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Validation and ecosystem applications of the EDEN water-surface model for the Florida Everglades†

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ABSTRACT

The Everglades Depth Estimation Network (EDEN) is an integrated network of real-time water-level monitoring, ground-elevation modelling, and water-surface modelling that provides scientists and water managers with current (2000-present), on-line water-level and water-depth information for the freshwater Everglades. Continuous daily spatial interpolations of surface water-level gage data from the EDEN water-surface model are presented on grid with 400-m spacing. The direct model output is continuous daily surface-water level, and other hydrologic data such as water depth and hydroperiod can be derived together with ground digital elevation models.

This paper validated the spatially continuous EDEN water-surface model for the Everglades, Florida by using an independent field-measured dataset. Three model applications were also demonstrated: to estimate site-specific ground elevation, to create water-depth time series for tree islands, and to generate contiguous water coverage areas. We found that there were no statistically significant differences between model-predicted and field-observed water-level data in central Everglades ($p = 0{\cdot}51$). Over 95% of the predicted-water levels matched observed-water levels within the range of ±5 cm. Overall, the model is reliable by a root mean square error (RMSE) of 3·3 cm.

The accurate, high-resolution hydrological data, generated over broad spatial and temporal scales by the EDEN water-surface model, provides a previously missing key to understanding the habitat requirements and linkages among native and invasive populations, including fish, wildlife, wading birds, and plants. The EDEN model is a powerful tool that could be adapted for other ecosystem-scale restoration and management programs worldwide. Copyright © 2009 John Wiley & Sons, Ltd.

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INTRODUCTION

It is widely recognized that hydrologic conditions provide the basic control of wetland structure and functioning (National Research Council, 1995). As an essential feature of prairie wetlands, oscillating water level is highly tied to flora and fauna of these wetlands (van der Valk, 2005). Water depth and hydroperiod are important in determining vegetation composition and structure in the Everglades (Mason and van der Valk, 2003; Givnish *et al.*, 2008). Water-level fluctuations can alter fish behaviour, distribution, and growth (Loftus and Eklund, 1994; Chick *et al.*, 2004; Cott *et al.*, 2008). Loftus and Eklund (1994) reported that in the pull-trap sites in upper Shark River Slough of the Everglades, fish species richness increased from 10 species in 1977–1978 to 17 species in 1984–1985 when the drying of the surrounding marshes concentrated all species into the depressions with water, and the highest monthly fish density (126 fish/m^2) from 1977 to 1985 was recorded during the 1985 drought. Water depth has been repeatedly shown to play an important role in determining where and when wading birds forage and in determining reproductive success (Kushlan, 1976; Frederick and Spalding, 1994; Gawlik, 2002; Gawlik and Crozier, 2007). Gawlik and Crozier (2007) examined foraging-habitat selection by free-ranging wading birds by conducting two experiments in eight and six replicate ponds adjacent to the northern border of the Everglades, and noticed that birds were significantly more attracted to ponds with shallow water (water depth of 10 cm) than to ponds with deep water (water depth of 37 cm) ($p = 0{\cdot}02$ for the eight ponds, and $p < 0{\cdot}01$ for the six ponds). For the endangered Cape Sable seaside sparrow *Ammodramus maritimus mirabilis* water level is a principal driver of fecundity and population dynamics in the Everglades (Nott *et al.*, 1998; Baiser *et al.*, 2008). Water depth and hydroperiod are among the important regional factors affecting distribution and abundance of alligators (*Alligator mississipiensis*) and crocodiles (*Crocodylus acutus*) (Mazzotti and Brandt, 1994; Mazzotti *et al.*, 2008).

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Spatially explicit hydrologic information can be critical in understanding and assessing changes in biotic communities in wetland ecosystems worldwide. In the Florida Everglades, there have been a variety of efforts to measure and link daily and seasonal surface-water depths to biotic communities (Loveless, 1959; Craighead, 1971; Cohen, 1984; Newman *et al.*, 1996; Busch *et al.*, 1998; Gawlik, 2002; Chick *et al.*, 2004; Palmer and Mazzotti, 2004; Trexler *et al.*, 2005; Elderd and Nott, 2008). A traditional way to obtain such hydrologic information is through repeated field measurement, but it is labour and time intensive and does not provide continuous hydrologic data across a large spatial area. Alternatively, hydrologic models can provide spatially and temporally continuous hydrologic information, and are frequently used in ecological and biological research in the Everglades (Fennema *et al.*, 1994; Curnutt *et al.*, 2000; Bolster and Saiers, 2002; Immanuel *et al.*, 2005; South Florida Water Management District, 2005).

Most recently, the Everglades Depth Estimation Network (EDEN) water-surface model was developed by Palaseanu and Pearlstine (2008) based on retrieved water-level data from over 200 real-time gage stations in the Everglades that are operated and maintained by four agencies including the US Geological Survey (USGS), the South Florida Water Management District (SFWMD), the Everglades National Park (ENP), and Big Cypress National Preserve (BCNP). Daily surface-water level is the direct model output. Other hydrologic data including water depth and hydroperiod (the number of days per year an area is inundated with water) can be derived in conjunction with ground digital elevation models (DEMs). EDEN is a collaborative project funded by the Comprehensive Everglades Restoration Plan (CERP) and the USGS Priority Ecosystem Sciences (PES) with support from federal and state government agencies, and scientists in South Florida. Everglades restoration is mainly an attempt to produce 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.*, 2002). The EDEN model provides such critical hydrologic information as water level, water depth, and hydroperiod to examine spatial linkages between habitats and flora and fauna, and to evaluate and assess wetland restoration alternatives in the Everglades. The fine resolution raster-based daily surface-water elevation of the EDEN model allows biologists and ecologists to assess trophic level responses to hydrodynamic changes due to Everglades restoration (Telis, 2006).

There are two objectives in the present paper. Our first objective is to validate the EDEN water-surface model for the central portion of the Florida Everglades by using an independent field-measured water-level dataset. Model validation is generally defined as the process of demonstrating that a given model is capable of making sufficiently accurate predictions. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits (Anderson and Woessner, 1992; Refsgaard, 1997). During model development, Palaseanu and Pearlstine (2008) assessed model performance using the leave-one-out cross-validation method that estimates generalization error based on re-sampling (Weiss and Kulikowski, 1991; Goutte, 1997). However, rigorous model validation requires testing model predictions against an independent dataset that was not used in the model development process (Klemes, 1986; Kirkby *et al.*, 1993; Volin *et al.*, 2008).

