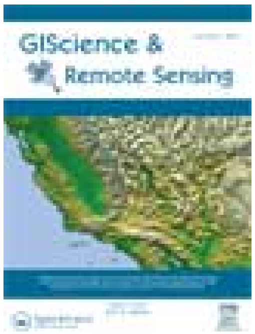

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Developing a Fine-Resolution Digital Elevation Model to Support Hydrological Modeling and Ecological Studies in the Northern Everglades

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Abstract: Accurate high-resolution terrain data are essential for hydrological modeling in lowlands. This study integrates elevation survey data and vegetation data at the point and 50 m scales to develop a fine-resolution digital elevation model (DEM) for the northern Everglades of Florida. The terrain was divided into two vertical strata (lowland and highland) based on a 50 m scale vegetation map. The DEM in highlands was interpolated with all the survey points and later adjusted using an association between vegetation and hydroperiod (the number of days per year that land is flooded). The DEM in lowlands was interpolated with elevation surveys tagged as lowland types. The two DEMs were then combined, forming a new DEM with a 7.7 cm mean absolute validation error—a significant (2.3 cm) improvement over the previous DEM.

INTRODUCTION

Understanding and modeling hydrology is of particular importance in wetland studies and restoration because the hydrologic regime is regarded as the most important driver of wetland structure and function (National Research Council, 1995). Accurate ground elevation data provides the foundation for modeling hydrological regimes at the landscape level. Previous studies (Stewart et al., 1999; Hudson and Colditz, 2003; Colby and Dobson, 2010) have demonstrated that accurate high-resolution terrain data greatly improved the predictive ability of hydraulic and hydrological models in lowland areas because lowland topography strongly influences hydrologic processes (Farajalla and Vieux, 1995; Bates et al., 1997; Hardy et al., 1999; Moglen

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and Hartman, 2001). High-resolution terrain data capture the heterogeneity of physical systems and derive important model parameters such as basin relief, flow length, flow depth and direction, hydroperiod, spatial and temporal extent of drying, runoff, and flood volume.

The Greater Everglades in south Florida is a unique subtropical wetland system. Once an immense freshwater marsh covering about 31,000 km^2 and known as the "River of Grass," it has been reduced to about 10,000 km^2 as a result of intensive land conversion and water management in the past several decades. The Everglades is extremely flat, with only a 55–135 cm difference in elevation from the highest points (tree islands) to the lowest (sloughs). Due to its unique ecological significance, enormous resources and efforts have been devoted to its restoration. Improvement of hydrology lies at the core of the Comprehensive Everglades Restoration Plan (CERP) (RECOVER, 2005; Sklar et al., 2005), a greater than $10.5 billon mission authorized by the U.S. Congress. Simply put, the CERP intends to restore the unique Everglades wetland ecosystem by producing water flows that mimic historical flows as closely as possible in depth, timing, spatial extent, and duration of flooding across the landscape (Sklar et al., 2005).

The importance of accurate digital elevation models (DEM) has been well recognized in CERP. The Everglades Depth Estimation Network (EDEN) project has been developed to provide critical, spatially continuous hydrologic datasets that support analysis and modeling of the Everglades ecosystem (Telis, 2006), including interpolated daily water depth surfaces and hydroperiods. EDEN data are actively used by various research teams and for restoration decisions. The foundation data in EDEN is a DEM at a 400 m resolution, and daily water-level surfaces for the past decade that share the same grid cell structure. While the EDEN DEM represents the most reliable DEM available for the Greater Everglades, there is a need to refine the Everglades ground DEM to a finer resolution if possible so that the micro-topography can be reflected and the hydrological regime pattern can be better characterized.

This study integrates elevation and vegetation data from the U.S. Geological Survey (USGS) High Accuracy Elevation Dataset (HAED), and the recently available South Florida Water Management District (SFWMD) 2004 vegetation map, to develop a 50 m resolution ground elevation model in Water Conservation Area One (WCA1), managed by the U.S. Fish and Wildlife Service as the the Arthur R. Marshall Loxahatchee Wildlife Refuge. A scale of 50 m was chosen because it is approximately the scale of the slough and ridge structure in the Everglades and it is the spatial resolution of the 2004 vegetation map. The resulting DEM will supply a sound foundation for scientific research and improved modeling of hydrological and ecological processes that are important indicators for CERP (RECOVER, 2005).

DATA AND METHODS

Data

High Accuracy Elevation Dataset. Elevations and vegetation types at elevation points were collected via Airborne Height Finder (AHF), an innovative field survey built on differential GPS technology, an airborne GPS platform, and a high-tech version of the surveyor's plumb bob (Desmond, 2003). The AHF was designed by the USGS to suit the unique terrain surface in the Everglades, which is typically underwater, obscured by vegetation, and extremely flat, thereby precluding the use of commonly recognized methods for accurate elevation data collection, such as photogrammetry, light detection and ranging (LiDAR), and interferometric synthetic aperture radar (IFSAR; Desmond, 2003). The HAED data are the most accurate system-wide point elevation data available for the Everglades. Collected at a roughly 400 m × 400 m grid, the general accuracy specification of AHF is 15 cm. However a test conducted by USGS in the year 2000 using 17 National Geodetic Survey first-order benchmarks indicated a better accuracy, with an average error of 3.3 cm, minimum of 0.2 cm, maximum of 8.6 cm, and a root mean square error (RMSE) of 4.1 cm (Desmond, 2003).

Vegetation Map. The SFWMD 2004 vegetation map is the latest reliable interagency vegetation map for WCA1, with vegetation types defined by Rutchey et al. (2006) and mapped by Rutchey et al. (2008). The vegetation map was produced using a stereoscopic analysis of 1:24,000-scale aerial color-infrared positive transparencies that were photographed in December 2003. The minimum mapping unit is 50 m × 50 m.

EDEN Water Levels. Daily median water-level data from January 1, 2000 to December 31, 2010 were downloaded from the SOFIA website (http://sofia.usgs.gov/EDEN, last accessed July 31, 2011). The median water level is derived from hourly water-level readings at approximately 250 real-time gaging stations. Artificial intelligence procedures were used for data gap-filling (Conrads and Roehl, 2007; Conrads and Petkewich, 2009).

EDEN Water Surfaces. Daily water-level surfaces since the year 2000 were created from the daily median water-level point data by the EDEN project team using a radial basis function (RBF) interpolation method (Pearlstine et al., 2007; Palaseanu and Pearlstine, 2008). Water-level surfaces share the same 400 m grid structure as the EDEN ground DEM, which is also available from the USGS SOFIA website. Liu *et al.* (2009) conducted a validation of EDEN water-level surfaces and reported a RMSE of 3.3 cm.

Researcher Water Depth Measurements. Water depth data were collected by five research teams (hereafter researchers) during the course of their field studies. Depths were measured at a total of 1,515 location and date combinations from 2000 to 2007. Some sites were visited multiple times.

