Applied Geography 31 (2011) 401–412

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Landscape unit based digital elevation model development for the freshwater wetlands within the Arthur C. Marshall Loxahatchee National Wildlife Refuge, Southeastern Florida

Zhixiao Xie [a,*], Zhongwei Liu [b], John W. Jones [c], Aaron L. Higer [a], Pamela A. Telis [d]

[a] Department of Geosciences, Florida Atlantic University, 777 Glades Rd., Boca Raton, FL 33431, USA
[b] School of Environmental and Public Affairs, University of Nevada, Las Vegas, NV, USA
[c] US Geological Survey, Reston, VA, USA
[d] US Geological Survey, Jacksonville, FL, USA

Keywords:
DEM
Freshwater wetland
Spatial interpolation
Stratified *kriging*

A B S T R A C T

The hydrologic regime is a critical limiting factor in the delicate ecosystem of the greater Everglades freshwater wetlands in south Florida that has been severely altered by management activities in the past several decades. "Getting the water right" is regarded as the key to successful restoration of this unique wetland ecosystem. An essential component to represent and model its hydrologic regime, specifically water depth, is an accurate ground Digital Elevation Model (DEM). The Everglades Depth Estimation Network (EDEN) supplies important hydrologic data, and its products (including a ground DEM) have been well received by scientists and resource managers involved in Everglades restoration. This study improves the EDEN DEMs of the Loxahatchee National Wildlife Refuge, also known as Water Conservation Area 1 (WCA1), by adopting a landscape unit (LU) based interpolation approach. The study first filtered the input elevation data based on newly available vegetation data, and then created a separate geostatistical model (universal *kriging*) for each LU. The resultant DEMs have encouraging cross-validation and validation results, especially since the validation is based on an independent elevation dataset (derived by subtracting water depth measurements from EDEN water surface elevations). The DEM product of this study will directly benefit hydrologic and ecological studies as well as restoration efforts. The study will also be valuable for a broad range of wetland studies.

Introduction

A digital elevation model (DEM), also known as a digital terrain model (DTM), is a representation of the earth's surface, providing a base dataset which can generate topographic parameters. Burrough (1986) defined a DEM as "any digital representation of the continuous variation of relief over space".

DEMs have a wide range of applications, within which hydrologic and ecological modeling are well known examples. DEMs have been extensively used in modeling surface hydrology. Example applications include: watershed delineation (Jana, Reshmidevi, Arun, & Eldho, 2007; Martz & De Jong, 1998; O'Callaghan & Mark, 1984); development of terrain features (Moore, Grayson, & Ladson, 1991, 1993; Callow, Van Niel, & Boggs, 2007) and drainage networks (Fairfield & Leymarie, 1991); hydrology and soil moisture estimation (Beven & Kirkby, 1979; O'Loughlin, 1986; Sandells, Davenport, & Gurney, 2008); determination of flow accumulation (Peuker & Douglas, 1975); flow direction and routing (Du, Xie, Hu, Xu, & Xu, 2009; Marks, Dozier, & Frew, 1984; Tarboton, 1997); and extraction of parameters (e.g., slope and upslope contributing area) for hydrologic or hydraulic modeling (Lacroix, Martz, Kite, & Garbrecht, 2002; Wu, Li, & Huang, 2008). DEMs have also been widely applied in analyzing ecological systems and are essential for calculation of spatial variables (e.g., terrain slope, aspect, and curvature) used in ecological studies as independent parameters (Brown, 1994; Moore et al., 1991; Tappeiner, Tasser, & Tappeiner, 1998). Some variables are derived from more complex calculations, e.g., flow accumulation (Jenson & Domingue, 1988), soil moisture content (Beven & Kirkby, 1979; Burt & Butcher, 1985), solar irradiation (Dubayah & Rich, 1995), terrain exposure to the wind (e.g., Antonic & Legovic, 1999), and depth in sink (Antonic, Hatic, & Pernar, 2001). Additionally, topographic variables derived from DEMs have been applied in building multivariate predictive models of potential archaeological sites (Vaughn & Crawford, 2009), analysis and planning of recreational trails (Gonçalves, 2010; Snyder, Whitmore, Schneider, &

* Corresponding author. Tel.: +1 561 297 2852; fax: +1 561 297 2745.
E-mail address: xie@fau.edu (Z. Xie).

0143-6228/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apgeog.2010.10.003

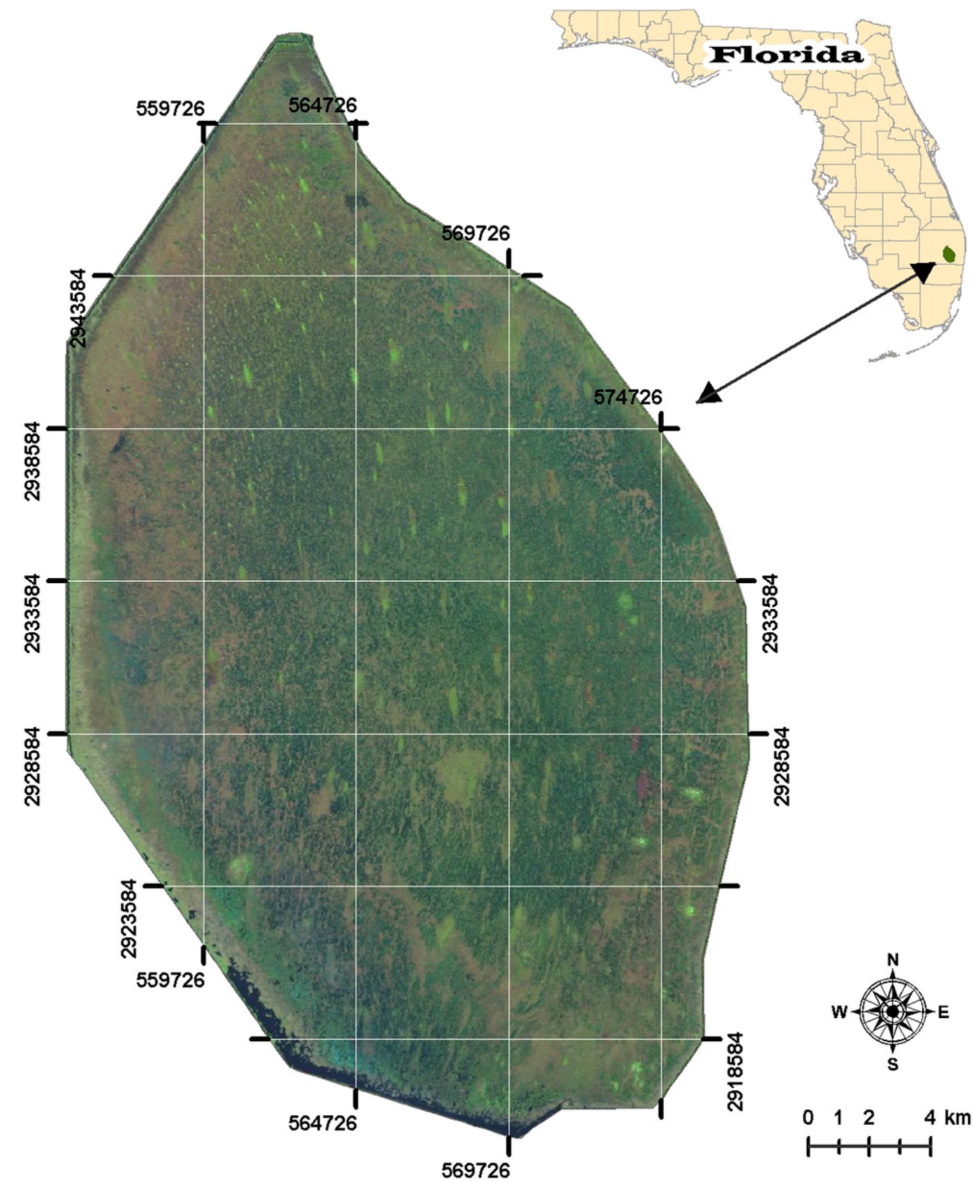

Fig. 1. The study area with satellite image as the background overlaid with UTM grid.

Becker, 2008), and examining the link of land use changes with elevation categories (Geri, Amici, & Rocchini, 2010).