Our second objective, presented in Section Ecosystem Applications, is to demonstrate three applications of the EDEN water-surface model. Specifically, we used the water surface model and observed water-depth data to estimate site-specific ground elevation, to create water-depth time series, and to demonstrate a large-scale model application by generating contiguous water coverage areas using a system-wide DEM (Jones and Price, 2007a,b).

Currently there are only over 54 000 surveyed elevation points at approximately 400 m intervals in the Everglades (Desmond, 2003). The first application we present, estimation of ground elevation, will help determine ground-surface elevation of tree islands in a relatively easier and more cost-effective way, and thus can be used to estimate effects of changes in water management regimes by SFWMD on inundation of islands, which is especially important for wildlife habitat conservation. Additionally, the application can make use of thousands of available field water-depth data in the Everglades from researchers in South Florida to provide the corresponding ground-elevation points, and will help verify and improve the EDEN DEM (Liu *et al.*, 2008; Volin *et al.*, 2008).

Some researches in the Everglades used water-level or water-depth variables from nearby gage stations (MacDonald-Beyers and Labisky, 2005; Baiser *et al.*, 2008; Elderd and Nott, 2008) by assuming a flat water surface or from linear regression equations established with nearby gages (Chick *et al.*, 2004; Ruetz *et al.*, 2005). However due to substantial natural variations of ground surfaces in the Everglades, Liu *et al.* (2008) demonstrated that there may be significant differences between gage data and EDEN model-predicted water-level data outside a 0·8 km (or 0·5 mile) radius from marsh gage stations. Site-specific water-depth data derived using the method introduced in this research are more accurate even than those obtained by subtracting the ground DEM from the EDEN water surface, as discussed in Pearlstine *et al.* (2007), as estimated site-specific ground elevation from the first application we present is more accurate than that of the regional 400-m resolution EDEN DEM grid (Jones and Price, 2007a,b). Moreover, this method is much more cost-effective for individual long-term research sites. For a location, only one field water-depth measurement is needed to generate continuous water-depth time series from 2000 to current. Ecologists and biologists have focused more explicitly on the importance of scale to ecological and biological patterns and processes (Turner, 1989; Wiens, 1989; Chick *et al.*, 2004). The application capability of the EDEN model to both site-specific and regional scales will help quantify wildlife responses to hydrology and would lead to more robust habitat models.

The third application, highlighted in this study, can be used to determine spatial locations of dry-down events for fish (water depth <5 cm, Ruetz *et al.*, 2005; or water depth <10 cm, Chick *et al.*, 2004), occurrence sites of wading birds (water depth of 10–30 cm, Gaff *et al.*, 2000), and habitats of Cape Sable seaside sparrows (flooded depths <15 cm, Curnutt *et al.*, 2000). Large-scale spatial loss and temporal loss of fish passage and habitats can also be delineated. Examination of long-period water coverage areas will provide valuable information for the development of fish and bird field-sampling design. Furthermore, nutrient transport patterns associated with fish movements due to draw down could be explained better (Stevenson and Childers, 2004).

METHODS

Study area

The Everglades, a subtropical marshland in South Florida created by the overflow of Lake Okeechobee, is a long, very wide, and extremely flat 'river of grass' flowing into the Atlantic Ocean and Gulf of Mexico (Figure 1). The natural flow of surface water through the Everglades wetlands is generally towards the southwest, following the gentle topographic gradient along the main axis of the Everglades. The Everglades has distinct dry (October–May) and wet (June–September) seasons, and rainfall normally varies during the year between those two seasons. The EDEN area (8192 km^2) is divided in eight distinct sections by canals and levees, with five sections belonging to three distinct water conservation areas (WCAs) surrounded by canals and levees. Those eight sections are WCA 1, WCA 2A, WCA 2B, WCA 3A North, WCA 3A South, WCA 3B, BCNP, and ENP (Figure 1).

Two managed compartments, WCA 3A South (1287 km^2) and WCA 3B (398 km^2), located between I-75 (Alligator Alley) and the Tamiami Canal/Trail, were selected as the study area due to the existence of the Florida Department of Environmental Protection (FDEP) benchmark network (Figure 1). Sheetflow enters WCA 3A South from BCNP to the west and through water-control structures that connect it with the compartments on the north and east. WCA-3B, surrounded by the L-67 canal and levees, receives very little surface-water flow and has become primarily a rain-fed system (Science Coordination Team, 2003). The FDEP benchmark network contains 31 benchmarks in WCA 3A and WCA 3B. Vertical control on those 31 benchmarks was established with Global Positioning System by Smith (2005). The vertical control information was 'Blue-booked' and sub-mitted to the National Geodetic Survey (NGS). Hydrologic connectivity between these areas divided the canals and levees is interrupted.

Historically Sawgrass (*Cladium jamaicense*) is the dominant vegetation cover comprising 70% of the area (Loveless, 1959). Currently, the study area is a mosaic of sawgrass marsh and wet prairie. Wet prairies are