Development of a 50 m DEM

The current release (January 2010) EDEN DEM in WCA1, developed with the USGS HAED data, is at 400 m resolution (Xie et al., 2011). This study developed a 50 m resolution DEM by HAED data filtering and lowland DEM development with filtered data, highland DEM development with all HAED data, DEM extraction and merging, DEM assessment, and DEM adjustments.

HAED Data Filtering and Lowland DEM Development. The relatively low lying areas in the Greater Everglades are of particular ecological significance because these areas may hold water in dry conditions and sustain forage fishes for some important indicator species, such as wading birds (*Pelecaniformes*), alligators (*Alligator mississippiensis*), etc. The latter are referred to as indicator species because their health indicates the success or failure of Everglades restoration efforts (RECOVER, 2004). WCA1 is characterized by numerous small elevated "spikes" (pop-up peat mats

Table 1. HAED Points in WCA1 and the Types Reclassified as Lowland Types

HAED vegetation type	*N* HAED points	Lowland
NODATA	17	
Alligator Hole	2	
Cattail	286	Yes
Lygodium	33	
Melaleuca	46	
Open Water	43	Yes
Sawgrass	999	Yes
Shrub	382	
Slough	580	Yes
Tree Island	119	
Wet Prairie	907	Yes
Willow Shrub	81	

colonized by vegetation, degraded and dissected tree islands, etc.). Interpolation with elevations surveyed on these "high points" may upwardly bias the DEM at nearby low-lying areas.

In the current release 400 m EDEN DEM, a filtering procedure was conducted to remove any HAED point falling on a highland if the highland is a minority in a 400 m EDEN grid cell. Vegetation types from the 2004 vegetation map (50 m resolution) were extracted at HAED points and aggregated into six categories over the 400 m grid cell. The categories were: (1) Slough or Open Water; (2) Wet Prairie; (3) Sawgrass and Emergent Marsh; (4) Upland; (5) Exotics and Cattails; and (6) Others (mostly wetland shrub and wetland forested). Categories (4) and (6) were deemed highland because wetland shrubs and forests, although flooded during parts of the year, are at a higher elevation than the surrounding marsh and wet prairie.

In this study, a different filtering procedure was implemented, using vegetation type data collected at the HAED points during the survey. Because these vegetation data are at a point scale, there was no need to apply the majority-based rule in a rather arbitrary 400 m square cell as in the 2004 vegetation map. The filtering therefore should be more objective and reliable. The HAED vegetation field has 11 types (Table 1). In this step, we only selected the HAED points at low-lying areas (hereafter lowland), including: (1) Cattail; (2) Open Water; (3) Sawgrass; (4) Slough; and (5) Wet Prairie. Because lowland areas are the background matrix of the WCA1 wetland landscape, a majority of the HAED data should fall within lowland and be sufficient for elevation interpolation at this vertical stratum. The selected lowland HAED points were then used to develop a DEM with kriging in ESRI ArcGIS 9.3.1. The DEM was rasterized to 50 m cells, spatially aligned with the 50 m minimum mapping units of the 2004 vegetation map.

Highland DEM Development. A DEM was developed for highlands with all HAED points in WCA1 using kriging in ESRI ArcGIS 9.3.1. All HAED data were

Table 2. Lowland Vegetation Types in WCA1 Extracted from the SFWMD Vegetation Map

Code	Vegetation type name	# Cells
MFB	Broadleaf Emergent Marsh	1091
MFBa	Leather Fern	39
MFF	Floating Emergent Marsh	2,173
MFG	Graminoid Freshwater Marsh	28
MFGa	Panicgrass	10
MFGc	Sawgrass	45,592
MFGe	Spikerush	106
MFGh	Common Reed	27
MFGtD	Cattail Dominant	6,282
MFGtM	Cattail Monotypic	5,348
MFGtS	Cattail Sparse	538
MFH	Herbaceous freshwater marsh	101
MFO	Open Marsh	111,916
OW	Open Water	1,914

used for interpolation instead of only the highland points because highlands are not as continuous as the lowlands spatially and mostly have the form of islands in a lowland matrix. The DEM was rasterized to the same 50 m cells, spatially aligned with the minimum mapping units of the 2004 vegetation map.

DEM Extraction and Merging. The two DEMs developed in the previous two steps were merged to form a unified DEM, so that both the highland and lowland areas were well represented. The 2004 vegetation map was utilized to first divide the WCA1 into lowland and highland areas (Table 2). The vegetation classification system is hierarchical and it was a relatively straightforward process to create the division. Lowland areas corresponded to the two top levels of the vegetation categories: Marsh and Open Water. Areas other than the lowland areas were combined to form the highland areas, although strictly speaking they also included categories such as exotic species. The delineated lowland boundaries were then used to extract the elevation from the lowland DEM developed in the preceding paragraph. The highland boundaries were used to extract elevation from the DEM described in this paragraph. The two extracted elevation datasets were then merged into one unified DEM for WCA1 (hereafter Merge DEM).

DEM Assessment with Independent Researcher Water Depths

The developed DEM was assessed with validation and cross-validation, two common DEM assessment methods (Maune et al., 2001). Following Xie et al. (2009, 2011), the validation was based on a secondary, independent elevation dataset which was the result of deducing researcher depth measurements from EDEN daily water-level surfaces on the date 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.

WCA1 Water-Level Surface Interpolation Model

A water-level surface is one of the key datasets for deriving other hydrological datasets, such as water depth and hydroperiod. It is also used to estimate ground elevation from researcher-surveyed depths. An EDEN system-wide water surface model has been utilized by various scientists for Everglades research. The water surface model, especially in western WCA1, has recently been revised by EDEN team. An initial study showed that water surface in western WCA1 in the revised model has been improved. The study also noticed that higher cross-validation errors were observed in the pseudo–canal stations used to represent the abrupt water-level changes across subareas such as WCA1 and WCA2, which are separated by levees and canals. Thus, a water surface model (hereafter subarea model) was developed specifically for the WCA1 water surface interpolation by incorporating the new understandings and removing pseudo-stations. The subarea model was run to produce daily median water surfaces from 2000 to 2010.

DEM Adjustment with Supplementary Data

It is not uncommon to adjust a DEM with supplementary data if these data are helpful. In a previous study, DEM smoothing was tested based on hydroperiod information in neighboring areas with a similar vegetation type (Xie et al., 2009). Wetland vegetation types in the Everglades are believed to be strongly influenced by hydroperiods; therefore, we also adjusted the DEM based on the association between vegetation types and hydroperiods, although not as in Xie et al. (2009) (Figure 1).

First, the vegetation-hydroperiod associations and outlier detection rules were computed based on the reclassified HAED vegetation, HAED elevation, and the new subarea model water-level surfaces from 2000 to 2010. Because the HAED data have fewer vegetation types, the vegetation of HAED and SFWMD vegetation maps were both reclassified so that the key types could be semantically matched (Tables 3 and 4). Only four reclassified vegetation types were used in the adjustment process based on their representativeness and data quantity: Forest (F), Shrubland (SS), Marsh (MF), and Water (OW).