Use of DEMs is especially important for wetland studies, because hydrology is the major limiting factor of wetland ecosystems and many important hydrologic data, including water depths and hydroperiods, may be derived from the combination of a ground DEM and water surface elevations. For example, water-depth time series were obtained by subtracting ground elevation from a series of water level surfaces (Pearlstine, Higer, Palaseanu, Fujisaki, & Mazzotti, 2007). Liu et al. (2009) used a DEM and

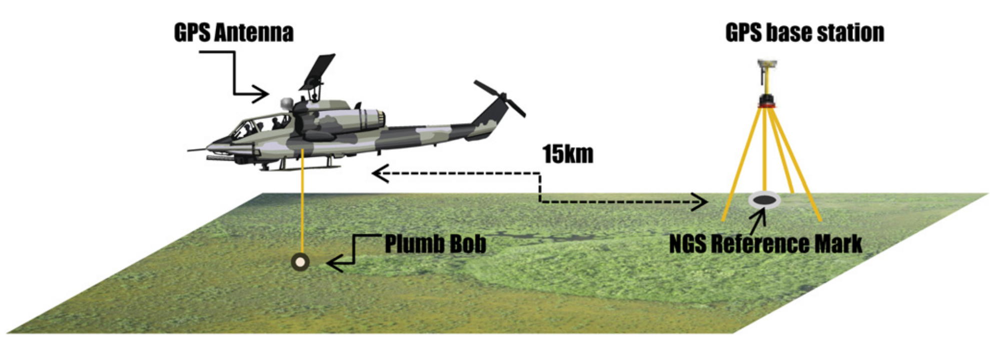

Fig. 2. Schematic illustration of AHF data collection with a high-tech version of the surveyor's plumb bob, aboard an airborne GPS platform, supported by differential GPS.

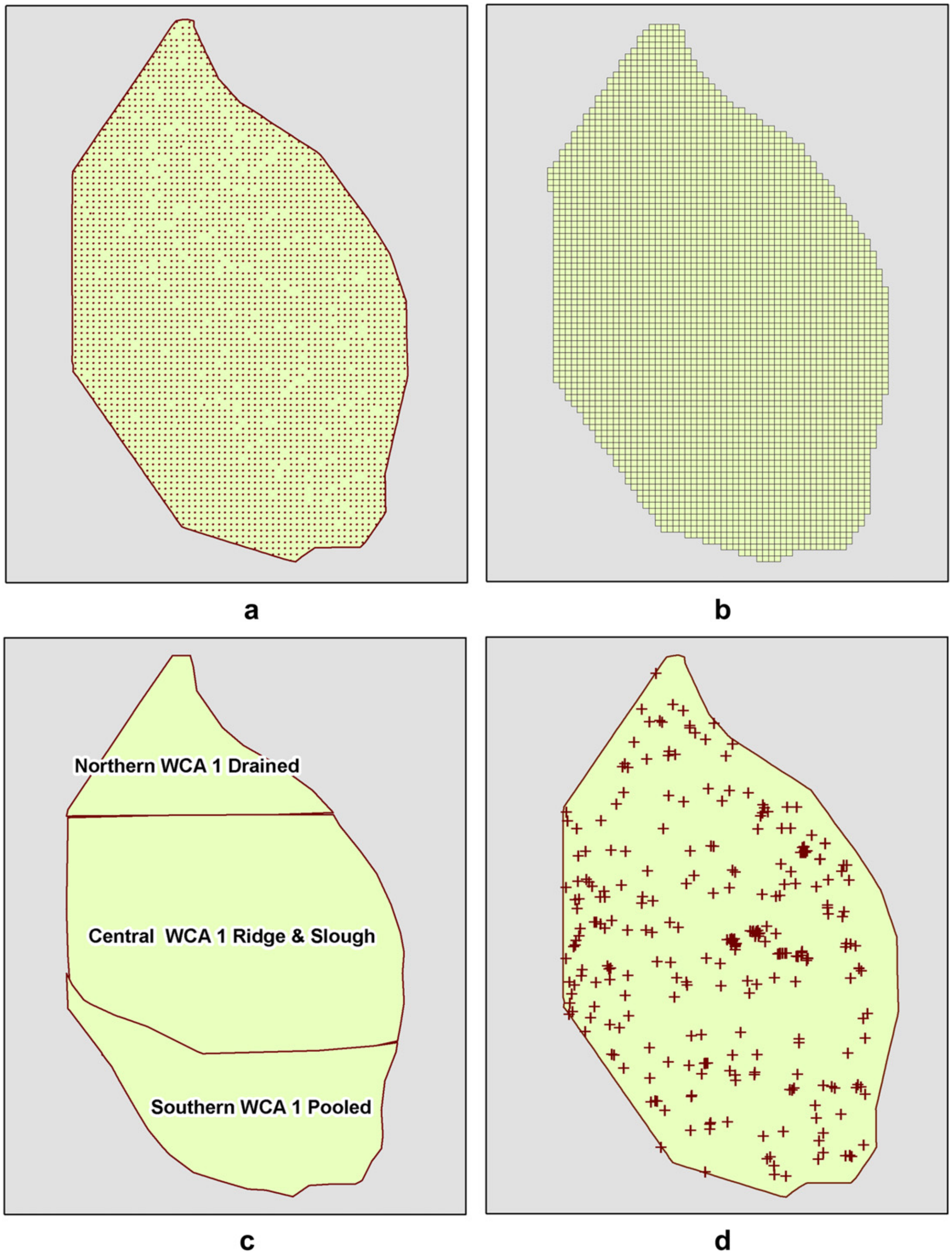

Fig. 3. Data for this study: (a) AHF data posting, (b) EDEN 400 m × 400 m grid, (c) landscape units, (d) PI data.

water-level surfaces to derive contiguous water coverage areas for studies of fish, wading birds, and Cape Sable seaside sparrows in the Everglades. Flooded areas could be estimated by specifying water depths > 0 cm or some other critical values with the use of a water surface and a ground DEM. Simard et al. (2006) used a ground DEM to calibrate radar derived elevation data for mapping height and biomass of mangrove forests in the Everglades National Park. To examine the hydroecological factors governing surface water flow in the central Everglades, Harvey et al. (2009) compared water levels with a ground DEM to verify total surface water inundation. Xie, Gawlik, Beerens, Liu, and Higer (2009) reported that the differences between a ground DEM and a reference elevation dataset were minimal but not uniform, and examined two smoothing approaches (i.e., neighbor average and neighbor match) to improve the DEM in Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) in the northern Everglades. Garcia-Aguirre, Ortiz, Zamorano, and Reyes (2007) analyzed the relationship between distribution of plant communities and landform relief properties derived from a DEM. By using MODIS remote sensing data, a DEM, and percent tree cover, Ordoyne and Friedl (2008) characterized seasonal inundation patterns in the Everglades.

Table 1
Major vegetation types in the study area in the vegetation map by the SFWMD and aggregated categories for AHF data filtering.

Code	Name	Description	Aggregated category
CSGc	Swamp scrub-sawgrass	Swamp scrub in a matrix composed predominately of Sawgrass (*Cladium jamaicense*).	(3) Sawgrass and emergent marsh
EmD	Melaleuca dominant	50%–89% areal coverage of Melaleuca.	(5) Exotics and cattail
FSB	Bayhead forest	Typical of tree islands in Shark River Slough, C-111, and the WCAs; commonly inundated 4–10 months a year.	(6) Others
MFB	Broadleaf emergent marsh	Broadleaf emergent dominated freshwater marsh.	(2) Wet prairie
MFF	Floating emergent marsh	Floating emergent dominated freshwater marsh	(2) Wet prairie
MFGc	Sawgrass	Sawgrass (*Cladium jamaicense*) dominated marsh	(3) Sawgrass and emergent marsh
MFGtD	Cattail dominant	50%–89% areal coverage of Cattail	(5) Exotics and cattail
MFGtM	Cattail monotypic	Greater than or equal to 90% areal coverage of Cattail	(5) Exotics and cattail
MFO	Open marsh	Open water dominated freshwater marsh often with a mix of sparse graminoids, herbaceous, and/or emergent freshwater vegetation.	(1) Slough or open water
OW	Open water	Open water areas such as ponds, lakes, rivers, bays, and estuaries.	(1) Slough or open water
SS	Swamp shrubland	Seasonally to semi-permanently flooded freshwater shrublands	(6) Others
SSB	Bayhead shrubland	Mix of Cocoplum (Chrysobalanus icaco), Swamp Bay (Persea palustris), Red Bay (Persea borbonia), Dahoon Holly (Ilex cassine), Willow (Salix caroliniana), Wax Myrtle (Myrica cerifera), Sweetbay (Magnolia virginiana), Cypress (Taxodium spp.), Pond Apple (Annona glabra), among others.	(6) Others
SSs	Willow shrubland	Willow (*Salix caroliniana*) dominant shrubland with sparse Leather Fern (*Acrostichum danaeifolium*), Cattail (*Typha* spp.), Sawgrass (*Cladium jamaicense*), Arrowhead (*Sagittaria* spp.), and other freshwater marsh species as possible understory components.	(6) Others

The importance of DEMs has been well recognized for wetland sciences and restoration in the greater Everglades and is one of the reasons for the development of the Everglades Depth Estimation Network (EDEN). EDEN is a collaborative program which provides critical hydrologic datasets that support analysis and modeling of the Everglades ecosystem for the Comprehensive Everglades Restoration Plan (CERP) (Telis, 2006). By combining daily water surfaces from approximately 250 water level gages with DEM data, EDEN provides water depths, hydroperiods, and daily water level surfaces. Modeled at a uniform 400-m grid cell resolution, EDEN data are being actively used by various research groups and for restoration decisions. Yet, the development of EDEN is an iterative process as additional high accuracy elevation data are collected, water surfacing algorithms improve, and additional ground-based ancillary data become available (Jones and Price, 2007a). This study represents a recent effort for DEM improvements in a part of the EDEN domain that has unique emergent terrain, many popup peat islands and degraded tree islands that make terrain modeling most challenging, and because hydrologic products computed based on the previous EDEN DEM have been reported to differ significantly from field observations. (Gawlik, Trexler, and et al., personal communication).