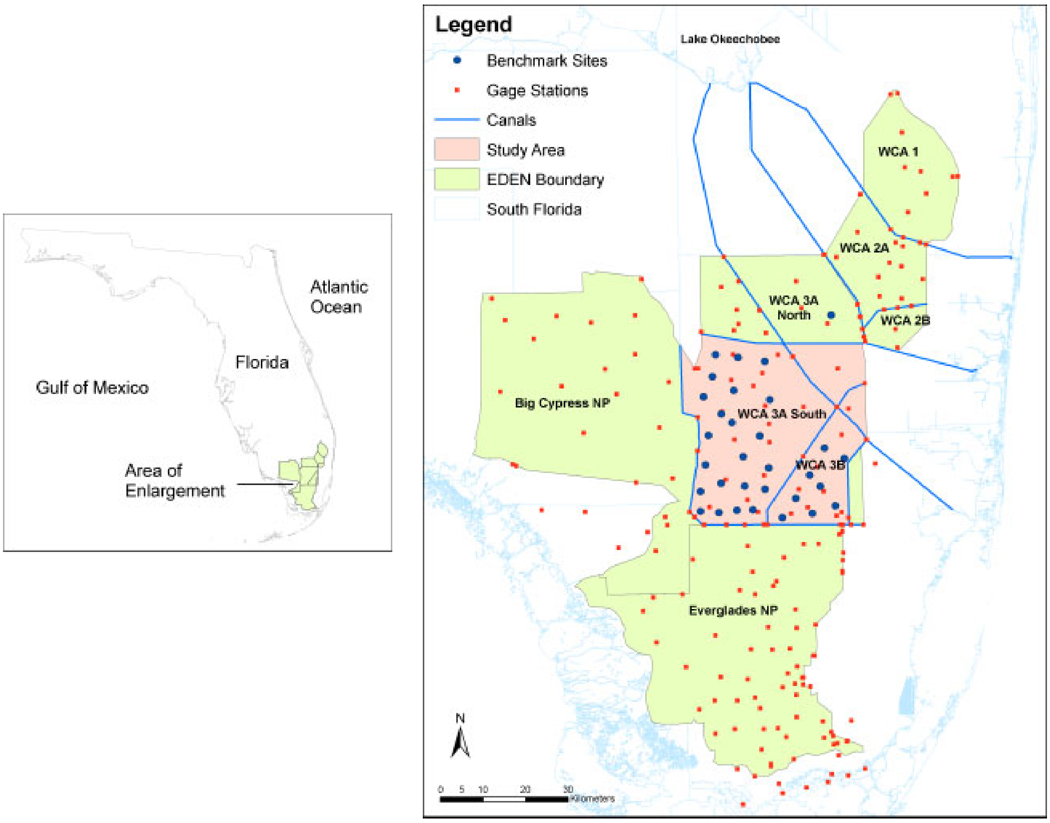

Figure 1. Location of the Everglades and EDEN gage stations.

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composed of grasses and low growing plants including beaksedge (*Rhynchospora tracyi*), spikerush (*Eleocharis cellulose)*, maidencane (*Panicum hemitomon*), and bladderwort (*Utricularia* spp.) (Loveless, 1959; Cleckner *et al*., 1999). Wet prairie marshes occur in poorly drained areas and characterized by relatively longer hydroperiod and higher mean water depth (Ross *et al*., 2003). The majority of the soils in WCA3 are Histosols, including Everglades peats and Loxahatchee peats (Gleason *et al*., 1974). Mixed marl peats, derived from the underlying limestone, are present in the western margin of WCA 3A South (Brown *et al*., 1991).

Another important landscape feature in the Everglades including the study area is tree islands. Tree islands consist of growths of low trees (e.g. bay, willow, and cypress) which occur on elevations slightly higher than the surrounding marsh (Loveless, 1959), and are tear-shaped islands whose long axis normally runs more or less north–south (i.e. upstream–downstream) (Sklar and van der Valk, 2002). Tree islands are one of the four major natural landscape features that make up the Everglades, the others including sawgrass plains and ridges, graminoid marshes (wet prairies), and deep-water sloughs (Kushlan, 1990; David, 1996). Tree islands provide an important home to many mammals that live in the Everglades, and are a site for wading and migratory bird rookeries.

EDEN water-surface model

The EDEN water-surface model was developed by Palaseanu and Pearlstine (2008) with the use of radial basis function (RBF) interpolation of water-level gage data and the multi-quadric method in ESRI ArcGIS version 9·1 (Johnston *et al*., 2004). The interpolation period ranges from January 1, 2000 to present.

A total of 240 gage stations were used for water-surface interpolation of the freshwater Everglades. Those water-level gages have been placed throughout the Everglades to automatically measure water level and transmit the data either via radio or satellite. Two general categories of gage stations are marsh stations (away from canals) and canal stations. Among the 240 stations, 23 stations were established in July 2006 to improve overall accuracy of spatial prediction. To obtain a complete daily gage data set, artificial neural network models were used to provide an estimate/hindcast of water level at the new 23 gage sites over the historic record (January 2000 to July 2006) (Conrads and Roehl, 2007). The vertical datum was converted from NGVD 29 to NAVD 88 for some gages. Daily median water levels were computed and used to avoid effects of occasional large measurement errors. To mimic interrupted water flows by canals and levees, pseudo data were created at 200-m intervals along canals by linearly interpolated water-level values at two neighbouring gages on a canal. Daily median water-level data including pseudo values along canals were then interpolated using multi-quadric RBF with an anisotropic-neighbourhood search to eight cardinal directions (Palaseanu and Pearlstine, 2008).

The multi-quadric method, established by Hardy (1971), is a case of biharmonic analysis with arbitrary number of dimensions (Dyn and Levin, 1980). The multi-quadric equations are continuously differentiable integrals. Franke (1982) reviewed 29 interpolation methods tested on generated mathematical surfaces, and noticed that Hardy's multi-quadric method performed the best or the second best (Franke, 1982, pp. 191). RBF, a special case of basis function, is referred to as an exact interpolation technique because the interpolated surface always passes exactly through the data points (Powell, 1987). RBF interpolations use a set of radial basis functions, one for each location, while minimizing the total curvature of the surface (Johnston *et al*., 2004). The smoothing parameter was set to the minimum distance between data points (gage locations).

In addition to the interpolated daily water-level data, another important indirect output is daily water-depth data (Pearlstine *et al*., 2007), which were created by subtracting the EDEN ground DEM from the daily water-level surface. To match with the spatial resolution of the DEM, the continuous mathematical representation of the water surface was resampled on a 400 m × 400 m grid spacing.

The system-wide EDEN DEM was developed by Jones and Price (2007a,b) based on ground-elevation points collected via helicopter and airboat. The USGS developed a helicopter-based instrument, known as the airborne height finder (AHF) to measure the terrain surface elevation in a non-invasive and non-destructive manner (Desmond, 2003). Over 43 000 AHF elevation data points were collected at approximately 400-m intervals with a grid pattern throughout the Everglades. Additionally, around 11 000 elevation points were collected by deploying surveyors on airboats. The average difference between the measured elevations and the NGS published data sheet values was 3·3 cm. The largest difference was 8·6 cm, and the smallest difference was 0·2 cm. To avoid biasing the dataset with tree islands, the DEM input data were 'smoothed' by removing 'upland' elevation points (classified as 'upland' by using Florida GAP data, Florida Cooperative Fish and Wildlife Research Unit, 2005). The DEM at a 400 m × 400 m cell resolution was produced using the anisotropic ordinary kriging interpolation approach in ArcGIS software (Jones and Price, 2007a,b).

Data collection

Field water-level data at 24 benchmarks of the FDEP network were collected in WCA 3A South (83 observations) and WCA 3B (eight observations) from April through September 2007, and were used to validate the EDEN water-surface model in these areas. There were 16 observations in the dry season and 75 in the wet season. Both airboat and helicopter were used to reach the benchmark sites. For the eight observations collected in WCA 3B in August 2007, the field team used a helicopter rather than an airboat because there was no continuous water surface around some benchmarks due to unusual dry field conditions.

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Modelled water-level data for the corresponding benchmarks and days were extracted from the EDEN water-surface model by using the EDEN xyLocator program developed by the Joint Ecosystem Modeling at the University of Florida (http://sofia.usgs.gov/eden/edenapps/xylocator.php). EDEN xyLocator returns values from EDEN spatial hydrology time series at specific x, y coordinates over a specified time period. The predicted water-surface value is for a 400-m grid cell that the measured point resides. With this available information, field-measured water-surface data at the benchmark sites were compared with the modelled water-level data.