Second, the outlier detection rules were based on analysis of percentiles of the hydroperiod distribution of a vegetation type, instead of strictly being based on boxplots of hydroperiod vs vegetation type, which could be misleading. Figure 2 shows the boxplot of reclassified vegetation types of the 2004 vegetation map vs. hydroperiods. If solely based on the boxplot, some forest cells with hydroperiods of over 350 days were still deemed non-outliers. This is highly suspect, given that forest types are located at the higher end of the elevation gradient in WCA1. Because HAED data may be subject to various errors and outliers, the hydroperiods at the 5th and 95th percentiles of a vegetation type were assumed to be the threshold for detecting potential outliers. (Table 5). These thresholds, established at the point scale, were applied to detect outliers in the 50 m Merge DEM, by comparing the thresholds against the tabulation of

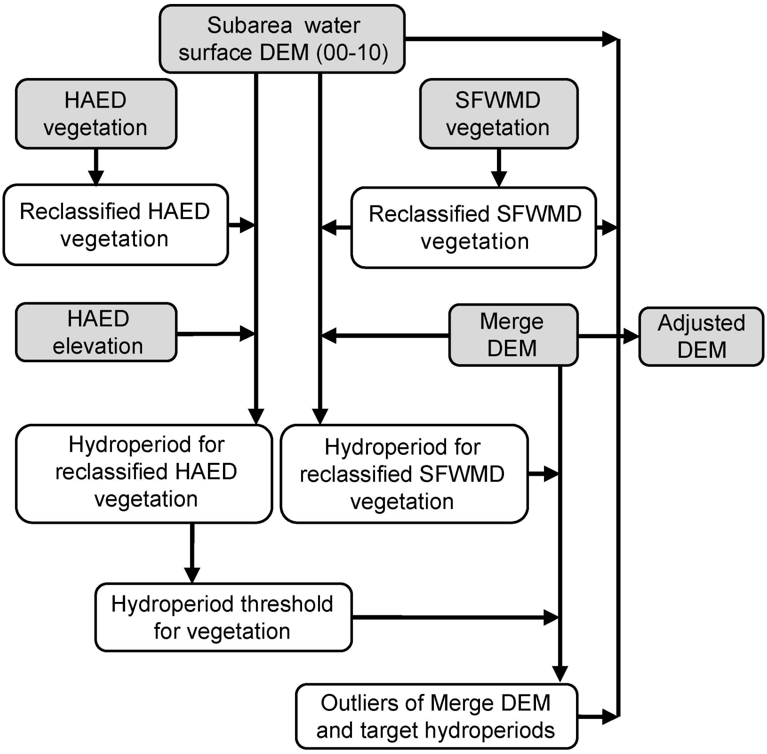

Fig. 1. Outline of the DEM adjustment workflow. The inputs and final output are shaded.

the modeled hydroperiods and reclassified SFWMD vegetation types at 50 m resolution. The modeled hydroperiods at 50 m resolution were computed from the subarea water surface model and Merge DEM.

Third, the DEM outliers were adjusted with elevation values reverse-calculated from a target hydroperiod and the modeled daily water surfaces for the period 2000–2010. For each vegetation type, a common hydroperiod, which is within the normal hydroperiod range of that vegetation type, was set as the target hydroperiod to be used for DEM outlier adjustment. Then for each DEM outlier cell (50 m), the water surface values of 4,015 (11 × 365) days at that DEM cell were analyzed to find the elevation that could result in the target hydroperiod.

RESULTS

HAED Data Filtering and DEM Development

There were 3,537 HAED points in WCA1, and one outlier was detected through exploratory spatial data analysis. Out of the remaining 3,536 HAED points, 2,845 points fell in lowlands, based on the HAED vegetation field. Because there is a slight spatial trend decreasing from north to south, consistent with the water flow direction, a universal kriging model was chosen for developing two DEMs with lowland data and

Table 3. SFWMD Vegetation and Reclassification

SFWMD vegetation map			Reclassification	
Code	*N* of cells	Name	Code	Name
CA	1,972	Canal	CA	Canal
CSGc	12,521	Swamp Scrub-Sawgrass	CS	Swamp-Scrub
CSO	442	Swamp Scrub-Open Marsh	CS	Swamp-Scrub
EcD	5	Australian Pine Dominant	Ec	Australian-Pine
EcS	1	Australian Pine Sparse	Ec	Australian-Pine
EcST	2	Treated Australian Pine Sparse	Ec	Australian-Pine
ElD	302	Cogongrass Dominant	El	Cogongrass
ElM	13	Cogongrass Sparse	El	Cogongrass
ElS	111	Cogongrass Monotypic	El	Cogongrass
EmD	699	Melaleuca Dominant	Em	Melaleuca
EmM	150	Melaleuca Monotypic	Em	Melaleuca
EmS	138	Melaleuca Sparse	Em	Melaleuca
EmMT	176	Treated Melaleuca Monotypic	Em	Melaleuca
EmDT	324	Treated Melaleuca Dominant	Em	Melaleuca
EmST	102	Treated Melaleuca Sparse	Em	Melaleuca
EsM	2	Brazilian Pepper Monotypic	Es	Brazilian Pepper
EsD	48	Brazilian Pepper Dominant	Es	Brazilian Pepper
EsS	38	Brazilian Pepper Sparse	Es	Brazilian Pepper
EsST	1	Treated Brazilian Pepper Sparse	Es	Brazilian Pepper
FS	63	Swamp Forest	F	Forest
FSB	3,591	Bayhead Forest	F	Forest
FHT	3	Temperate Hardwood Hammock	F	Forest
FSH	6	Hardwood Swamp Forest	F	Forest
FSt	1	Cypress Forest	F	Forest
MFB	1,091	Broadleaf Emergent Marsh	MF	Marsh
MFBa	36	Leather Fern	MF	Marsh
MFF	2,173	Floating Emergent Marsh	MF	Marsh
MFG	28	Graminoid Freshwater Marsh	MF	Marsh
MFGa	10	Panicgrass	MF	Marsh
MFGe	106	Spikerush	MF	Marsh
MFGh	27	Common Reed	MF	Marsh
MFGc	45,591	Sawgrass	MF	Marsh
MFGtD	6,282	Cattail Dominant	MF	Marsh
MFGtM	5,348	Cattail Monotypic	MF	Marsh
MFGtS	538	Cattail Sparse	MF	Marsh
MFH	101	Herbaceous freshwater marsh.	MF	Marsh
MFO	111,916	Open Marsh	OW	Water
OW	1,914	Open Water	OW	Water
PS	2	Pump Station	PS	Pum-Station
SP	1,109	Spoil	SP	Spoil
SS	15,566	Swamp Shrubland	SS	Shrubland
SSB	8,039	Bayhead Shrubland	SS	Shrubland
SSl	44	Primrosewillow Shrubland	SS	Shrubland
SSs	6,378	Willow Shrubland	SS	Shrubland
SSa	2	Pond Apple Shrubland	SS	Shrubland