In the following sections we describe the unique data used in the study as well as the methods for interpolating DEMs and improving DEM accuracy. It is followed by the results of the DEM development, validation and refinement. The final section provides discussion and conclusions.

Data and methods

Study area

Designated in 1951, the LNWR or WCA1 is approximately 57 thousand hectares in size (USFWS, 2000). It is completely surrounded by canals and levees to regulate inflows and outflows. The interior marsh is a peat-based wetland system consisting of wet prairies,

Table 2
The *kriging* models, cross-validation, and validation results for the whole WCA1 and LU-based DEM development approaches.

	WCA1	North-LU	Center-LU	South-LU
Kriging method	Universal	Universal	Universal	Universal
Lag size	400m	400m	400m	400m
Number lags	46	20	30	20
Trend	1st	1st	1st	1st
Anisotropy	Yes	Yes	Yes	Yes
Semivariogram model	Spherical[a]	Gaussian[b]	Spherical[c]	Gaussian[d]
Number of points (after/before outlier removal)	3318/3319	526/526	1856/1857	935/936
Cross-validation with AHF data				
Mean error (m)	−0.03206	−0.001409	0.0001672	−0.007889
Root-mean-square error (m)	*0.1581*	*0.1308*	*0.1385*	*0.2017*
Average standard error (m)	0.1598	0.1294	0.1391	0.1952
Validation with elevation from PI Depth				
Number of PI points	798	36	602	160
Mean error (m)	0.0745	−0.003736	0.05592	0.134
Root-mean-square error (m)	*0.14*	*0.07985*	*0.1217*	*0.1983*
Average standard error (m)	0.1587	0.1293	0.1381	0.1937

[a] 0.018902*Spherical(17764,10850,313.4)+0.023129*Nugget.
[b] 0.011311*Gaussian(7985,5658.5354.6)+0.015379*Nugget.
[c] 0.0077704*Spherical(11963,8326.8347.0)+0.017647*Nugget.
[d] 0.034934*Gaussian(7985,5214.2300.7)+0.035432*Nugget.

aquatic sloughs, strands of sawgrass, cattail, patches of brush, and tree islands (USFWS, 2000). Of these vegetation types, tree islands are at the highest end of the elevation gradient, followed by peat ridge, bedrock formations, and mats of floating vegetation (Brandt, Portier, & Kitchens, 2000). The area is ecologically very complex largely due to the presence of many small "pop-up" tree islands, so named due to their unique round shape compared to the normally elongated tree islands found elsewhere in the Everglades. Degradation appears to have occurred on many of the larger strand islands, both from hydrologic alteration and the invasion of exotic species (Rutchey, SFWMD, personal communication). This complexity presents a great challenge for elevation measurement and estimation. As a result, EDEN DEM for this sub-region has the highest error among the Water Conservation Areas (Jones and Price, 2007a) (Fig. 1).

Elevation data

An important prerequisite for a high quality DEM, like any modeling, is a set of high quality input (sample elevation) data. In general, there are many effective approaches for digital elevation data collection. However, elevation data collection proved to be a huge challenge in the Everglades wetland system. First, due to extremely flat terrain, data has to be collected with high vertical accuracy to be suitable for hydrologic regime characterization and model input. Field surveying is usually one of the most reliable approaches for high-accuracy elevation data collection. But the expansive spatial coverage and a harsh and inaccessible wilderness environment (shallow marsh covered with dense vegetation) make conventional field survey too costly to implement. The commonly used remote sensing approaches, such as photogrammetry, lidar, IFSAR, etc., are difficult to accurately employ in this area, due to light impenetrability through dense emergent vegetation (e.g., sawgrass), floating periphyton, as well as fluffy underlying peat (Desmond, 2003). Limited success was achieved under special circumstances. For example, lidar was used to accurately measure elevations in a "highland" portion of the Everglades after wildfire had burned off vegetation and exposed bare ground (Maune, Huff, & Guenther, 2001). However, for other Everglades marshlands with

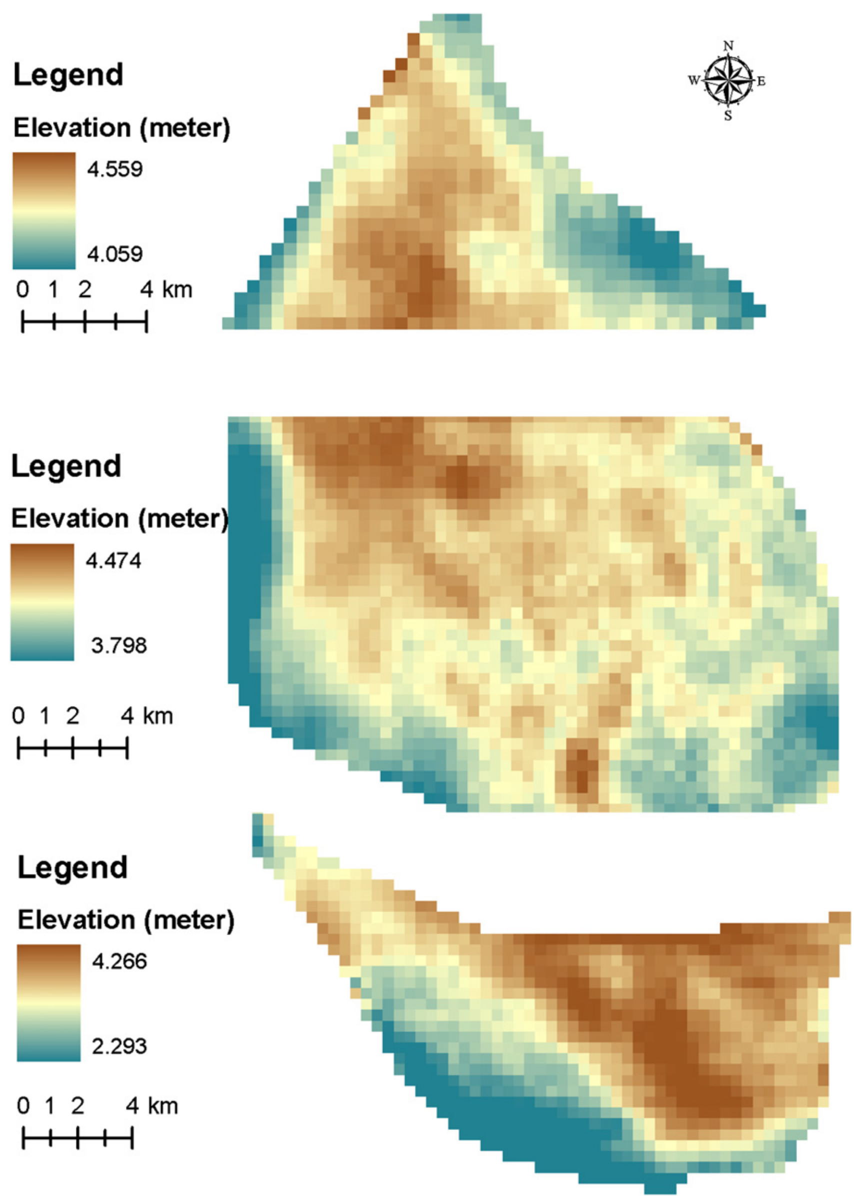

Fig. 4. The LU-based DEMs for the WCA1.