Analysis methods

Graphic, statistical, and geographic information systems (GIS) analyses were used to validate the EDEN water-surface model. As a powerful data integration and spatial analysis tool, the GIS software ArcGIS version 9·2 was used to aggregate, synthesize, and analyse the observed and predicted datasets, and to identify spatial relationships.

Three types of error statistics were used to analyse the overall performance of the EDEN water-surface model: mean absolute error (MAE), mean biased error (MBE), and root mean squared error (RMSE) (Willmott, 1982; Li *et al*., 2006; Sousa *et al*., 2007). These error formulations are all valid measures of accuracy but may reveal slightly different interpretations. The MAE is a weighted average of the absolute errors. The MBE (also called mean error) is a measure of the bias of model predictions—whether the model over or under estimate the measured data. Positive and negative MBEs indicate an over or under prediction bias by the model, respectively. Both MAE and RMSE measure residual errors, which give a global idea of the difference between the observed and modelled values (Sousa *et al*., 2007). The RMSE measures error magnitude and addresses the limitations of MBE. In addition, large errors have a greater impact on RMSE than in the MAE or MBE. The units of the MAE, MBE, and RMSE statistics are the same as the variable simulated by the model. Each of the error statistics was calculated for WCA 3A South, WCA 3B, and the whole study area. The interpolation error or water-level difference was defined as model-predicted water level subtracted by observed water level.

The data distribution normality was assessed with the Shapiro-Wilk test by using SAS version 9·1 (SAS Institute Inc., 2004). Only the predicted and observed water-level data in WCA 3B were normally distributed. Three data transformation methods, square root, logarithmic, and inverse were applied to normalize the water-level data. None of the transformation methods was appropriate. Therefore non-parametric statistical analysis methods were mainly employed in SAS version 9·1 to examine the statistical relationship between the observed and predicted data. Those non-parametric methods were Spearman's rank correlation analysis (Snedecor and Cochran, 1989), Wilcoxon signed rank test for paired data (Siegel and Castellan, 1988), and Kruskal-Wallis non-parametric analysis of variance (ANOVA, Siegel and Castellan, 1988)). The p-values less than 0·05 were considered as statistically significant.

Six major land cover types re-classified for the EDEN network were selected to examine the water-level differences among different vegetation types: (1) slough or open water, (2) wet prairie, (3) ridge or sawgrass and emergent marsh, (4) upland, (5) exotics and cattail (*Typha* spp.), and (6) other (mostly wetland shrub and wetland forested) (Telis, 2006). Those types were aggregated from the Florida Gap Analysis Program (FLGAP) dataset (Florida Cooperative Fish and Wildlife Research Unit, 2005) and the South Florida Water Management District (Rutchey *et al*., 2005).

To further assess the agreement between benchmark data and EDEN model predictions, without the confounding effect of spatio-temporal autocorrelation, ArcGIS 9·2 was used to generate the spatial distance matrix among benchmark sites, and benchmark water-level measurements were temporally de-trended using a temporal trend model derived from regional water-level data. According to the method of Dutilleul (1993), Spearman's rank correlation analyses of the temporally de-trended data were corrected for the significance inflation caused by spatial autocorrelation using spatial analysis in macroecology (SAM) software developed by Rangel *et al*. (2006).

VALIDATION RESULTS AND DISCUSSION

In general, the EDEN model performed very well as assessed by the major statistics of interpolation errors listed in Table I. The overall MAE, MBE, and RMSE were 2·38, −0·08, and 3·3 cm, respectively. By region, the model performed better in WCA 3A South than in WCA 3B as assessed by all the error statistics. As indicated by Willmott (1981), for model evaluation the RMSE is often more informative. The RMSE of WCA 3A South was 2·48 cm, which was less than that of WCA 3B (7·76 cm). The currently widely used hydrologic model for extraction of water-level data in the Everglades is the South Florida Water Management Model (SFWMM, Fennema *et al*., 1994; South Florida Water Management District, 2005). As a spatially explicit computer model, SFWMM simulates the hydrology of South Florida using climatic data for the 1965–2000 period with a spatial resolution of 3·218 km × 3·218 km (2 × 2 miles). The RMSEs of water-level prediction from SFWMM range from 8·3 to 25·1 cm (calibration) and from 6·6 to 27·6 cm (validation) at 25 gage stations in WCAs 3A and 3B (South Florida Water Management District, 2005). As a site-specific and coupled surface water-groundwater model exclusively developed for South Florida, SFWMM simulates the natural hydrology (e.g. flow, water level) together with the management processes that satisfy policy-based rules to meet flood control, water supply, and environmental needs (South Florida Water Management District, 2005). The EDEN water-surface model

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Table I. Major statistics of interpolation errors for water level.

Type	N	Min (cm)	Max (cm)	Standard deviation	Standard error[a]	MAE	MBE	RMSE
WCA 3A South, 3B	91	−17·6	4·9	3·32	0·35	2·38	−0·08	3·30
WCA 3A South	83	−5·1	4·9	2·47	0·27	2·11	0·32	2·48
WCA 3B	8	−17·6	1·7	6·97	2·46	5·15	−4·2	7·76

[a] Standard error = standard deviation/$\sqrt{N}$.

is not a typical surface-water/groundwater model which generally incorporates inputs (e.g. rainfall), outputs (e.g. runoff), boundary conditions (e.g. fluxes), and physical properties (e.g. saturated hydraulic conductivity). Those typical surface-water/groundwater models are lumped or conceptual models with hydrologic processes either described by differential equations based on simplified hydraulic laws or expressed by empirical algebraic equations, or physically-based distributed models based on conservation of mass, energy, and momentum (Arnold *et al.*, 1998). However, compared with SFWMM, the EDEN model provides much more accurate water-level predictions at a finer resolution of 400 m × 400 m and across a large spatial extent. This demonstrates that for the predications of surface-water level and subsequent water depth in the Everglades, the EDEN model provides a relatively simple but very effective modelling and application approach.