Table 4. HAED Vegetation Types and the Reclassification to Match SFWMD Vegetation Reclassification

HAED vegetation type	*N* *of* points	Reclassification name	SFWMD vegetation code
NODATA	17		
Alligator Hole	2	Alligator Hole	
Cattail	286	Marsh	MF
Lygodium	33	Lygodium	
Melaleuca	46	Melaleuca	EM
Open Water	43	Water	OW
Sawgrass	999	Marsh	MF
Shrub	382	Shrub	SS
Slough	580	Water	OW
Tree Island	119	Tree	F
Wet Prairie	907	Marsh	MF
Willow Shrub	81	Shrub	SS

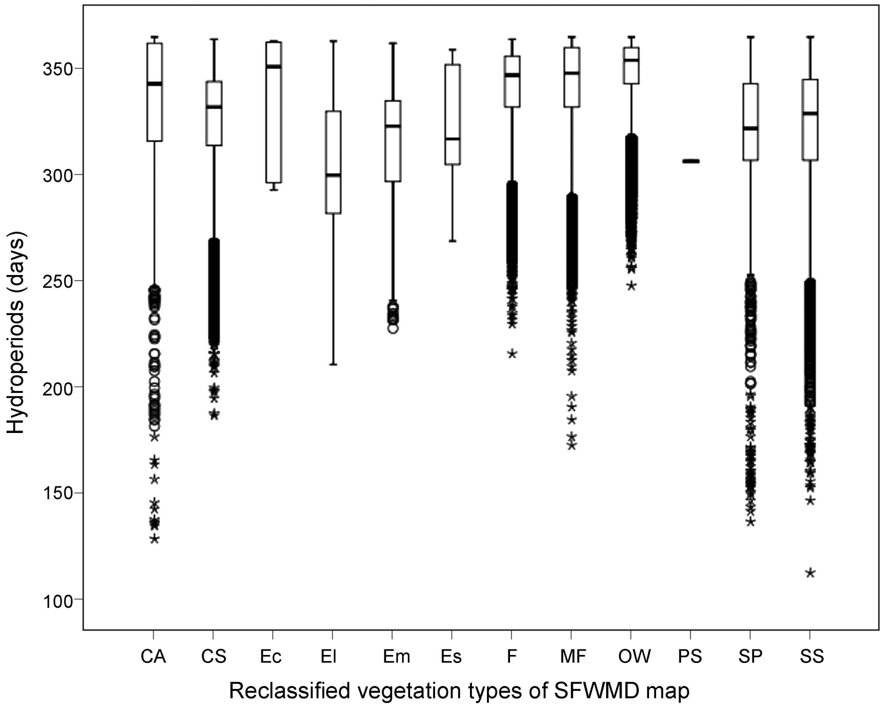

Fig. 2. Boxplot of reclassified vegetation types of SFWMD map vs. hydroperiods.

Table 5. Hydroperiod Percentiles for HAED Data

Reclassified HAED vegetation types	Hydroperiod percentiles (days)						
	5	10	25	50	75	90	95
Marsh	***273***	298	322	344	359	363	364
Shrub	132	191	271	305	331	350	***358***
Forest	2	11	112	212	288	317	***328***
Water	***327***	336	352	361	364	365	365

[a]Values in bold italicized type were chosen as thresholds. The Merge DEM cells with hydroperiod higher than the 95 percentile thresholds for forest and shrubland, or lower than the 5% percentile thresholds for marsh and water, are deemed potential outliers for DEM adjustment.

Table 6. Kriging Models and Cross-Validation Results for the 50 m DEM with Filtered Lowland Data and the 50 m DEM with All Data

	DEM with lowland data[a]	DEM with all data[b]
Model details		
Kriging method	Universal	Universal
Lag size	400 m	400 m
Number lags	46	46
Trend	1st	1st
Anisotropy	Yes	Yes
Semivariogram model	Spherical (1)	Spherical (2)
Number of points	2285	3536
Cross-validation		
Mean error (m)	–0.003473	–0.003036
Root mean square error (m)	0.1379	0.1589
Average standard error (m)	0.1431	0.1587
Mean standardized (m)	–0.02395	–0.01861
Root mean square standardized (m)	0.9608	0.9978

[a]0.01535 × spherical(18026,13210,306.4) + 0.018527 × nugget.
[b]0.019805 × spherical(17744,10873,314.1) + 0.022809 × nugget.

all data respectively. The DEMs were rasterized to 50 m cells, spatially aligned with the minimum mapping units of the 2004 vegetation map. The models and the cross-validation results are shown in Table 6. The two DEMs are also shown in Figure 3.

Figure 4 shows the DEM extracted with lowland and highland masks for representing the terrain in those strata, as well as the merged DEM (hereafter Merge DEM)

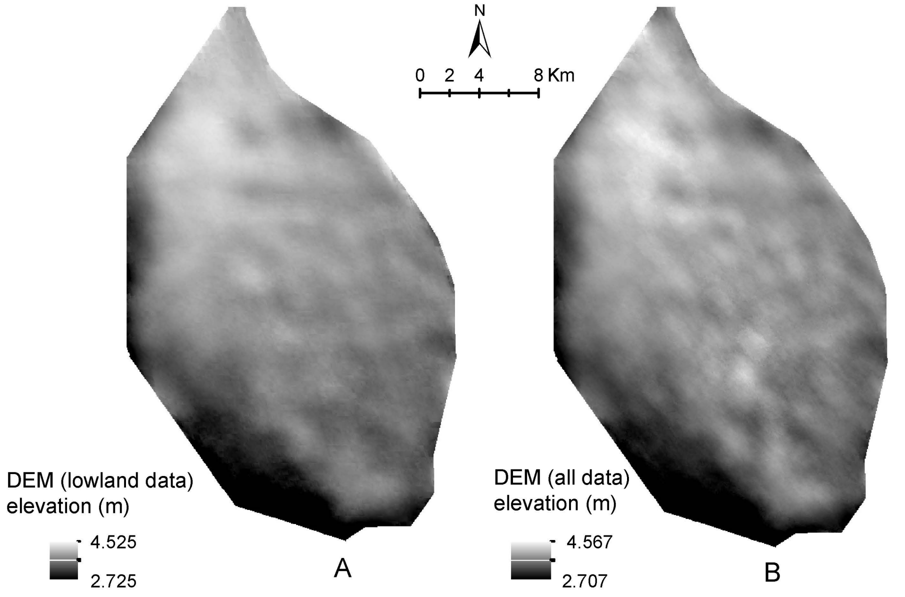

Fig. 3. DEMs developed with (A) filtered lowland HAED data and (B) all HAED data.

and the current EDEN DEM. Compared with the current EDEN DEM, the Merge DEM clearly preserves more micro-topography, which was largely smoothed out in the 400 m cells of the EDEN DEM.