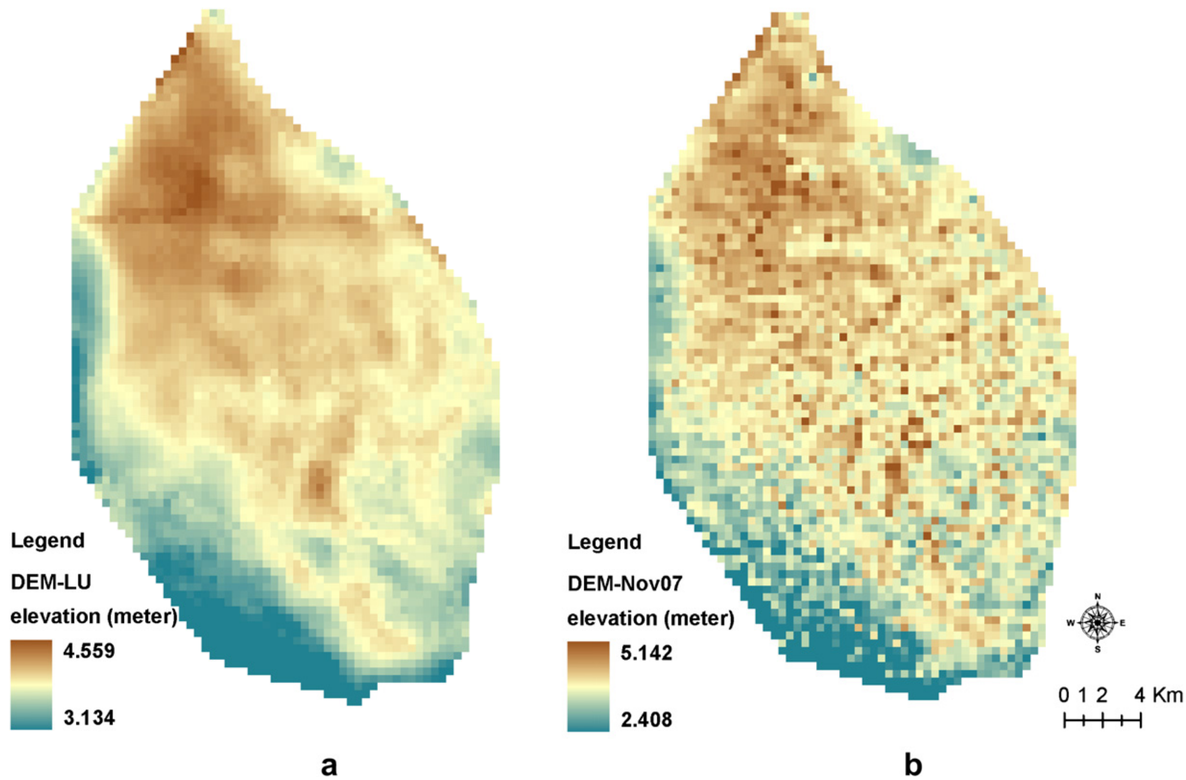

Fig. 5. Maps of the two DEMs: (a) the mosaiced LU-based DEMs, and (b) the previous released DEM or the WCA1-wide DEM.

terrain and vegetation more like those of the study area lidar has not produced adequate accuracy even following drought and similar vegetation removal by wildfire (Jones, Desmond, Henkle, & Glo, in press).

To collect elevation data for the unique ground terrain surface in the Everglades, the U.S. Geological Survey (USGS) developed an innovative approach (Fig. 2) that relies on differential GPS and an instrument deployed via helicopter. Named the Airborne Height Finder (AHF), a high-tech version of the surveyor's plumb bob is used to physically penetrate vegetation and murky water to provide reliable measurements of the underlying topographic surface (Desmond, 2003). The data were collected using an approximate horizontal spacing of 400-m to balance cost of collection, model resolution, and user needs (Desmond, 2003) (Fig. 3a).

To facilitate data organization and exchange, an EDEN grid framework was defined as a set of regular 400 m by 400 m square cells (UTM North Zone 17, North American Datum 1983, Fig. 3b). Each cell is uniquely identified with a key (Master ID) and a cell label. EDEN DEM and other products are stitched to this grid before distributing for public access (Jones and Price 2007b).

DEM development

After sample elevation points are collected, DEM surfaces are often created through spatial interpolation processes. Many different spatial interpolation methods are available, for example, Thiessen polygons, inverse distance (weighted) interpolation, Spline, Geostatistical methods, etc. (Burrough & McDonnell, 1998; Issaks & Srivastava, 1989). These methods can be grouped as global versus local, exact versus approximate, stochastic versus deterministic, etc. (Johnston, Ver Hoef, Krivoruchko, & Lucas, 2001). Of these methods, geostatistical methods are believed to be superior when the stochastic component of the process is stationary through time/space, autocorrelation is present in the data, and sufficient data are available to produce satisfactory semi-variograms (Burrough & McDonnell, 1998; Issaks & Srivastava, 1989).

In earlier version of EDEN (Nov. 2007), the DEM in WCA1 was produced by "anisotropic ordinary *kriging*", with all surveyed AHF data in this region as input (Jones and Price, 2007a). The validation process was a leave-one-out cross-validation, with an RMSE of 16.16 cm. In this study, several experiments were tried to improve the DEM accuracy, including data filtering based on recent vegetation map, landscape unit based DEM development, DEM validation based on secondary but independent dataset, and DEM refinement. More information on EDEN DEM development is described in Jones et al. (in press).

Filtering out unrepresentative AHF points

In some important ecological studies and applications in WCA1 and the Everglades in general, there is a need to have a more accurate estimation of the DEM at relatively low lying areas because these are the areas where water would be available in dry conditions. These are the refugia where prey (e.g., fish) will concentrate,

Table 3
Statistics on value differences (m) of two DEMs (the previous release DEM minus the mosaiced LU-based DEM) at AHF points in WCA1 summarized by independent land cover types.

	Open water	Slough	Wet prairie	Cattail	Shrub	Melaleuca	Tree island
Mean (m)	−0.17	−0.08	−0.04	0.01	0.04	0.06	0.14
Standard deviation	0.23	0.12	0.08	0.15	0.11	0.12	0.18
Number of samples	46	580	907	307	385	46	119

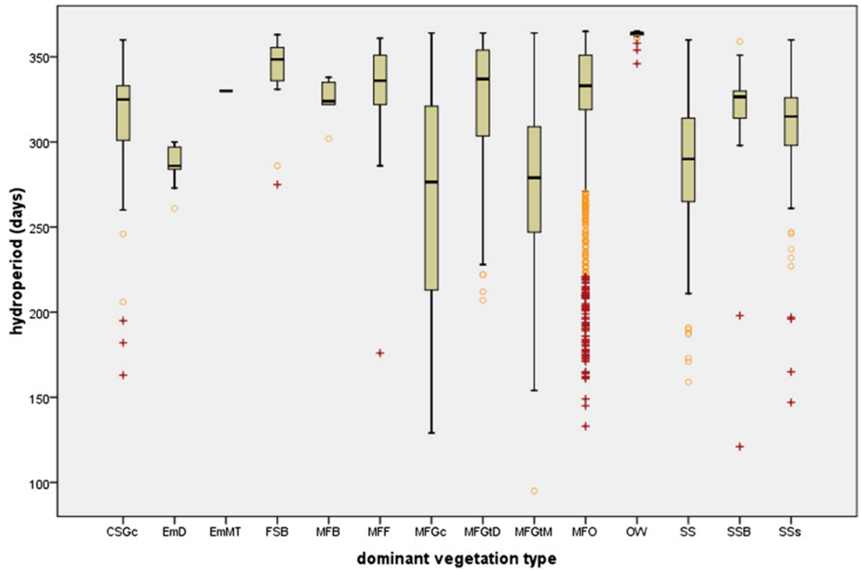

Fig. 6. Boxplot of hydroperiods vs. dominant vegetation types.

survive and/or be consumed by predators (wading birds, alligators, etc.). Because alligators and wading birds are recognized as important indicator species to signal the success or failure of Everglades restoration efforts (RECOVER, 2004), these areas are of ecological significance. Because WCA1 has numerous small-size elevated "spikes" (pop-up peats colonized by vegetation, degraded and dissected tree islands, etc.), elevations surveyed on these "high points" create unwanted bias in a DEM intended for low lying area water depth estimation. Therefore, a method that removes from consideration AHF points collected on upland, when only the minority of the EDEN grid cell is upland (Jones et. al., in press), was applied. The filtering was conducted using vegetation types defined (Rutchey et al. 2006) and mapped (Rutchey, Schall, & Sklar, 2008) by the South Florida Water Management District (SFWMD). The SFWMD vegetation map for WCA1 was produced through stereoscopic analysis of 1:24,000 scale color-infrared positive transparencies flown in December 2003. With a minimum mapping unit of 50 m × 50 m, it represents the most recent and detailed map of WCA1 vegetation cover. The classification system developed by Rutchey et al. (2006) and the major vegetation types in WCA1 are listed in Table 1.