Significant positive correlations were found between the predicted water-level values and observed ones (Spearman's rank correlation, for overall, $r = 0{\cdot}98$, $p < 0{\cdot}0001$; for WCA 3A South, $r = 0{\cdot}98$, $p < 0{\cdot}0001$; and for WCA 3B, $r = 0{\cdot}83$, $p = 0{\cdot}01$). Additionally, the correlation in WCA 3B, though statistically significant, was less strong than that in WCA 3A South, which was consistent with the previous results. Model-predicted water levels were not significantly different from the observed water levels (Wilcoxon's signed rank test, for overall, $W = 166{\cdot}5$, $p = 0{\cdot}51$; for WCA 3A South, $W = 263{\cdot}0$, $p = 0{\cdot}23$; and for WCA 3B, $W = -8{\cdot}0$, $p = 0{\cdot}30$). Figure 2 presented the scatter plots between model-predicted and observed values with the 95% confidence intervals in WCAs 3A South and 3B ($R^2 = 0{\cdot}985$, $p < 0{\cdot}0001$), 3A South ($R^2 = 0{\cdot}982$, $p < 0{\cdot}0001$), and 3B ($R^2 = 0{\cdot}81$, $p = 0{\cdot}002$), respectively. The statistical analysis further indicated that the slopes of the regression lines were not different from one another, supporting the good predictive performances of the EDEN model. The plot for all benchmarks (Figure 2a) illustrated that the greatest deviation between observed and expected values occurred in the lower range of water-surface elevations. Those under-predictions suggested that the EDEN model provided relatively conservative estimates for low water-level values, mainly in WCA 3B (Figure 2c).

Table II summarizes the results of Kruskal-Wallis ANOVA tests, which were applied to examine water-level differences spatially, temporally, and among different vegetation types. The mean difference between predicted and observed water levels did not vary significantly between the two regions, WCAs 3A South and 3B ($p = 0{\cdot}06$). However, the difference between predicted and observed water-level data was significantly greater during the dry season than during the wet season ($p = 0{\cdot}008$), and the agreement between predicted and observed values also differed significantly among the three vegetation types (Sawgrass, Exotics and Cattail, and Upland; $p = 0{\cdot}002$). Field data were collected within 4 months of wet season (June–September) and only 2 months of dry season (April and May). Among 91 observations, only eight were in WCA 3B, with a single observation at each of eight benchmark sites, and those eight observations were all taken in the wet season (August). This is also consistent with the mean differences of −1·44 cm (underestimate) and 0·21 cm (overestimate) for the dry and wet seasons, respectively (Table II). Any interpretations in terms of model over- or under-estimation should be made with caution due to limited and unbalanced observations. The water-level differences for the vegetation type of exotics and cattail ($n = 6$, range: 0·5–2·6 cm) were all positive. A detailed examination of the water-level differences together with seasons revealed that the three highest differences among all the data points were negative (range: −6·3 to −17·6 cm), were in the wet season, and were all associated with sawgrass. This showed that the EDEN model provided underestimates of water levels at the sawgrass habitat in the wet season. Newman *et al.* (1996) have suggested that the combination of elevated nutrients and increased water depth will favour the growth of cattail over sawgrass in the Everglades. On the basis of the range of water depths obtained by subtracting the EDEN DEM from observed water levels (range: 17·0–29·3 cm for exotics and cattail; and range: 20·2–29·0 cm for the three highest differences with sawgrass), our research did not demonstrate that cattail is more associated with deeper water, although more field data in other areas are needed for comparison.

Spearman's rank correlation coefficient was also calculated using temporally de-trended data to remove temporal autocorrelation (Table III). The results of these analyses confirmed that EDEN model predictions showed excellent, highly significant agreement with benchmark data in both WCA 3A South and WCA 3B.

The above validation results were consistent with the findings shown in Figure 3. Figure 3 is a graduated symbol map created in ArcGIS to identify the spatial pattern of interpolation errors, which were defined as predicted water levels subtracted by observed ones. There were four benchmarks with absolute interpolation errors more than 5 cm, and three of them, including two over 10 cm, were located within WCA 3B. The

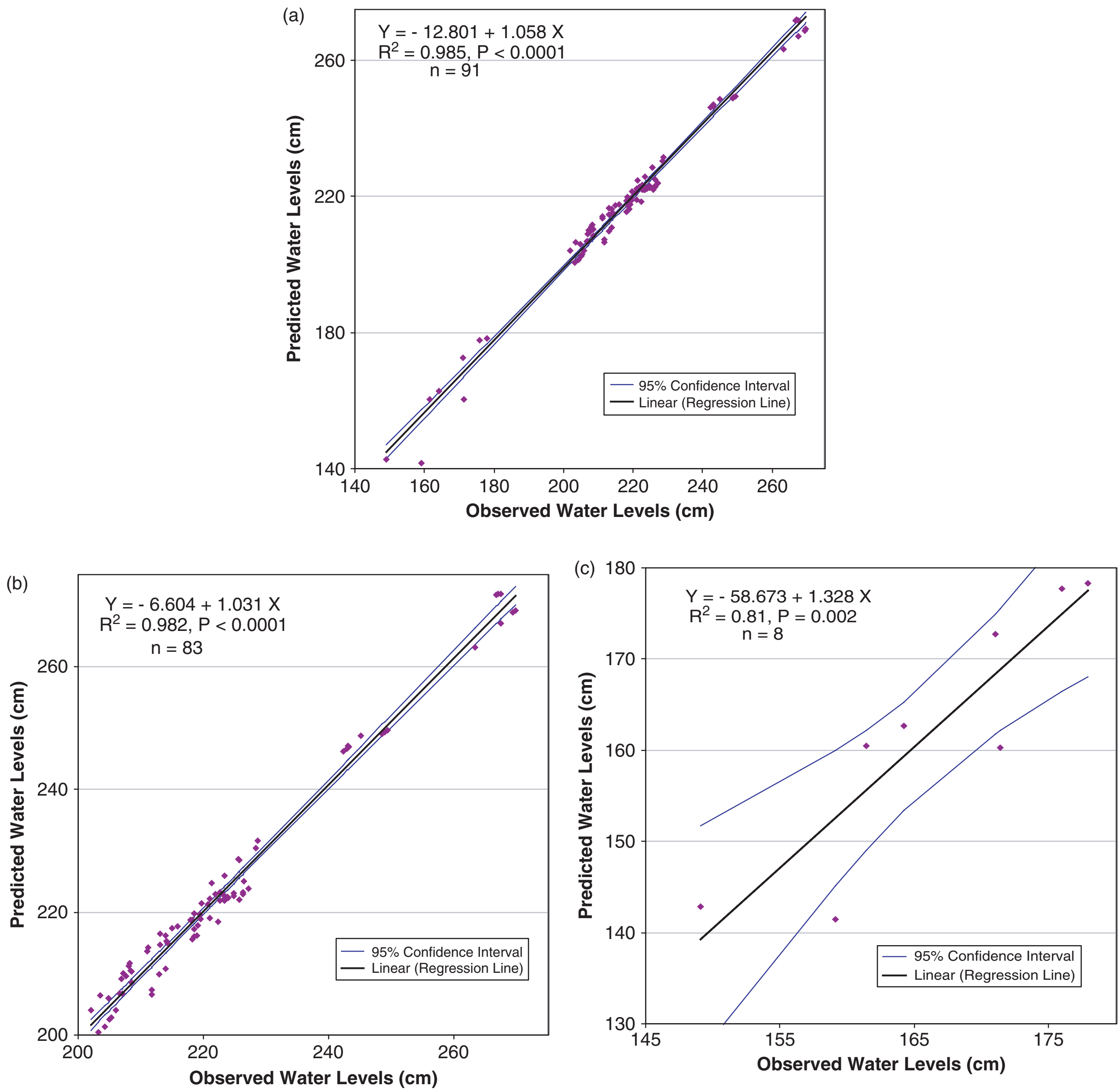

Figure 2. Comparison of observed water level at FDEP elevation benchmarks and predicted water level from the EDEN water-surface model (vertical datum: NAVD 88). (a) WCAs 3A South and 3B; (b) WCA 3A South; (c) WCA 3B.