Validation with Researcher-Derived Elevation Data

The locations of researcher measurements are shown in Figure 5. Table 7 presents the statistics (mean, standard deviation) of the errors or differences between the elevation derived from researcher water depths (**O**) and the three DEMs (**P**): EDEN 400 m DEM (**EDEN DEM**), 50 m DEM with all HAED data (**All50 DEM**), and 50 m DEM by merging the lowland and highland DEMS **(Merge DEM**). We included the All50 DEM in comparison to examine whether the performance differences between the EDEN DEM and the Merge DEM were related to the interpolation scales of either 400 m or 50 m. The Merge DEM reduced the average differences from –25.3 cm to –19.8 cm as compared to the current release EDEN DEM. The improvements mainly ocurred when the observed elevation was lower than the model-predicted elevation, indicating that Merge DEM had less overestimation of elevation than did the EDEN DEM. All50 DEM performance was intermediate between the two.

In Table 7, each survey (point and date combination) was treated as one sample. In Table 8, each location was given the same weight, with the average elevation being used when the location was suveyed multiple times. The table shows that the magnitude of average differences was greatly reduced in all three models; however, the Merge DEM again had the best overall performance. Not surprisingly, the All50 DEM performed similarly to the EDEN DEM because they use similar input datasets.

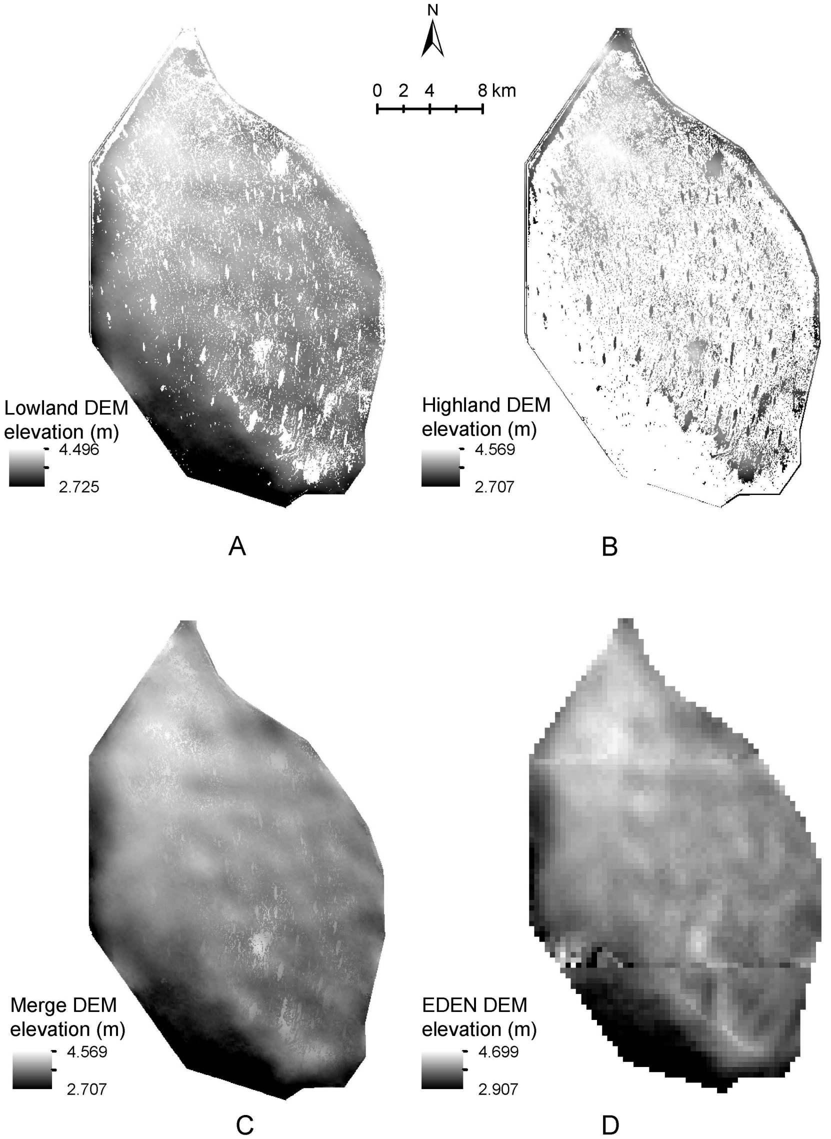

Fig. 4. DEMs extracted with lowland and highland masks for representing the terrain in (A) lowland areas and (B) highland areas. The merged DEM is shown in (C) and the current EDEN DEM in (D).

Tables 9 and 10 show the statistics of the absolute difference between observed and modeled elevation, statistics by researcher, and differences due to measurement methods or locations. The Merge DEM had significantly smaller differences from observed than did the EDEN DEM. Also, one research group (N) had dramatically larger differences from the modeled elevation, even using the Merge DEM. As shown in Figure 5, the survey from researcher N (713 records) covered multiple dates, but

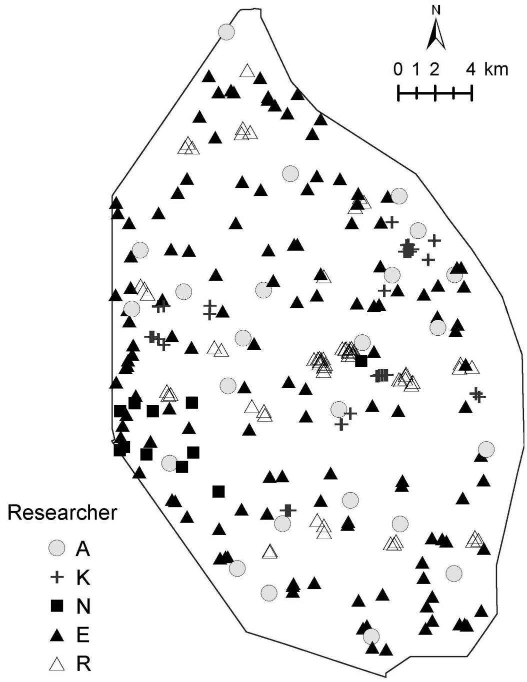

Fig. 5. Locations of depth measurements by five different researchers. Some sites were surveyed multiple times.

Table 7. Statistics for the Difference (cm) between the Elevation Derived from Researcher Depths (O) and the Three DEMs (P)[a]

(O – P)	O – EDEN DEM			O – All50 DEM			O – Merge DEM		
	Overall	O < P	O > P	Overall	O < P	O > P	Overall	O < P	O > P
N of records	1515	1277	238	1515	1262	253	1515	1176	339
Ave diff (O – P)	–25.3	–31.2	6.3	–22.1	–27.8	6.2	–19.8	–27.4	6.6
SD	29.4	28.2	5.3	27.0	25.9	6.0	27.9	27.0	6.3

[a]The three DEMS are EDEN 400 m DEM (EDEN DEM), 50 m DEM with all HAED data (All50 DEM), and 50 m DEM by merging the lowland and highland DEMS (Merge DEM). The number of records represents the total number of point and date combinations.

was concentrated in only 11 locations in the midwest corner of the study area. Because the researcher repeated the measurements multiple times, we surmised that the large errors are unlikely due to measurement, but are possibly from the DEM or water surface models. Other researchers and the EDEN team also noticed potential problems with the water surface models in the same areas, which was one of the reasons motivating the development of a subarea model.