These vegetation types were first aggregated into six major categories: (1) slough or open water, (2) wet prairie, (3) sawgrass and emergent marsh, (4) upland, (5) exotics and cattail, and (6) others (mostly wetland shrub and wetland forested). The resultant aggregated vegetation map was next overlaid with AHF points and the EDEN grid. An AHF point was removed if it falls on an "upland" or "other" vegetation location and less than 33% of the EDEN grid cell to which the point belongs is also "upland" or "other" (Jones et. al., in press). In this way, cells that are not dominantly upland do not influence semi-variagram development.

Landscape Unit–based DEM development

The filtered AHF points were used to develop DEMs with *kriging* in ESRI ArcGIS 9.3[1]. For the previous version of the EDEN DEM the whole WCA1 was treated as one region. For this revision, we tried a landscape unit (LU) based approach. These LUs were outlined by ecologists with extensive knowledge of the Everglades to represent distinct landscape patterns and/or management units in the greater Everglades (RECOVER, 2004). There are three LUs in the WCA1 study area: north drained, central ridge & slough, and south pooled (Fig. 3c). In essence, the LU-based DEM development is one implementation of "stratified *kriging*", dividing the study area into meaningful sub-areas for separate interpolation that, if done properly, should reduce interpolation errors (Burrough & McDonnell, 1998).

For each LU, a separate *kriging* model was developed and assessed. In building each *kriging* model, the spatial trend of the ground elevation was examined and factored into model selection (universal *kriging* vs. ordinary *kriging*). The potential outliers of the input data were identified and removed before model development. The other key parameters were also carefully selected, including directional differences (anisotropy), lag size, and number of lags. The DEMs for all the LUs were mosaicked into a unified DEM for WCA1. For comparison, we also constructed a k*riging* model for the whole WCA1 without dividing into LUs.

DEM validation and evaluation

DEM models are generally assessed through validation and cross-validation (Maune et al., 2001). Validation requires the withholding of some input elevation data (points) or the collection of separate elevation observations (ideally of similar or better accuracy than that of the model input data) for comparison against interpolated values. In contrast, cross-validation only withholds points while the remaining data are used to estimate the value at the withheld points. Depending on how many data are withheld each time, cross-validation can vary from leave-one-out to leave-*n*-out. Although cross-validation uses every sample, the actual inputs for the final interpolation model and assessment are slightly different (by one or *n* input data points) and the assessment has inherent bias (the same data for model building are used for model evaluation).

Because the surveyed AHF data are very valuable, it is more desirable to use all data for model building; hence, cross-validation seems the logical validation choice. Both validation and cross-validation are used in the EDEN DEM development process (Jones and Price, 2007a; Jones et al., in press) and in this DEM study. However, in this case we conducted an additional validation with

[1] Use of product and trade names is for illustrative and informational purposes only and does not represent an endorsement by the U.S. Government.

Table 4
The number of outliers by each dominant vegetation type, as computed by the boxplot of hydroperiods versus dominant vegetation types.

Dominant vegetation types		Number of outliers
Code	Description	
CSGc	Swamp scrub-sawgrass	5
EmD	Melaleuca dominant	1
FSB	Bayhead forest	2
MFB	Broadleaf emergent marsh	1
MFF	Floating emergent marsh	1
MFGtD	Cattail dominant	4
MFGtM	Cattail monotypic	1
MFO	Open marsh	181
OW	Open water	5
SS	Swamp shrubland	7
SSB	Bayhead shrubland	3
SSs	Willow shrubland	9

a secondary but independent elevation dataset for an unbiased assessment. The additional validation elevation dataset was derived by deducing elevation values from EDEN generated daily water-level surfaces and depth measurements made by different scientists in the field at different locations and on various dates (called Principle Investigator or PI depth data here) Fig. 3d.

The water-level surfaces were created by the EDEN project team via the radial basis function (RBF) interpolation method, with field observed water level readings at approximately 250 real-time gaging stations (Palaseanu & Pearlstine, 2008; Pearlstine et al., 2007). Although each station records water level every 30 min, only the daily median reading of each gage was used to create a water surface for each day from January 1, 2000 to present. There are some cases when water level is not available for certain stations, e.g., a station was constructed after January 1, 2000 or when a gage occasionally malfunctions. Water levels for these cases are predicted using a special artificial intelligence process (Conrads & Petkewich, 2009; Conrads & Roehl, 2007). The water-level surfaces share the same 400-m grid structure as the EDEN DEM. Liu et al. (2009) conducted a validation of EDEN water-level surfaces and reported a root-mean-squared-error (RMSE) of 3.3 cm. The PI depth data were collected by four research groups for different research projects during the period from 2000 to 2007. Depths were measured at a total of 1491 data locations. The ground elevation was derived by subtracting the water depth measurement from a daily EDEN water surface DEM on the dates when measurements were taken. Due to the extremely low slope and slow water flow, the water surface elevation is considered to be flat across a 400-m EDEN cell. When there are multiple depth measurements at one location, multiple ground elevation values were produced and the average value was used for evaluation.

DEM refinement

The mosaiced LU-based DEM was further refined through two experiments. In the first, we exercised a wetland DEM refinement procedure developed by Xie et al. (2009). The fundamental principle underlying the procedure is to adjust the modeled elevation value at selected locations based on the correlation between hydroperiods and vegetation types as well as autocorrelation of elevation within a small spatial neighborhood. Assignment of vegetation type for this refinement is simpler than that outlined in Section 2.3.1. Here, the dominant vegetation type in the SFWMD map that has the greatest portion of area for each EDEN grid cell

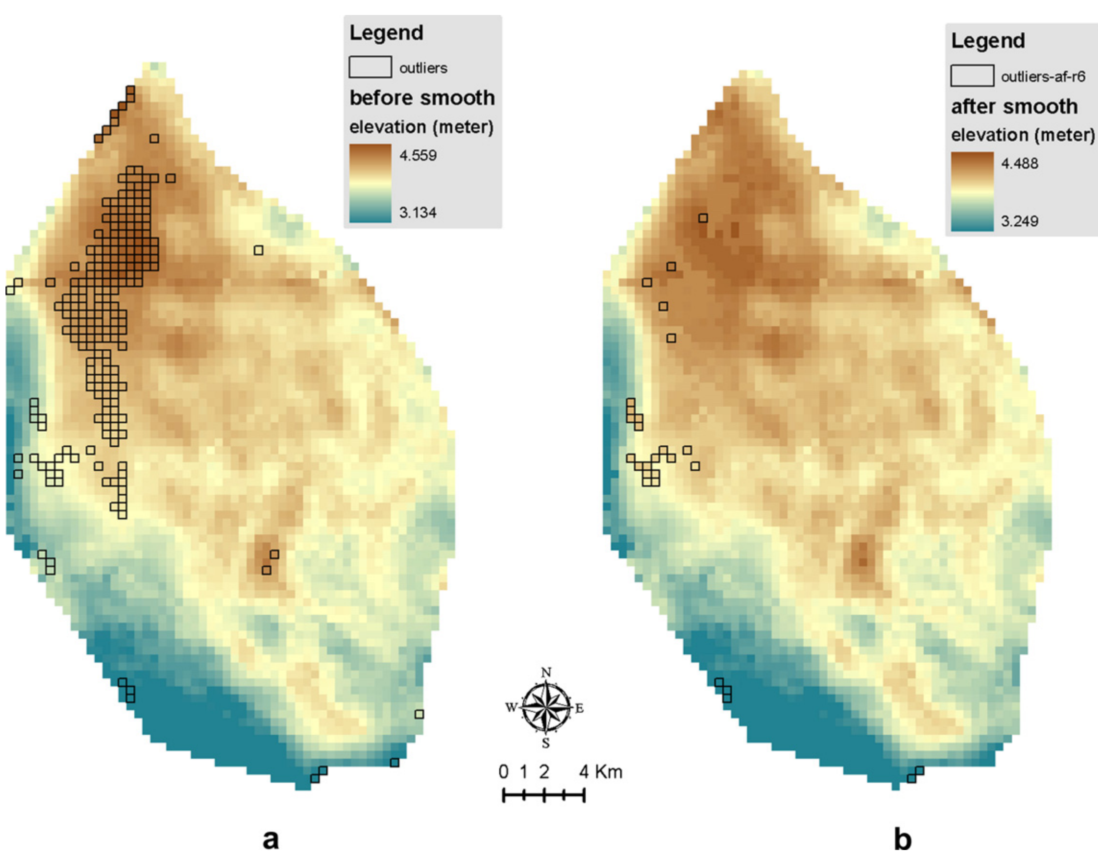

Fig. 7. The mosaiced LU-based DEM (a) before and (b) after applying six rounds of smoothing algorithm based on hydroperiods and vegetation types relationship.

was used. The hydroperiod is defined as the number of days the ground surface is under water in this context. It is believed that hydroperiods have a very close correlation with vegetation types in the Everglades and the same dominant vegetation tends to live in areas with similar hydroperiods. With daily water surfaces and the revised DEM ready for WCA1, a hydroperiod value was computed for each year, from 2000 to 2008, for each EDEN cell. An average annual hydroperiod was also computed for each cell.

