (GIS) cataloguing capabilities are used to provide metadata on the intended use, date of production, modifications from previous DEM versions and spatial characteristics for the DEM. This approach is iterative and flexible. It can be repeated for individual or all sub-areas as better subregional segmentation methods are devised, erroneous points are identified, additional data are collected or improved interpolation techniques are developed. If the process is applied only to a chosen sub-area, the results of that new analysis can be inserted into the existing regional one.

5. The Everglades Depth Estimation Network example

The outlined approach to HAED-based DEM development, evaluation and revision can be illustrated using an example of the Everglades Depth Estimation Network (EDEN) project. The EDEN is an operational system (Telis 2006) that relies on interpolation of daily median values of hourly water levels (Palaseanu and Pearlstine 2008) collected from approximately 250 gauges in the Everglades in combination with a DEM to help guide restoration research and resource management. (For more information on EDEN see sofia.usgs.gov.) As a primary application for EDEN is aquatic species monitoring, research and modelling, priority is placed on the estimation of water depth in slough environments. This is accomplished through the use of the EDEN grid, a 400 m resolution mesh covering all of South Florida that provides a standard foundation for EDEN elevation and water modelling (Jones and Price 2007), and for which water depth and hydroperiod values are calculated.

The first step in EDEN DEM development was the filtering of the HAED to remove unrepresentative 'upland' elevation points that would introduce a non-slough, positive bias in elevation (and subsequent depth) estimates. These assignments are made on the basis of vegetation information. Through EDEN development, vegetation information sources have evolved from USGS GAP analysis project (gapanalysis.nbii.gov) assemblages to vegetation composition derived through the interpretation of airborne imagery by the SFWMD (Rutchey *et al.* 2008) and to land-cover assignments made to each AHF point by the operator during collection. Vegetation data were recast into upland and non-upland classes based on interpretation of assemblages or composition. Then, the percent upland area of each EDEN grid cell was tabulated. If a cell was less than 33% upland, but the AHF data posting was collected in an upland area, the AHF point was deemed unrepresentative for EDEN water-depth-focused simulations, and the cell was removed from the model input data set. As the influence of tides is not yet accounted for in EDEN, HAED data within the zone that hydrodynamic modelling and gauge data indicate are influenced by tidal cycles were also removed from the DEM development process.

In the second step, the HAED data were segregated by WCA and National Park boundaries so that local trends were isolated, subregion-specific interpolation models were developed and realistic breaks in elevation along subregion boundaries (levees and canals) were imbedded in a final, region-wide DEM. The results of the filtering and segregation steps for WCA1 are provided in figure 5. For illustrative purposes, the AHF operator attribution of land cover was relied upon for the WCA1 modelling shown here. For this WCA1 example, the original number of 3547 HAED points within the conservation area was reduced to 2901 (an 18% reduction) through the filtering and segmentation steps. For step 3, 15% of the remaining data were randomly extracted and withheld from model development in preparation for split-sample or true validation based on the supposition that input data sets would be reduced by roughly that amount when upland points were filtered out, to provide practical insights regarding method performance. The results of true validation, cross validation and coefficient of determination based on true-validation points (i.e. steps 5 and 6 in table 3) that were output from exploratory modelling of WCA1 are provided