Table 8. Statistics for the Difference (cm) between the Elevation Derived from Researcher Depths (O) and the Three DEMs (P)[a]

(O – P)	O – EDEN DEM			O – All50 DEM			O – Merge DEM		
	Overall	O < P	O > P	Overall	O < P	O > P	Overall	O < P	O > P
N of unique points	809	595	214	809	598	211	809	515	294
Ave diff (O – P)	–8.3	–13.8	5.7	–8.4	–13.3	5.4	–4.8	–11.0	6.0
SD	12.9	10.9	4.5	12.4	10.5	4.7	12.3	10.7	5.6

[a]The three DEMs are EDEN 400 m DEM (EDEN DEM), 50 m DEM with all HAED data (All50 DEM), and 50 m DEM by merging the lowland and highland DEMS (Merge DEM). For each point with surveys at multiple dates, the average elevation is used for that point.

Table 9. Statistics for the Absolute Difference (cm) Between the Elevation Derived from Researcher Depths (O) and the Three DEMs (P)[a]

Researcher (*N* of points)	|O – EDEN DEM|		|O – All50 DEM|		|O – Merge DEM|	
	Ave.	SD	Ave.	SD	Ave.	SD
A (24)	17.8	15.2	17.5	15.2	16.2	15.4
K (575)	11.2	8.2	10.9	8.5	8.4	7.7
N (713)	45.2	30.0	39.1	28.6	38.2	29.0
E (133)	9.6	12.5	8.8	11.4	9.0	11.2
R (70)	12.8	9.5	13.3	9.6	10.5	9.3
Overall (1515)	27.3	27.5	24.2	25.1	22.7	25.5

[a]The three DEMS are the EDEN 400 m DEM (EDEN DEM), 50 m DEM with all HAED data (All50 DEM), and the 50 m DEM by merging the lowland and highland DEMS (Merge DEM). The number of records represents the total number of point and date combinations. The statistics are tabulated by different researchers.

Subarea Model Development

The differences between the current EDEN water surface model and the subarea model are shown in Table 11. Two subarea models were tested with different Radial Basis Function (RBF) kernels. The first subarea model used the same kernel setting as the current EDEN domain model. The second subarea model model relaxed the neighborhood search from eight sectors to one sector, and from a minimum of eight neighbors to four, because of the small number of gages in WCA1 and because we felt the new setting may utilize the gages more effectively. The second subarea model also changed from the multiquadric kernel to the inverse multiquadric kernel, with the kernel parameter optimized in ArcGIS 9.3.1. There was a slight change of input in subarea models: one canal gage (G301-T) was removed from the input based on recent

Table 10. Statistics for the Absolute Difference (cm) Between the Elevation Derived from Researcher Depths (O) and the three DEMs (P)[a]

Researcher (N of points)	|O – EDEN DEM|		|O – All50 DEM|		|O – Merge DEM|	
	Ave.	SD	Ave.	SD	Ave.	SD
A (24)	17.8	15.2	17.5	15.2	16.2	15.4
K (573)	11.2	8.2	10.9	8.4	8.4	7.7
N (11)	40.0	18.7	32.8	18.4	31.5	19.5
E (133)	9.6	12.5	8.8	11.4	9.0	11.2
R (68)	12.9	9.5	13.4	9.6	10.6	9.4
Overall (809)	11.7	10.2	11.2	10.0	9.2	9.5

[a]The three DEMS are the EDEN 400 m DEM (EDEN DEM), the 50 m DEM with all HAED data (All50 DEM), and the 50 m DEM by merging the lowland and highland DEMS (Merge DEM). For each point with surveys at multiple dates, the average elevation is used for that point. The statistics are tabulated by different researchers.

Table 11. Model Parameters of the EDEN Domain Model and the WCA1 Subarea Models

	EDEN domain model	WCA1 subarea model-1	WCA1 subarea model-2
Kernel type	Multiquadric	Multiquadric	Inverse multiquadric
Kernel parameter	16.77	16.77	4527.10
Neighbours max	1	1	8
Neighbours min	1	1	4
Sector type	Eight	Eight	One
Angle	350	350	350
Major semi-axis	31000	31000	31000
Minor semi-axis	30000	30000	30000

recommendations by the EDEN team. Another major difference not shown in the table was that a large number of pseudo canal gages defining the sourthern WCA1 boundary were used as input to the EDEN water surface model but not the subarea model because the original reasons for having these gages is not applicable in the subarea models. A validation with water levels surveyed at six benchmarks with a total of 18 records did not show significant differences between these models. The average absolute difference between observed and predicted water levels was about 7 cm for all three models. However, as shown in Figure 6, the resulting surfaces of the two subarea models seem more reasonable. The second submodel created a smoother surface than the first, and hence it was chosen as the preferred subarea model.