The average hydroperiod dataset was next overlaid with the dominant vegetation dataset to derive paired hydroperiod-vegetation information for each EDEN cell to prepare for outlier detection and post processing. The outlier cells were identified through a box plot approach with dominant vegetation type as the group variable and hydroperiod as the dependent variable. A cell was labeled as an outlier if its hydroperiod was outside the normal hydroperiod ranges of its dominant vegetation type.

After the outlier cells were detected, two scenarios were applied to adjust the hydroperiod and elevation of each outlier cell. First, the eight direct neighbors of each outlier cell were examined to find those with the same dominant vegetation type as the focus cell. If multiple neighbor cells were found, the one with the most similar areal coverage of the dominant vegetation type was chosen and its hydroperiod and elevation were applied to the focus cell. In cases when no neighbor cells could be found with the same dominant vegetation, a simple average of the hydroperiod and elevation values of all the neighbors was applied to the focus cell. If needed, this procedure was applied several times until the number of outlier cells is acceptable or cannot be reduced.

In the second refinement attempt, we further divided the southern LU with high validation RMSEs into two parts and developed DEMs for each part individually, following similar interpolation and validation procedures described in prior sections.

Results

Data filtering and DEM development

The upland vegetation filtering protocol based on the SFWMD vegetation data input removed 218 non-representative AHF points out of the total 3537 in the study area. An additional suspected outlier was identified and removed through exploratory spatial data analysis of the variogram and overlay of data points on satellite imagery. A spatial trend was found in the area, decreasing from north to south, which is consistent with the overall water flow direction. After experimenting with different parameters, a universal *kriging* model

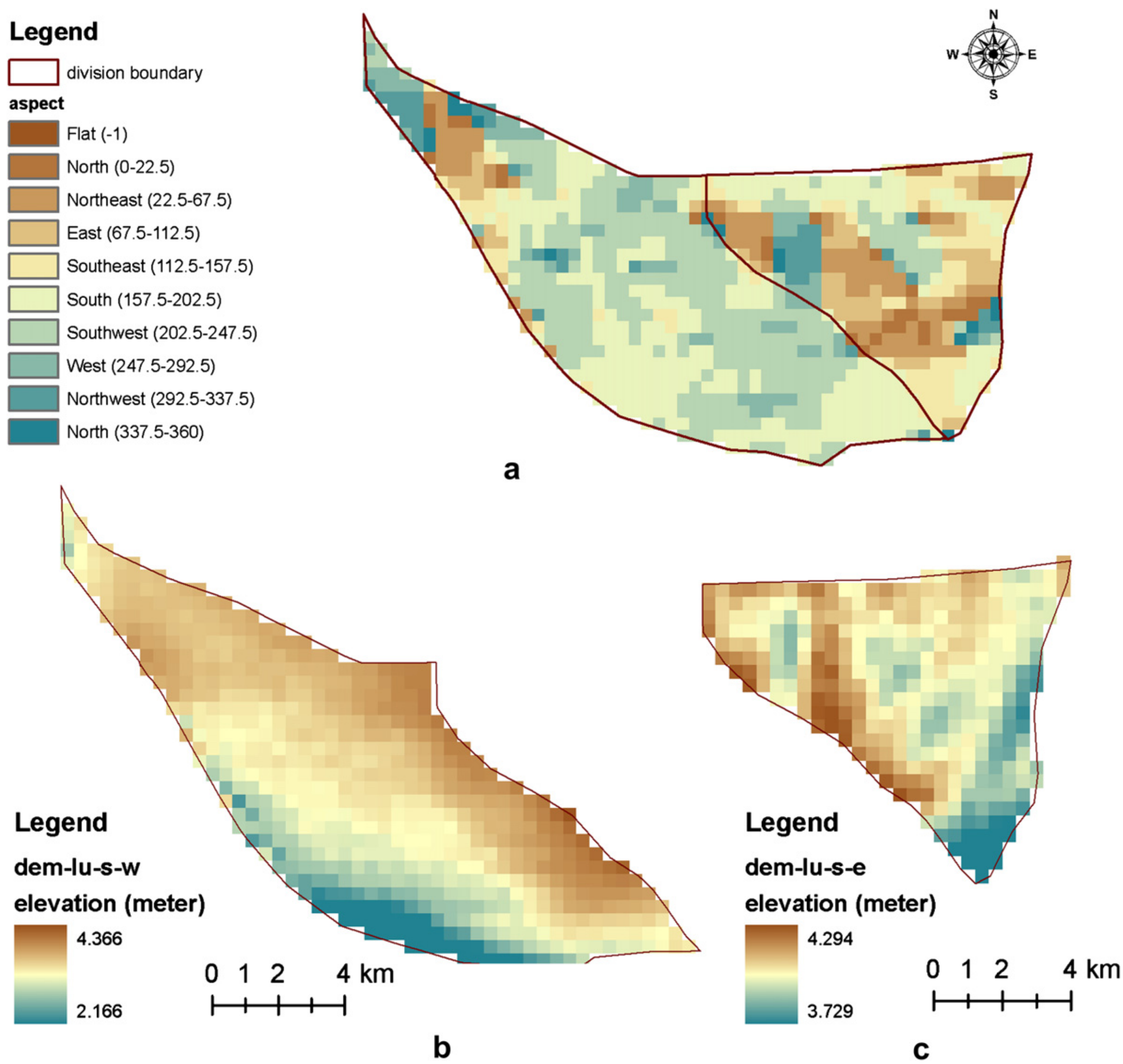

Fig. 8. The division of south LU-based mainly on (a) aspect calculated from LU-based DEM in south LU, and (b) the resultant DEM in south-LU west part, and (c) south-LU east part.

was chosen for the whole WCA1 (Table 2). The cross-validation and validation results are also shown in Table 2.

For each LU, the AHF data were examined for spatial trends with outliers removed (1 outlier for central and south LU respectively). In the end, universal *kriging* (first- order trend, anisotropy) was used to create a DEM for each LU (Fig. 4). Table 2 lists the model parameters, cross-validation, and validation results.

With the exception of the south LU, LU-based DEM models generally led to slightly lower cross-validation and validation errors (lower RMSEs). The LU-based DEMs were mosaiced into the EDEN 400-m grid (Fig. 5a) for further assessment. The new DEMs have lower cross-validation RMSEs than the previous release DEM (16.16 cm for WCA1) (Jones and Price, 2007a). Compared with a previous release (Fig. 5b), the new LU-based DEM in WCA1 also has a much smoother surface largely due to the filtering process based on the SFWMD vegetation data. While being collected, each WCA1 AHF data point was also assigned a vegetation cover type (Jones et al., in press). The average differences between LU-based and WCA1-wide DEM values as a function of these land cover assignments suggests that the overall terrain variation in the revised DEM is decreased (e.g., lower tree islands, higher open water areas), producing desired results for its intended applications in aquatic ecology (Table 3).

DEM refinement

Additional smoothing process

The boxplot of dominant vegetation types versus Hydroperiods is shown in Fig. 6. Based on the boxplot analysis, 220 cells were identified as outliers (Fig. 6) and are listed by vegetation type in Table 4. Six iterations of the smoothing procedure outlined in 2.5 were applied, with the number of outliers decreasing gradually: 220, 138, 90, 62, 41, 29 and 27. The outliers remained almost the same in the last two rounds, which suggests the DEM refinement should stop after five rounds in this case. Fig. 7 shows the LU-based DEM before and after smoothing.

Further subdivision of the south LU

As discussed in Section 3.1, the south LU had higher validation and cross-validation errors. Several approaches to further divide the south LU were evaluated. In the end, division of the south LU into two sections (WCA1S-W and WCA1S-E), based on calculated slope aspect from the revised DEM produced in Section 3.1 produced the best result. The WCA1S-W subzone mainly covers west and south aspect cells. The WCA1S-E subzone includes largely north and east aspect cells (Fig. 8a). The interpolated DEMs for the two sections are shown in Fig. 8b and c respectively. The validation and cross-validation results are shown in Table 5. After subdividing south LU, the east section of the south LU has lower validation errors when compared with the undivided south LU. However, it should be noted that the errors in the west section increased given this further subdivision.