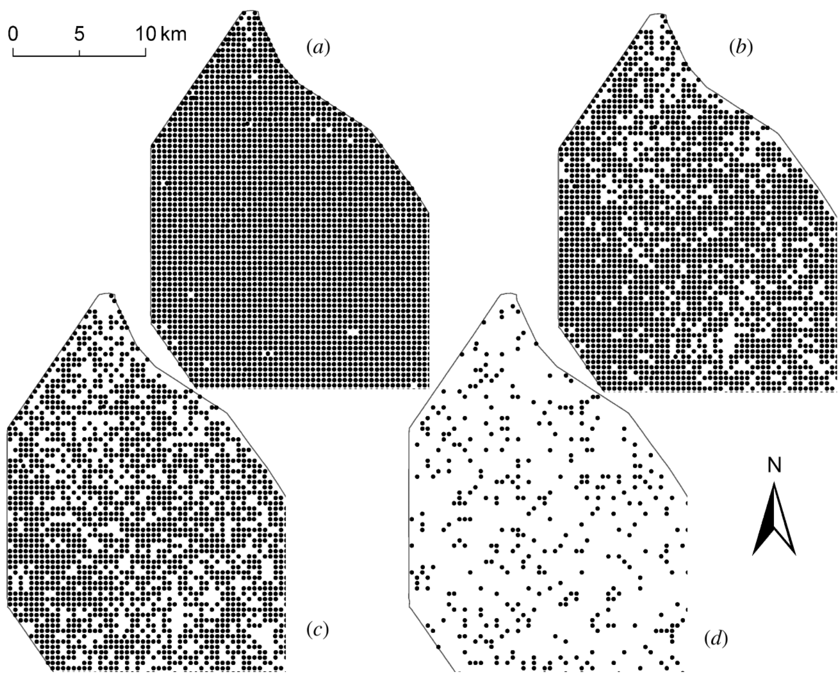

Figure 5. A Water Conservation Area 1 (WCA1)-focused subset of the High-Accuracy Elevation Database (HAED) to illustrate input data filtering and random data extraction processing steps. (*a*) All WCA1 HAED points, (*b*) points remaining after 'upland' (e.g. tree island, shrub and willow attributed) points removal, (*c*) remaining points for initial model exploration (i.e. table 3, step 4) given random removal of 15% and (*d*) points withheld for validation.

Table 4. Evaluation statistics, for example, WCA1 DEMs produced using five different interpolation methods.

Method	Model	TV RMSE (m)	MPE (m)	CV RMSE (m)	R
TOPOGRID	N/A	0.1678	N/A	N/A	0.51
IDW	N/A	0.1439	0.0019	0.1659	0.63
RBF	Spline with tension	0.1447	0.0008	0.1510	0.63
Ordinary kriging	Exponential	0.1443	0.0000	0.1493	0.64
Universal kriging	Exponential	0.1443	−0.0039	0.1454	0.65
N	N/A	436	2465	2465	436

Note: WCA1, Water Conservation Area 1; DEM, digital elevation model; TOPOGRID, ESRI interpolator; IDW, inverse distance weighted; RBF, radial-based function; TV RMSE, true-validation root mean square error; MPE, cross-validation mean prediction error; CV RMSE, cross-validation root mean square error; R, coefficient of determination for withheld verses modelled elevation; N, number of observations; N/A, not applicable.

Table 5. Summary statistics for WCA1 true-validation residuals (withheld HAED elevation – predicted elevation) for different interpolation methods.

Method	Min (m)	Max (m)	Mean (m)	Std Dev (m)	Skewness	Kurtosis	RMSE (m)
TOPOGRID	−1.0658	0.8064	0.0085	0.1825	0.1147	8.2282	0.1678
IDW	−0.5312	0.4854	0.0009	0.1438	0.1014	4.4613	0.1439
RBF	−0.5619	0.5061	0.0005	0.1445	0.0198	4.7798	0.1447
Ordinary kriging	−0.5513	0.5086	0.0014	0.1442	0.1396	4.6789	0.1443
Universal kriging	−0.5223	0.51928	0.0065803	0.14518	0.22304	4.8289	0.1443

Note: WCA1, Water Conservation Area 1; HAED, High-Accuracy Elevation Database; TOPOGRID, ESRI interpolator; IDW, inverse distance weighted; RBF, radial-based function; RMSE, root mean squared error; Min, minimum; Max, maximum; Std Dev, standard deviation; $N = 436$.

in table 4. While the TOPOGRID algorithm generated more extreme individual residual values, average results are similar across all methods (table 5). Results of tests for significant differences among true-validation residuals are provided in table 6. While there are no significant differences among models based on these metrics for WCA1, kriging approaches have an added appeal (Smith *et al.* 2005) for EDEN application as they allow for the estimation of error at each DEM grid point. This estimate can be used to index water depth simulation results with confidence values on an EDEN grid cell basis.

Table 7 shows the RMSEs generated through the cross validation of anisotropic, ordinary kriging for each Everglades subregion, demonstrating the possible range of error as a function of sub-area. It also shows the direction of anisotropy for each sub-area model. These directions appropriately reflect those of the general water flow that affect topography and vegetation pattern and are visible in the remotely sensed imagery of the Everglades (Jones 2001). Finally, table 7 shows the proportion of potential HAED input points that are removed through the vegetation filtering process. Excluding the BCNP as an outlier given incomplete HAED coverage that is focused in southern upland areas of the preserve, the average reduction in points through filtering

Table 6. WCA1 mean residual error (m) and p-values from tests for statistically significant differences among true-validation residuals (withheld HAED elevation – predicted elevation) for five different interpolation methods.