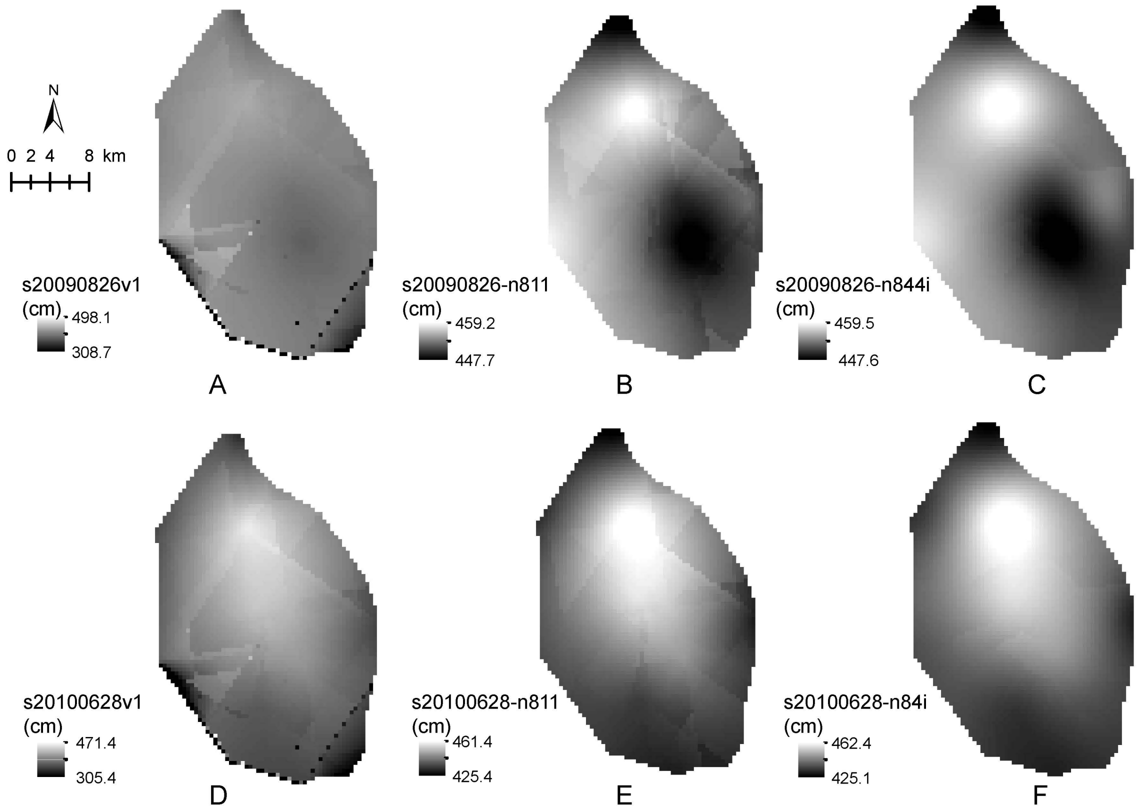

Fig. 6. Water surfaces from the curent EDEN domain model (A) and (D) and the two WCA1 subarea models: the first shown in (B) and (E) and the second shown in (C) and (F), for a dry (upper figures) and wet (lower figures) date.

Table 12. Statistics for the Absolute Difference (cm) between the Elevation Derived from Researcher Depths (O) and the Three DEMs (P)[a]

Researcher (*N* of points)	|O – EDEN DEM|		|O – All50 DEM|		|O – Merge DEM|	
	Ave	SD	Ave	SD	Ave	SD
A (24)	10.9	7.7	9.9	7.6	9.1	7.4
K (575)	10.2	7.3	9.9	7.5	7.5	6.6
N (713)	15.2	12.5	11.4	9.9	10.8	10.0
E (133)	9.5	11.5	8.6	10.9	9.0	10.6
R (70)	8.8	6.0	9.0	6.2	6.3	4.8
Overall (1515)	12.4	10.7	10.4	9.0	9.1	8.8

[a]The three DEMs are the EDEN 400 m DEM (EDEN DEM), the 50 m DEM with all HAED data (All50 DEM), and the 50 m DEM by merging the lowland and highland DEMS (Merge DEM). The number of records represents the total number of point and date combinations. The statistics are tabulated by different researchers. The new subarea model water surfaces are used in researcher elevation computation.

Table 13. Statistics for the Absolute Difference (cm) between the Elevation Derived from Researcher Depths (O) and the Three DEMs (P)[a]

Researcher (*N* of points)	|O – EDEN DEM|		|O – All50 DEM|		|O – Merge DEM|	
	Ave.	SD	Ave.	SD	Ave.	SD
A (24)	10.9	7.7	9.9	7.6	9.1	7.4
K (573)	10.2	7.3	9.8	7.5	7.5	6.6
N (11)	13.0	9.6	10.6	10.3	9.2	10.7
E (133)	9.5	11.5	8.6	10.9	9.0	10.6
R (68)	8.8	6.0	9.0	6.1	6.3	4.8
Overall (809)	10.0	8.1	9.6	8.1	7.7	7.4

[a]The three DEMs are the EDEN 400 m DEM (EDEN DEM), the 50 m DEM with all HAED data (All50 DEM), and the 50 m DEM by merging the lowland and highland DEMS (Merge DEM). For each point with surveys at multiple dates, the average elevation is used for that point. The statistics are tabulated by different researchers. The new subarea model water surfaces are used in researcher elevation computation.

Validation with Elevation Data Derived from Subarea Model and Researcher Depth Measurement

The new water-level surface dataset was used to derive ground elevations from the researcher depth measurements as in the section entitled "Validation with Researcher-Derived Elevation Data," to further validate the DEMs (Tables 12 and 13). The validation based on the newly derived elevation dataset was greatly improved for all DEMs, but the new Merge DEM had significantly lower differences between observed and modeled elevations for all researchers. The largest decrease in errors was for researcher N, from over 30 cm to below 11 cm. Because this researcher conducted repeated surveys at fixed sites over multiple years and dates, the results suggest that the new surfaces should be more accuate and the DEM validation with the new dataset is more reasonable. The Merge DEM had better accuracy than the current release DEM. The new water-level surfaces were used in hydroperiod calculation at both the point and the 50 cm scales.

DEM Adjustments

As discussed in the methods section, based on the statistics of hydroperiods vs. reclassified vegetation types at the point scale, the outlier thresholds for each of the four key vegetation types were set: forest (hydroperiod > 95 percentile, i.e > 328 days), shrub (> 95%, i.e. > 358), marsh (< 5%, i.e. < 273), water (<5%, i.e. < 327). Only a one-sided threshold was set because the major goal is not to under-estimate the elevation of highland and not to over-estimate the elevation of lowland. Outliers were identified in the Merge DEM after overlaying the reclassified vegetation map and computing hydroperiods for each DEM cell. The orginal Merge DEM and the outliers for each of the four types are shown in Figures 7A and 7B. Two types of target hydroperiods were tested for DEM reverse computation and adjustments: (1) 90% hydroperiod for forest and shrub, and 10% hydroperiod for marsh and water; and (2) 95% hydroperiod for only forest and shrub. The first type (90% or 10%) was applied to adjustments of all four kinds of outliers, and the resulting DEM is shown in Figure 7C. To evaluate whether the adjustment was appropriate, we overlaid the researcher data over the adjusted cells and compared the researcher elevation with the modeled elevation before and after adjustments. Only 13 researcher sites fell in the outlier cells and all but 2 of them were “Water” or “Marsh” types, understandably, because these researchers surveyed in only those types. The results showed that the adjusted DEM for the lowland outliers was actually worse than the unadjusted one. As demonstrated in the validation with researcher data, the modeled elevation for lowland may already be accurate. Two highland researcher sites that were classified as forest were very likely mixed cells. The adjustment made one elevation better and the other worse, but both overadjusted the elevation, suggesting the adjustment should be done at a smaller magnitude. In the second type of adjustment (95%), only the highland types of outliers were adjusted, and the resultant DEM is shown in Figure 7D. The elevation accruacy got better for one researcher point, and changed little for the other. A comparison between the DEM before and after adjustment (Figs. 7A and 7D), showed that the adjustment better matched the pattern of tree islands and seemed more appropriate for elevation pattern modeling in WCA1.