Merged DEM production

In the mosaicing process, we merged the DEMs of the north LU, central LU, and the two subzones of the south LU (WCA1S-W and WCA1S-E). To reduce artificial breaks in elevation along WCA1 subarea boundaries, models were overlapped by 1 cell at these boundaries and, for the North, Central and South zone boundaries, overlapping model values were averaged during mosaicing. For the boundaries between the Southwest (WCA1S-W) and Southeast (WCA1S-E) zones, cell values were "blended" based on weighted distance from the boundary edge. Visually apparent straight line edges resulted along the boundaries of the North/Central and Central/South zones. However, differences in values along these straight edges were much lower than the error associated with the interpolation technique. Therefore, to create a less-artificial boundary among these zones, points along the North/Central and Central/South zone edges were subjectively selected and changed by adding or subtracting 0.03 m to particular cells based on nearby cell values. This slightly reduced apparent artifacts without drastically affecting the integrity of the model.

Table 5
The *kriging* model parameters and validation results for the south LU and the further subdivisions.

	South-LU	S-LU-w	S-LU-e
Kriging method	Universal	Universal	Universal
Lag size	400m	400m	400m
Number lags	20	15	15
Trend	1st	1st	1st
Anisotropy	Yes	Yes	Yes
Semivariogram model	Gaussian	Gaussian[a]	Exponential[b]
Number of points (after/before outlier removal)	935/936	598	328
Cross-validation with AHF data			
Mean error (m)	−0.007889	−0.01063	0.004889
Root-mean-square error (m)	*0.2017*	*0. 2158*	*0.1712*
Average standard error (m)	0.1952	0.2101	0.1737
Validation with elevation from PI depth			
Number of PI points	160	134	26
Mean prediction error (m)	0.134	0.147	0.08454
Root-mean-square error (m)	*0.1983*	*0. 2057*	*0. 1489*
Average standard error (m)	0.1937	0.2081	0.1729

[a] 0.021443*Gaussian(5993.3,3612.3,302.7)+0.040753*Nugget.
[b] 0.0051858*Exponential(5993.3,2842,21.9)+0.025891*Nugget.

Conclusions and discussion

Use of ground DEMs is critical for accurate hydrologic and ecological modeling. This is especially true in the Everglades wetlands where terrain is extremely flat and several centimeters of elevation difference are significant. This paper described several experiments to improve the EDEN WCA1 DEM. Anisotropic universal *kriging* by landscape units, with properly selected parameters, led to lower cross-validation and validation results relative to ordinary kriging over the entire area. The validation results with independent PI datasets are especially encouraging since estimation of water depths for use by these PIs is a primary application of the DEM. Subdivision of the south LU into two zones reduced the error in one, while increasing it in another. This may reflect the complex terrain conditions of the south and southwestern LU, and the difficulty for reliable elevation modeling there, due to long-term impounded and altered ground condition. However, given the intended application of the DEM, reduction of error in one portion of the south zone at the expense of error increase within the subzone for which hydroperiod/depth are less important, is acceptable. It also further demonstrates another benefit of "stratified *kriging*", i.e., helps pinpoint the areas where complex terrain exists.

This study used the close correlation between hydroperiods and vegetation types in a unique wetland environment for elevation modeling to demonstrate another promising approach. Different than in a previous application by Xie et al. (2009), multiple iterations of smoothing/adjustment were applied in this study. However, there is a side effect from applying multiple rounds of smoothing as some important local variations may be smoothed out. Therefore, this approach needs further improvement and was not implemented for the new release (Jan. 2010) of EDEN WCA1 DEM.

The input AHF data were filtered based on a newly available vegetation map. Compared with the previously released DEM, the overall decreased terrain variation in the revised DEM is more suitable as input to the ecological applications to which the DEM is being applied. This was confirmed by comparison with independent PI depth data, and other analyses. The idea of filtering data to suit DEM interpolation for targeted applications would be useful in a broad array of application settings. Ideally, it may be preferable to have a universal, high accuracy DEM interpolated with all the available sample data in a study area; however, a DEM with filtered data may be a better alternative if the resultant DEM has lower errors in the targeted strata of terrain.

One may argue that the PI dataset in this study may not be ideal for validation because it is a secondary dataset and no information is available for its accuracy. To a certain degree, the validation with PI data may be better categorized as a precision assessment or consistency analysis between the modeled elevation and PI dataset. No matter which categorization is used, it is clear that a higher consistency between the modeled elevation and PI dataset is a welcomed evidence of the DEM quality, particularly since the PI data were collected over multiple years and dates, at different locations, and by different scientists. Because the DEM is developed to support relevant research and management activities in the Everglades, this validation is actually of more significance.

Finally, the current DEM is developed at a resolution of 400 m, largely due to the 400-m sample spacing of the input AHF data. It has been noted that there is a need for accurate high resolution terrain data to improve the realism of the predictive ability of hydraulic and hydrological models in lowland areas (Bates, Horritt, Smith, & Mason, 1997; Farajalla & Vieux, 1995; Hardy, Bates, & Anderson, 1999; Moglen & Hartman, 2001). Because lowland topography strongly influences hydrologic processes (Colby & Dobson, 2010; Hudson & Colditz, 2003; Stewart, Bates, Anderson, Price, & Burt, 1999), accurate high resolution terrain data is needed to capture the heterogeneity of physical systems and derive important model parameters, e.g., basin relief, flow length, flow depth and direction, hill slope runoff, water surface elevation, and flood volume. An accurate high resolution DEM will certainly benefit the ecosystem sciences and restoration efforts in the greater Everglades, and it should be improved when appropriate data and methods are available in the future.

Acknowledgement

The project is funded by the USGS through a CESU agreement G10AC00011. The authors would like to thank the scientists who shared their field measurements in the Everglades, including Todd Z. Osborne (University of Florida), Dale E. Gawlik (Florida Atlantic University), Michael S. Ross (Florida International University), and Joel C. Trexler (Florida International University). Finally, the comments from the editor and anonymous reviewers helped improve the manuscript and are appreciated.

References

Antonic, O., & Legovic, T. (1999). Estimating the direction of an unknown air pollution source using a digital elevation model and a sample of deposition. *Ecological Modelling, 124*, 85–95.

Antonic, O., Hatic, D., & Pernar, R. (2001). DEM-based depth in sink as an environmental estimator. *Ecological Modelling, 138*, 247–254.

Bates, P. D., Horritt, M. S., Smith, C. N., & Mason, D. (1997). Integrating remote sensing observations of flood hydrology and hydraulic modeling. *Hydrological Processes, 11*(14), 1777–1795.

Beven, K., & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin, 24*(1), 43–69.

Brandt, L. A., Portier, K. M., & Kitchens, W. M. (2000). Patterns of change in tree islands in Arthur R. Marshall Loxahatchee National Wildlife Refuge from 1950 to 1991. *Wetlands, 20*(1), 1–14.

Brown, D. G. (1994). Predicting vegetation types at treeline using topography and biophysical disturbance variables. *Journal of Vegetation Science, 5*, 641–656.

Burrough, P. A. (1986). *Principles of geographical information systems for land resources assessment*. Oxford: Clarendon Press.

Burrough, P. A., & McDonnell, R. A. (1998). *Principles of geographical information system*. New York: Oxford University Press Inc.

Burt, T. P., & Butcher, D. P. (1985). Topographic controls of soil moisture distributions. *Journal of Soil Science, 36*, 469–486.

Callow, J. N., Van Niel, K. P., & Boggs, G. S. (2007). How does modifying a DEM to reflect known hydrology affect subsequent terrain analysis? *Journal of Hydrology, 332*(1–2), 30–39.

Colby, J. D., & Dobson, J. G. (2010). Flood modeling in the coastal plains and mountains: analysis of terrain resolution. *Natural Hazards Review, 11*(1), 19–28.

Conrads Paul, A. & Petkewich, M. D. (2009). Estimation of missing water-level data for the Everglades Depth Estimation Network (EDEN): U.S. geological survey open-file report 2009–1120, 53 p.

Conrads, P. A. & Roehl, E. A., Jr. (2007). Hydrologic record extension of water-level data in the Everglades Depth Estimation Network (EDEN) using artificial neural network models, 2000–2006: U.S. geological survey open-file report 2007-1350, 56 pp.

Desmond, G. D. 2003. Measuring and mapping the topography of the Florida Everglades for Ecosystem Restoration. U.S. geological survey fact sheet 021–03.

Du, J., Xie, H., Hu, Y., Xu, Y., & Xu, C. Y. (2009). Development and testing of a new storm runoff routing approach based on time variant spatially distributed travel time method. *Journal of Hydrology, 369*, 44–54.

Dubayah, R., & Rich, P. M. (1995). Topographic solar radiation models for GIS. *International Journal of Geographical Information Systems, 9*, 405–419.