	TOPOGRID	IDW	RBF	Ordinary kriging	Universal kriging
Mean residual error	0.0085	0.0009	0.0005	0.0014	0.0066
TOPOGRID		0.49	0.47	0.53	0.86
IDW	0.49		0.97	0.95	0.56
RBF	0.47	0.97		0.92	0.53
Ordinary kriging	0.53	0.95	0.92		0.60
Universal kriging	0.86	0.56	0.53	0.60	

Note: WCA1, Water Conservation Area 1; HAED, High-Accuracy Elevation Database; TOPOGRID, ESRI interpolator; IDW, inverse distance weighted; RBF, radial-based function; $N = 436$.

Table 7. Cross-validation results for the seven sub-areas of the EDEN using 'non-upland' HAED points as defined by GAP data and input to anisotropic ordinary kriging.

Sub-area	RMSE (m)	Direction	Nt	Nnu	%
WCA1	0.1616	309	3175	2363	26
WCA2	0.1141	92	3188	2641	17
WCA3AN	0.0975	60	3265	2386	26
WCA3AS	0.1146	29	10149	9408	7
WCA3B	0.0887	32	6330	6016	5
BCNP	0.1297	94	2026	1114	45
ENP	0.1311	298	14479	12063	17

Note: EDEN, Everglades Depth Estimation Network; HAED, High-Accuracy Elevation Database; RMSE: root mean squared error; WCA, water conservation area; BCNP, Big Cypress National Preserve; ENP, Everglades National Park; Direction: azimuth of anisotropy, Nt: total number of HAED observations, Nnu: total number of non-upland observations, %: per cent removed by filtering.

is 16%, suggesting the *a priori* 15% random reduction of points for true-validation purposes approximates the point loss associated with filtering. Figure 6 shows the revision of the region-wide DEM that is currently publicly available and resulted from the approach represented in table 3. EDEN maps of daily median Everglades water surfaces are now being differenced with this DEM to simulate daily water depths from 2000 to present. In addition, the DEM's utility is being evaluated by comparing EDEN simulated depths against carefully screened water depths measured by particular Everglades scientists during field campaigns (unpublished data). Note that because EDEN generates daily water depth maps for the entire EDEN domain, data exist for comparison with any single point value collected on particular days. These daily maps of water depth are also being analysed to produce a period of inundation (or hydroperiod) for comparison against simulations from hydrodynamic models as well as field-based data during Everglades research. Feedback on the utility of the DEM for these activities is being gathered for further DEM evaluation and refinement. Comparison of simulated depths and hydroperiods with those observed in the field has highlighted problems with EDEN DEM performance in WCA1 – the sub-area with the greatest elevation range and spatial heterogeneity. WCA1 is therefore an area of focused research.