Table II. Kruskal-Wallis non-parametric ANOVA tests for the differences between observed and predicted water-level data by season, region, and vegetation type.

Source	Class	N	Median difference[a] (cm)	df[b]	Kruskal-Wallis test statistic (H)	p-value of H
Season	Dry season (November–May)	16	−2·15	1	7·04	0·008
	Wet season (June–October)	75	0·6			
Region	WCA 3A South	83	0·4	1	3·48	0·06
	WCA 3B	8	−1·2			
Vegetation	Sawgrass	72	−0·2	2	12·45	0·002
	Upland	13	3·6			
	Exotics and Cattail	6	1·55			

[a] Median difference = the median of water-level differences (predicted—observed). The mean differences are: −1·44 (dry), 0·21 (wet), 0·32 (WCA 3A South), −4·2 (WCA 3B), −0·62 (sawgrass), 2·19 (upland), and 1·55 (exotics and cattail).
[b] Degrees of freedom.

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Table III. Spearman's rank correlations between observed and predicted values for temporally de-trended water-level data, with degrees of freedom and significance tests corrected for spatial autocorrelation according to the method of Dutilleul (1993) as implemented by Rangel *et al*. (2006).

Type	Spearman's rank correlation coefficient	Corrected df[a]	Corrected *p*-value
WCA 3A South, 3B	0·91	17·29	<0·001
WCA 3A South	0·88	5·54	<0·001
WCA 3B	0·83	5·28	<0·004

[a] Corrected degrees of freedom.

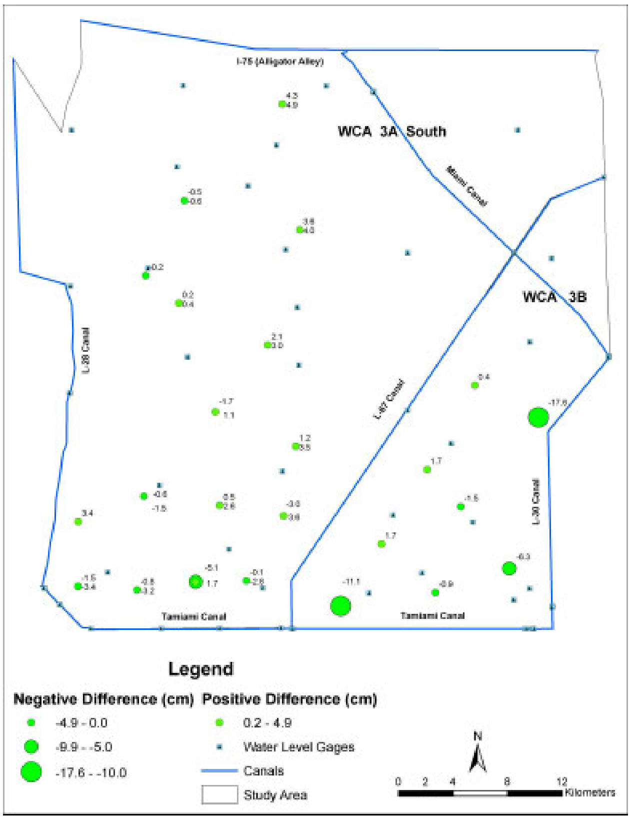

Figure 3. Water-level validation at FDEP benchmark sites in WCAs 3A South and 3B. Water-level difference (unit: cm) = predicted water level—observed water level. The minimum and maximum water-level differences are labelled at the benchmarks. Underestimates and overestimates are represented by negative and positive values, respectively.

highest absolute interpolation difference in WCA 3A South is 5·1 cm. Those high interpolation errors mainly occur near EDEN boundaries of Tamiami Canal, L-30 Canal, and L-67 Canal (Figure 3). From the model cross-validation results, a reduced confidence in the interpolated water surface occurs close to the canals (Palaseanu and Pearlstine, 2008). The canal and levee boundaries act as major discontinuities in the EDEN area, and water levels from one section have minimal or no influence into adjacent sections. Steep changes in elevation can occur between areas at these levees. Water level near section boundaries is further influenced by the SFWMD's operation of massive pumps and canals to distribute water for natural areas, agriculture, urban use, and flood protection.

As indicated by Poiani and Johnson (1993), for the purpose of investigating wetland processes related to climate, the hydrologic model ideally should estimate water levels to within 5–10 cm of observed values. For biological and ecological assessment of trophic level responses to hydrodynamics, model-estimated water levels should be within ±5 cm of measured values (J.C. Trexler, Florida International University, pers. comm., 2007; D.E. Gawlik, Florida Atlantic University, pers. comm., 2007). Our research found that for WCAs 3A South and 3B, 95·6% of the predicted water levels matched actual water levels within the range of ±5 cm; and by region, the matched percentages within ±5 cm were 98·8% (WCA 3A South) and 62·5% (WCA 3B), respectively. When a benchmark reports high interpolation errors and high mismatch percentages, it is likely to be near boundaries. For the benchmark with water-level difference of −17·6 cm in WCA 3B, there are no nearby water-level gages (Figure 3), and the benchmark is close to L-30 Canal. The long linear interpolation of the adjacent canal might introduce the error. The benchmark with water-level difference of −11·1 cm is close to Tamiami Canal and L-67 Canal, which has almost twice the error of the benchmark with water-level difference of −6·3 cm. However, the benchmark in the middle is very accurate (water-level difference = −0·9 cm). A closer look is needed to examine the underlying factors including canals, vegetation type, and season. We suspect that the benchmarks with higher differences are in corners of the canals, which might play a role.

The field data in WCA 3B in August of 2007 were not collected by airboat due to the unusual dry field conditions. There was no continuous water surface around the area of some of the benchmarks. This may also have affected the surface provided by the EDEN water-surface model at that time.