Fairfield, J., & Leymarie, P. (1991). Drainage networks from grid digital elevation models. *Water Resources Research, 27*(5), 709–717.

Farajalla, N. S., & Vieux, B. E. (1995). Capturing the essential spatial variability in distributed hydrological modelling: infiltration parameters. *Hydrological Processes, 9*, 55–68.

Garcia-Aguirre, M. C., Ortiz, M. A., Zamorano, J. J., & Reyes, Y. (2007). Vegetation and landform relationships at Ajusco volcano Mexico, using a geographic information system (GIS). *Forest Ecology and Management, 239*, 1–12.

Geri, F., Amici, V., & Rocchini, D. (2010). Human activity impact on the heterogeneity of a mediterranean landscape. *Applied Geography, 29*, 370–379.

Gonçalves, A. B. (2010). An extension of GIS-based least-cost path modelling to the location of wide paths. *International Journal of Geographical Information Science* 983–996.

Hardy, R. J., Bates, P. D., & Anderson, M. G. (1999). The importance of spatial resolution in hydraulic models for floodplain environments. *Journal of Hydrology, 216*(1–2), 124–136.

Harvey, J. W., Schaffranek, R. W., Noe, G. B., Larsen, L. G., Nowacki, D. J., & O'Connor, B. L. (2009). Hydroecological factors governing surface water flow on a low-gradient floodplain. *Water Resources Research, 45*, W03421. doi:10.1029/2008WR007129.

Hudson, P. E., & Colditz, R. (2003). Flood delineation in a large and complex alluvial valley: the lower Panuco Basin, Mexico. *Journal of Hydrology, 280*(1–4), 229–245.

Issaks, E. H., & Srivastava, R. M. (1989). *An introduction to Applied Geostatistics*. Oxford University Press.

Jana, R., Reshmidevi, T. V., Arun, P. S., & Eldho, T. I. (2007). An enhanced technique in construction of the discrete drainage network from low-resolution spatial database. *Computers and Geosciences, 33*(6), 717–727.

Jenson, S. K., & Domingue, J. O. (1988). Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing, 54*(11), 1593–1600.

Jones, J. W. & Price, S. D. (2007a). Initial Everglades Depth Estimation (EDEN) digital elevation model research and development. U.S. geological survey open-file report 2007–1034.

Jones, J. W. & Price, S. D. (2007b). Conceptual design of the Everglades Depth Estimation Network (EDEN) grid. U.S. geological survey open-file report 2007–1200.

Jones, J. W., Desmond, G. B., Henkle, C, & Glover, R. An approach to regional wetland digital elevation model (DEM) development using differential GPS and a custom-built helicopter based surveying system. *International Journal of Remote Sensing*, in press.

Johnston, K., Ver Hoef, J. M., Krivoruchko, K., & Lucas, N. (2001). *Using ArcGIS geostatistical analyst*. Redlands, California: ESRI Press.

Lacroix, M., Martz, L. W., Kite, G. W., & Garbrecht, J. (2002). Using digital terrain analysis modeling techniques for the parameterization of a hydrologic model. *Environmental Modelling and Software, 17*, 125–134.

Liu, Z., Volin, J., Owen, D., Pearlstine, L., Allen, J., Mazzotti, F., et al. (2009). Validation and ecosystem applications of the EDEN water-surface model for the Florida Everglades. *Ecohydrology, 2*(2), 182–194.

Maune, D. F., Huff, L. C., & Guenther, G. C. (2001). DEM user applications. In D. F. Maune (Ed.), *Digital elevation model technologies and applications: The DEM users manual*. Bethesda, Maryland: ASPRS.

Marks, D., Dozier, J., & Frew, J. (1984). Automated basin delineation from digital elevation data. *Geoprocessing, 2*(4), 299–311.

Martz, L., & De Jong, E. (1998). CATCH: a FORTRAN program for measuring catchment area from digital elevation models. *Computers and GeoSciences, 14*(5), 627–640.

Moglen, G. E., & Hartman, G. L. (2001). Resolution effects on hydrologic modeling parameters and peak discharge. *Journal of Hydrologic Engineering, 6*(6), 490–497.

Moore, I. D., Grayson, R. B., & Ladson, A. R. (1991). Digital terrain modelling: a review of hydrological, geomorphological, and biological applications. *Hydrologic Process, 5*, 3–30.

Moore, I. D., Gessler, P. E., Nielsen, G. A., & Peterson, G. A. (1993). Soil attribute prediction using previous terrain analysis. *Soil Science Society of America Journal, 57*, 443–452.

O'Callaghan, J. F., & Mark, D. M. (1984). The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics and Image Processing, 28*, 323–344.

O'Loughlin, E. M. (1986). Prediction of surface saturation zones in natural catchments by topographic analysis. *Water Resources Research, 22*(5), 794–804.

Ordoyne, C., & Friedl, M. A. (2008). Using MODIS data to characterize seasonal inundation patterns in the Florida Everglades. *Remote Sensing of Environment, 112*, 4107–4119.

Palaseanu, M., & Pearlstine, L. (2008). Estimation of water surface elevations for the Everglades, Florida. *Computers and Geosciences, 34*(7), 815–826.

Pearlstine, L., Higer, A., Palaseanu, M., Fujisaki, I., & Mazzotti, F. (2007). *Spatially continuous interpolation of water stage and water depths using the Everglades Depth Estimation Network (EDEN), spatially continuous interpolation of water stage and water depths using the Everglades Depth Estimation Network (EDEN)*. CIR1521. Institute of Food and Agricultural Sciences, University of Florida.

Peuker, T., & Douglas, D. (1975). Detection of surface-specific points by local parallel processing of digital terrain elevation data. *Computer Graphics and Image Processing, 4*, 375–387.

RECOVER. (2004). *CERP monitoring and assessment plan: Part 1. Monitoring and supporting research. Restoration coordination and verification program, c/o United States Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, and South Florida Water Management District, West Palm Beach, Florida*.

Rutchey, K, Schall, T. N., Doren, R. F., Atkinson, A., Ross, M. S., Jones, D. T., et al. (2006). Vegetation classification for South Florida natural areas. U.S. geological survey open-file report 2006–1240.

Rutchey, K., Schall, T. N., & Sklar, F. (2008). Development of vegetation maps for assessing Everglades restoration progress. *Wetlands, 28*, 806–817.

Sandells, M. J., Davenport, I. J., & Gurney, R. J. (2008). Passive L-band microwave soil moisture retrieval error arising from topography in otherwise uniform scenes. *Advances in Water Resources, 31*, 1433–1443.

Simard, M., Zhang, K. Q., Rivera-Monroy, V. H., Ross, M. S., Ruiz, P. L., Castaneda-Moya, E., et al. (2006). Mapping height and biomass of mangrove forests in Everglades National Park with SRTM elevation data. *Photogrammetric Engineering and Remote Sensing, 72*, 299–311.

Snyder, S. A., Whitmore, J. H., Schneider, I. E., & Becker, D. R. (2008). Ecological criteria, participant preferences and location models: a GIS approach toward ATV trail planning. *Applied Geography, 28*, 248–258.

Stewart, M. D., Bates, P. D., Anderson, M. G., Price, D. A., & Burt, T. P. (1999). Modeling floods in hydrologically complex lowland river reaches. *Journal of Hydrology, 223*(1–2), 85–106.

Tappeiner, U., Tasser, E., & Tappeiner, G. (1998). Modelling vegetation patterns using natural and antropogenic influence factors: preliminary experience with a GIS based model applied to an Alpine area. *Ecological Modelling, 113*, 225–237.

Tarboton, D. G. (1997). A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources Research, 33*(2), 309–319.

Telis, P. A. (2006). The Everglades Depth Estimation Network (EDEN) for support of ecological and biological assessments. U.S. geological survey fact sheet 2006–3087.

USFWS. (2000). *A.R.M. Loxahatchee National Wildlife Refuge comprehensive conservation plan*. Boynton Beach, FL: U.S. Fish and Wildlife Service.

Vaughn, S., & Crawford, T. (2009). A predictive model of archaeological potential: an example from northwestern Belize. *Applied Geography, 29*, 542–555.

Wu, S., Li, J., & Huang, G. H. (2008). A study on DEM-derived primary topographic attributes for hydrologic applications: sensitivity to elevation data resolution. *Applied Geography, 28*, 210–223.

Xie, Z., Gawlik, D. E., Beerens, J. M., Liu, Z., & Higer, A. (2009). Variability patterns and outlier smoothing of the Everglades Depth Estimation Network digital elevation model in the Northern Everglades. *Papers of the Applied Geography Conferences, 32*, 342–351.