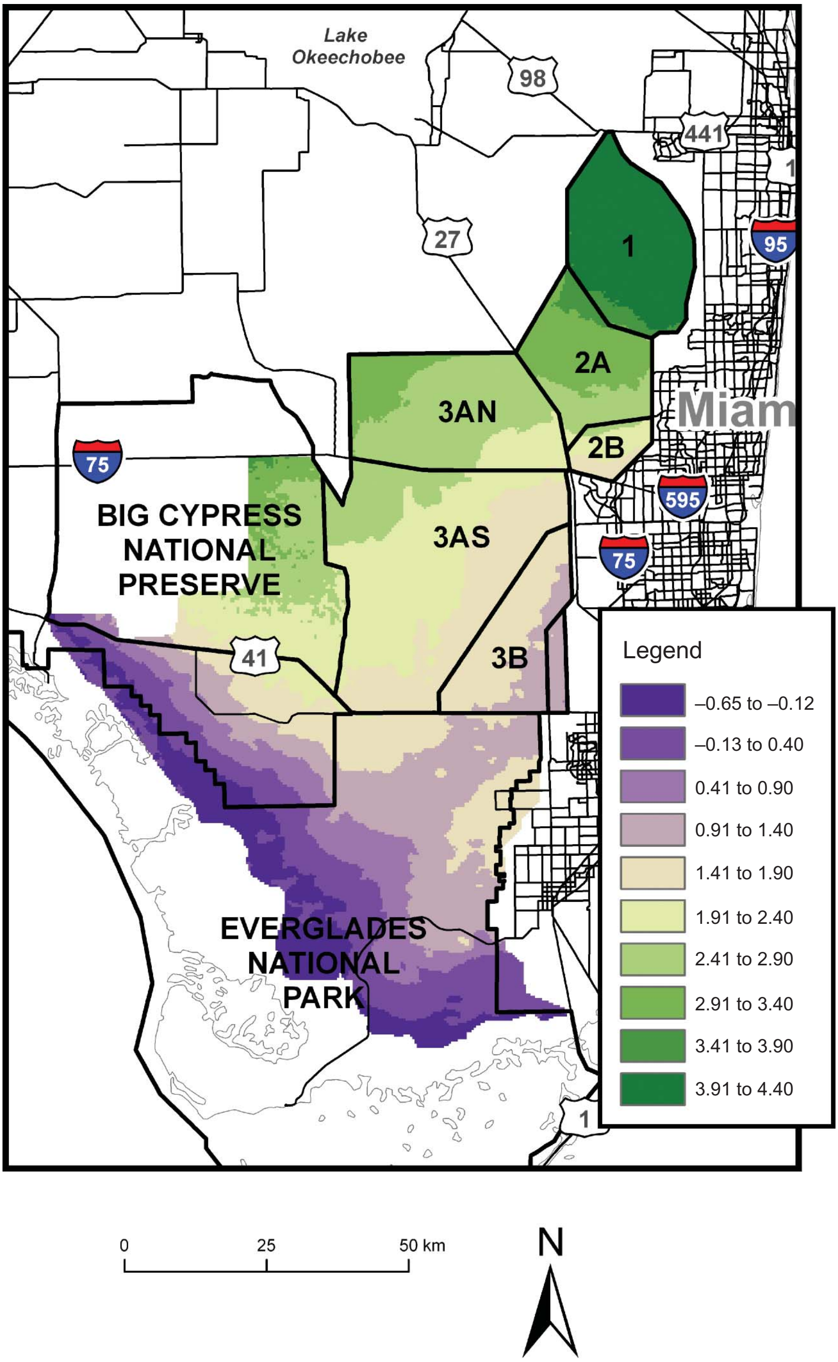

Figure 6. The Everglades Depth Estimation Network (EDEN) digital elevation model (DEM) used in EDEN water depth and hydroperiod modelling research. Note that the range in elevation over a distance of nearly 200 km is approximately 5 m.

6. Conclusions and future research

Everglades restoration science and resource management require better elevation data than is typically available at regional scale. As Everglades vegetation and soils are vulnerable to disturbances by foot and airboat travel, the impact of a region-wide conventional survey would be unacceptable, even if financially feasible. While airborne LiDAR systems may yield high-accuracy ground elevations in many environments, the vegetation and the water covering most of the Florida Everglades impede their use for region-wide elevation data collection. High-percentage vegetation cover and stem densities obscure the view of what are often water-covered ground surfaces from optical remote-sensing instruments, making measurement of sub-water ground surface elevation through remote sensing difficult. To meet requirements for the restoration of the Everglades region, the USGS has developed some novel solutions to wetland elevation modelling challenges. As this unique environment and DEM accuracy requirements challenge conventional remote sensed and ground-based data-collection methods, the USGS has adapted a classical data collection instrument to new technologies and modelling techniques. A structured and iterative approach to the analysis of these data produces DEMs for large regions of the Everglades that are useful in hydrologic modelling.

Current research is developing ways to further subdivide the Everglades for purposes of elevation modelling and ecological study using multi-temporal satellite imagery. Improved DEM statistical analyses, error examination, evaluation and visualization procedures (Fisher and Tate 2006) are being formalized on the basis of theoretical advances and findings (e.g. Li 1991, Aguilar *et al.* 2007, 2010, Hohle and Hohle 2009). At the same time, new elevation and field data are becoming available and the EDEN study area is expanding. With these developments, the steps in this approach are being refined and repeated to produce and revise a DEM covering all non-tidal wetlands within the Greater Everglades region for use in EDEN applications and other scientific and management activities. Future plans include the exploration of higher resolution elevation model development using statistical examination of HAED elevation postings and land-cover information derived through remote sensing.

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