DISCUSSION AND CONCLUSIONS

The DEM development adopts a divide-and-conquer strategy to divide the terrain into two vertical strata (lowland and highland) and interpolate them separately before merging back into a whole DEM. Highland data were excluded from interpolation of the lowlands, whereas all the HAED data were used for interpolation of uplands and adjusted based on the association between vegetation types and hydroperiods. The use of the HAED vegetation field for filtering HAED data should be more reliable than

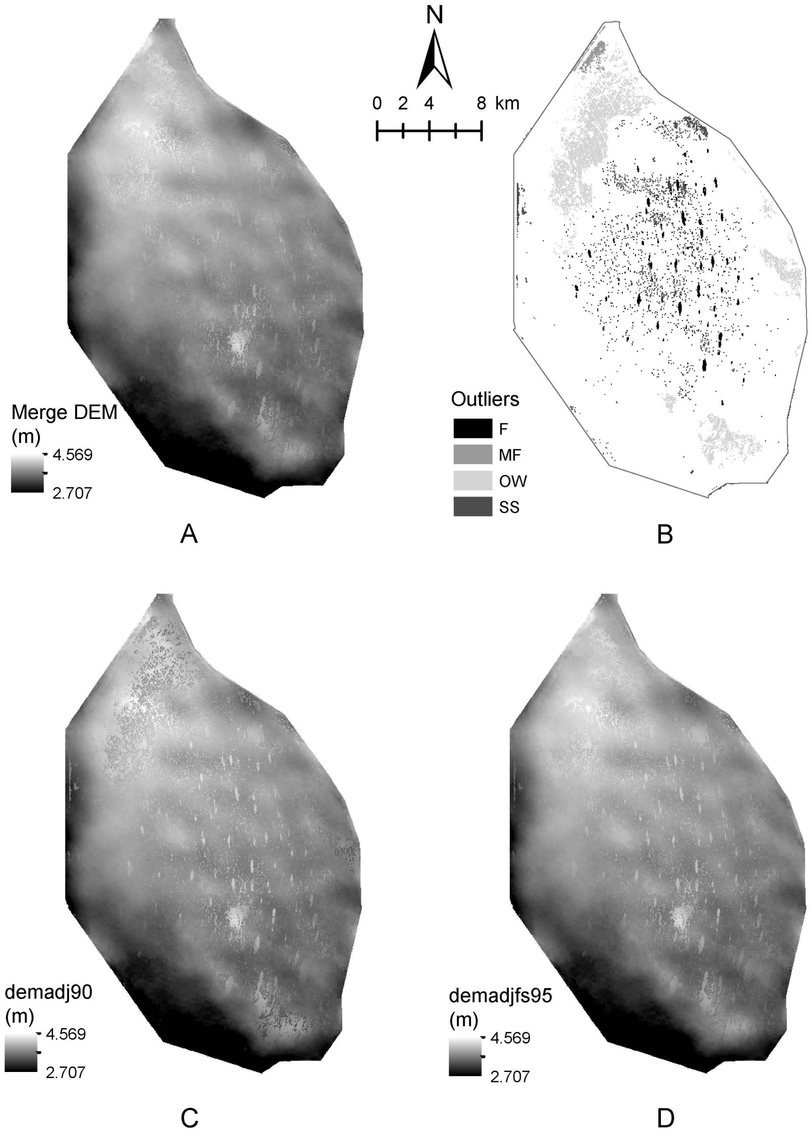

Fig. 7. The Merge DEM (A) before adjustment, (B) the outliers, and (C) the adjusted DEM with target hydroperiod of 90% (F, SS) or 10% (MF, OW), and (D) the adjusted DEM with target hydroperiod of 95% (F, SS).

using information extracted from each 400 m EDEN grid cell overlaid with the 2004 vegetation map, because the vegetation field is part of *in situ* HAED data collection and can be regarded as being at the point scale, whereas the 2004 vegetation map describes a majority of vegetation at arbitrarily delineated 50 m cells, many of which are mixed cells. The overlaying and summary over a 400 m EDEN grid cell before filtering, as was done in previous filtering, introduced another arbitrary boundary and uncertainty that was avoided in the new approach. Adjustment of the highland DEM should also be necessary, as it is unlikely that the HAED survey spaced at a 400 m grid will cover the numerous highlands in WCA1, nor will the interpolation process be able to model all the highlands without proper data support. As a result of all these measures, the developed DEM had a better validation accuracy, with a 7.7 cm overall MAE and a 2.3 cm improvement over the current EDEN DEM. The accuracy improvement is not trivial, given that the Everglades vegetation is responding to an extremely flat elevation gradient—5 cm to 19 cm surface elevation differences among vegetation types in WCA1 (Brandt et al., 2000). Because the HAED data had a RMSE of 4.1cm in a validation with 17 NGS first-order benchmarks (Desmond, 2003) and the current EDEN water surface has an validation RMSE of 3.3 cm (Liu et al., 2009), the accuracy of the Merge DEM should be highly acceptable. It should also be noted that the validation dataset mostly occurred in the targeted lowland areas. Therefore the proposed divide-and-conquer DEM development strategy was most effective in achieving the goal of improving elevation modeling in low-lying areas. The strategy also improved discrimination of highland areas in an apparently realistic fashion; however, additional field observations of highland elevations are necessary to validate these areas.

The secondary elevation data derived from researcher water depths, together with a water surface DEM, have been documented for a DEM validation in previous studies (Xie et al., 2009, 2011). For a more reliable validation, this study developed a subarea water surface model specifically for WCA1. The new water surface DEMs were used for assessing validation with researcher data, computing hydroperiods, and reverse computing elevations from target hydroperiods. The great reduction of validation MAE (over 20 cm), especially for one researcher group, provides good evidence for how errors can propagate in the modeling process. It also suggests that an accurate representation of hydrological regime and pattern depend on the quality of all relevant data models, including ground elevation and water surfaces, and it can be enhanced by the collaborative efforts of scientists in different domains.

To avoid a brute force number-crunching method for outlier detection, the study adopted a simple hydroperiod threshold approach to detect outliers and set adjustment targets. Whereas the DEM adjustments for the highland areas improved the elevation pattern in WCA1, future studies are needed for outlier detection and setting of target hydroperiods essential to a more successful adjustment, especially in other subareas. Nevertheless, the improvement of the micro-topography spatial pattern with this simple approach shows that a careful adjustment could be very beneficial for development of a DEM when elevation survey data are not sufficient. In addition, the divide-and-conquer approach makes it convenient to incorporate other elevation analyses. For example, the ongoing efforts to create elevation models of tree islands could be readily included as part of the adjustment process. The DEM development and adjustment approach described in this study could be extended to develop an Everglades system-wide 50 m resolution DEM once the 50 m resolution vegetation map is completed for the entire area. The resulting DEM would provide more accurate foundation data for Everglades science, restoration, and long-term management.

The AHF elevation survey was a key dataset for DEM development in this study. The AHF elevation survey was very accurate, but it was also costly and hence was conducted at a coarse resolution. The common remote sensing methods for elevation derivation were hindered by the wetland context as well as some operational issues.

However, the recently available small unmanned aerial systems (Hardin and Jensen, 2011a, 2011b; Stefanik et al., 2011) could potentially be very useful for mapping elevation in wetlands because of its rapid deployment and low operational cost.

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