Another factor might be due to the selected RBF interpolation parameters. The current EDEN model uses a single set of RBF interpolation parameter for all the eight EDEN sub-regions to minimize overall cross-validation errors (Palaseanu and Pearlstine, 2008). A different set of RBF interpolation parameters, including shape, angle, major semiaxis, and minor semiaxis, might need to be optimized and computed for WCA 3B due to such different areal features as area and canal boundaries.

In addition to the boundary conditions and data collection issues discussed previously, missing or faulty gage data might have some localized impacts on the water surface in the EDEN network. The EDEN station network is operated by four agencies to meet their individual missions for operations, regulations, planning, and research. To meet their goals, the stations are operated at different time lines and tolerances for missing gage record. Ideally, EDEN water-surface model requires no missing record and if there are missing records, they are estimated to produce the best quality-modelled surface.

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However, each agency has different guidelines and procedures on estimating missing record. For example, the USGS discourages estimating water-level data and only estimates flow data, and removes data for periods when the water gage is dry. EDEN surfaces may be affected by these agency data management decisions. The verification of the model surface in this paper used a dataset of measurements at the FDEP benchmarks from April to September 2007. In WCA 3A and 3B, the un-operational water gage stations at the time of these measurements were 6 (April), 6 (May), 9 (June), 11 (July), 5 (August), and 2 (September), respectively, which appear to have no effects. However, system wide, there were 90 gage stations not operating for short periods that might have caused localized problems in other EDEN areas (Volin *et al*., 2008). The user needs to take into account that there are local problems with the water surface caused by changing boundary conditions and missing or faulty gage data.

The good performance of the EDEN model ultimately relies on extensive water-level monitoring gage stations. The densities of all gage stations and marsh gage stations in the study area are 2·6/100 and 1·9/100 km^2, respectively. Moreover, the Everglades water surface has an extremely shallow slope (*ca* 3 cm/km in the absence of storm events, Givnish *et al*., 2008). Those two aspects should also be considered for the application and extension of the EDEN model to other geographic areas in the world.

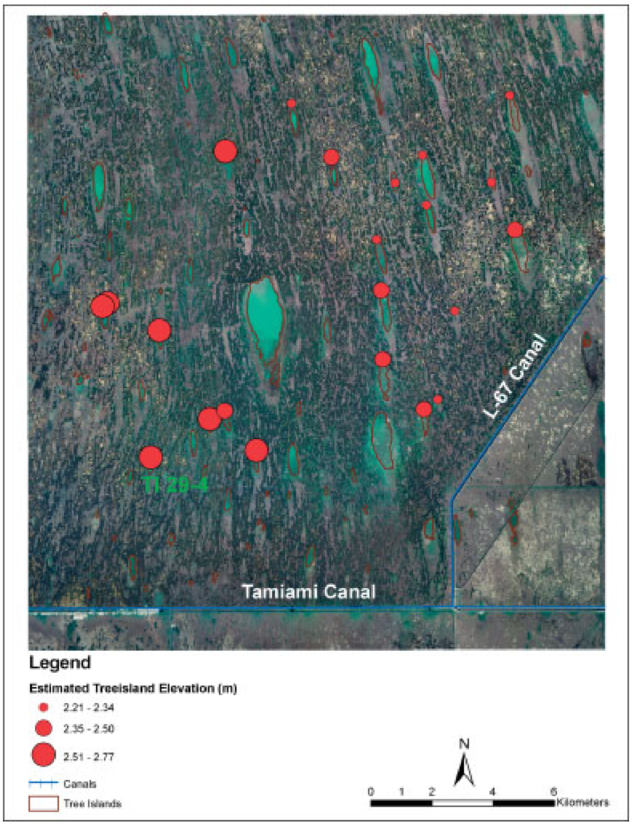

Figure 4. Estimates of tree island elevations (units: m; vertical datum: NAVD 88) in WCA 3A South, calculated by subtracting water depth measured at a tree island, on a given date, from the predicted EDEN water surface for the grid cell in which that tree island is located, on the same date. The background imagery is 1-m resolution digital orthophoto quarter quads (DOQQs) from FDEP Land Boundary Information System. (LABINS, http://data.labins.org/2003).

ECOSYSTEM APPLICATIONS

Estimation of ground elevation

For this application, water depths were measured on tree islands accessed by airboat. Ground elevation for specific locations was calculated from the EDEN model water-surface data and available field-measured water-depth data by the formula of ground elevation = predicted water level—observed water depth. Figure 4 shows the estimated ground elevations for tree islands in WCA 3A South.

Estimation of water-depth time series

An extension of the tree island ground-elevation estimates described above made use of the EDEN time series of water levels to generate the time series of above or below-ground water depth for tree islands in WCA3A South. An example is shown in Figure 5. Water depth measured at any tree island on a given day was related to the EDEN water level for the same day to determine the offset between the EDEN water level and the ground elevation of the tree island. The offset was then used to generate the hydrograph of water depth for that tree island from the EDEN time series. The validity of this approach does not depend on the accuracy of the water-surface elevation (Givnish *et al*., 2008), but does assume that model error at a given location is constant through time. Measures of hydrological conditions such as hydroperiod and maximum inundation depths, from January 2000 to the present, can be further derived from the water-depth time series. The application was used by Givnish *et al.* (2008) to analyse variation of vegetation composition in relation to surface-water depths over a 6-year period (2000–2005) in central Everglades, and four hydrologic variables (maximum, minimum, average water depth, and hydroperiod) were calculated for 562 quadrats to relate to local and landscape-level factors. System-wide water-depth time series could be obtained when ground elevation from DEM is subtracted from EDEN water level (Pearlstine *et al*., 2007). However, to obtain more accurate water-depth data, a better digital ground-elevation map is needed by using the method highlighted in Section Ecosystem Applications.

Additionally, peat formation, accumulation and destruction are important processes in the Everglades. As a vast peatland, Everglades are with a substrate composed of partly decomposed plant remains. As water levels vary and production and decomposition respond non-linearly to changes of water depth, the ground topographic gradient may itself change (Givnish *et al*., 2008). Thus estimates of ground elevation and water depth could be further affected by the peat shrinkage particularly during extreme droughts.

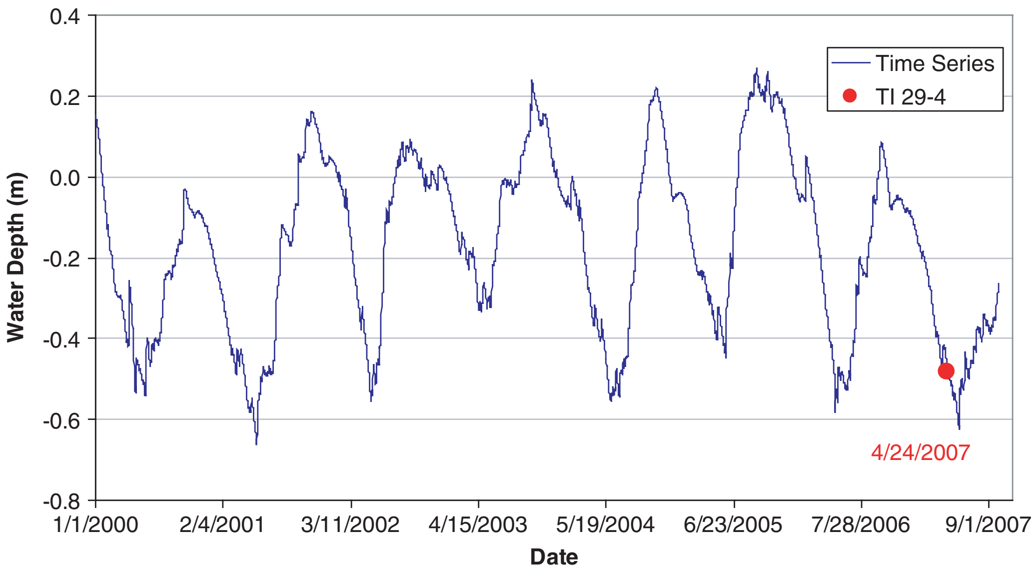

Figure 5. Example of water-depth time series for a tree island in WCA 3A South. Water depth and GPS location were measured for a tree island (TI 29-4) on the date indicated. Time series of water-surface elevation within the corresponding EDEN grid cells were then used to generate the time series of above or below-ground water depths for the tree island. Water depths are in meters relative to a ground-surface height of 0 for the island (water depth = predicted water level—estimated tree island elevation).

Estimation of contiguous water coverage areas

Another model application is to derive contiguous water coverage areas for studies of fish, wading birds, and Cape Sable seaside sparrows. Completely flooded areas in the EDEN boundary could be estimated by specifying water depths >0 cm or any other critical values with the use of the EDEN water-surface model and DEM. By using modelled water-depths on multiple dates, a rate of change could be further calculated. Figure 6 shows one example of 94 contiguous water coverage regions on April 30, 2007 with water depths > = 5 cm, which was generated on the basis of the EDEN water surface and EDEN DEM in ArcGIS 9·2 with the functions of raster calculation and region group.

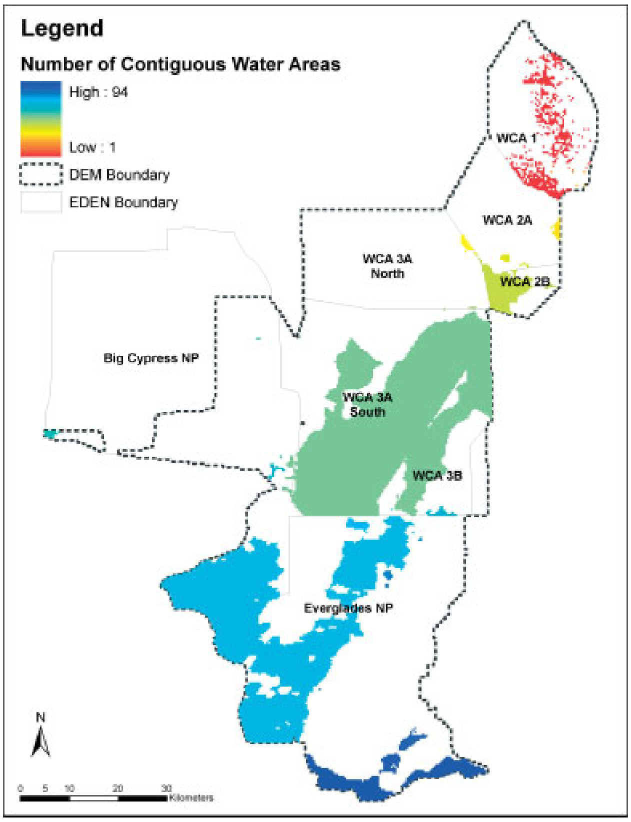

Figure 6. Example of contiguous water coverage regions on April 30, 2007 with water depths > = 5 cm based on the EDEN water surface and DEM.

CONCLUSIONS

The landscape-scale EDEN hydrological model, developed by Palaseanu and Pearlstine (2008), has wide application for ongoing research and management efforts that are vital to restoration of the Everglades. The accurate and high-resolution hydrological data produced from the EDEN model, provide a previously missing key to understand the habitat requirements and linkages among native and invasive biotic communities, for example, fish, wading birds, alligators, and plants.

The water-surface elevations predicted from the EDEN model are more accurate than those from SFWMM, from nearest recording stations and from those derived by linear regression, due to substantial natural variations of ground surfaces in the Everglades. The EDEN model supports applications at multiple spatial scales, including landscape and site levels as demonstrated by Givnish *et al*. (2008). As an exact interpolation method, RBF provides interpolated surfaces passing exactly through the data points (Powell, 1987), which could be applied to assess alternative restoration scenarios by providing hypothesized water-level inputs at gage stations. RBF can also be used to develop minimum flow and level regulations in Florida and in other states intended to prevent ecological harm from water withdrawal (Munson and Delfino, 2007). RBF interpolation works well with wide and flat water surfaces in marsh wetlands, lakes, and rivers, although localized algorithm adjustments might be necessary to account for boundary conditions and for severe drought events. RBF used by the EDEN model could be adapted for other ecosystem-scale hydrologic models that are needed to support restoration and management programs worldwide.

This research demonstrates that the EDEN water-surface model, developed for a large and complex wetland and across a long time period, is a reliable and useful water level and water-depth estimation tool for the support of ecological and biological assessments in the Everglades, Florida. For future work, more field observations of dry and wet seasons and in another six benchmark sites in WCA 3A South are needed to fully evaluate the EDEN water-surface model. It is also desirable to obtain some field water-surface data in other WCAs and the Everglades National Park. The model would be modified and improved by closer examination of the causes of interpolated estimation errors at the three benchmarks with highest errors near canal boundaries in WCA 3B. Furthermore, we would like to compare the modelling results from the RBF interpolation with other interpolation techniques, for example, the spatial-temporal interpolation method from Li *et al.* (2006). Additionally, to obtain more accurate water-depth data, a better regional digital elevation map could be produced by subtracting available field water-depth measurements from model-predicted water surface in the Everglades.

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