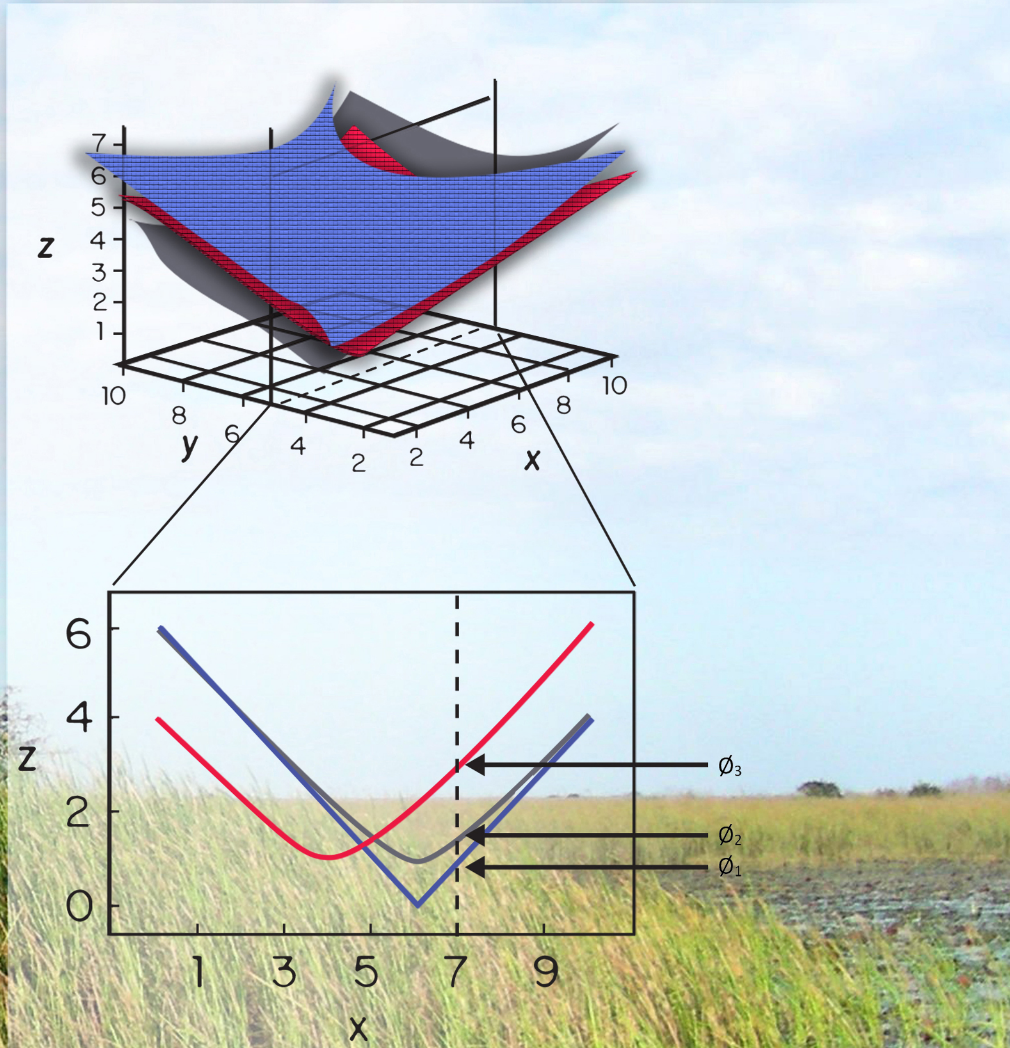
Prepared as part of the U.S. Geological Survey Greater Everglades Priority Ecosystem Science and in cooperation with the U.S. Army Corps of Engineers

The Everglades Depth Estimation Network (EDEN) Surface-Water Model, Version 2



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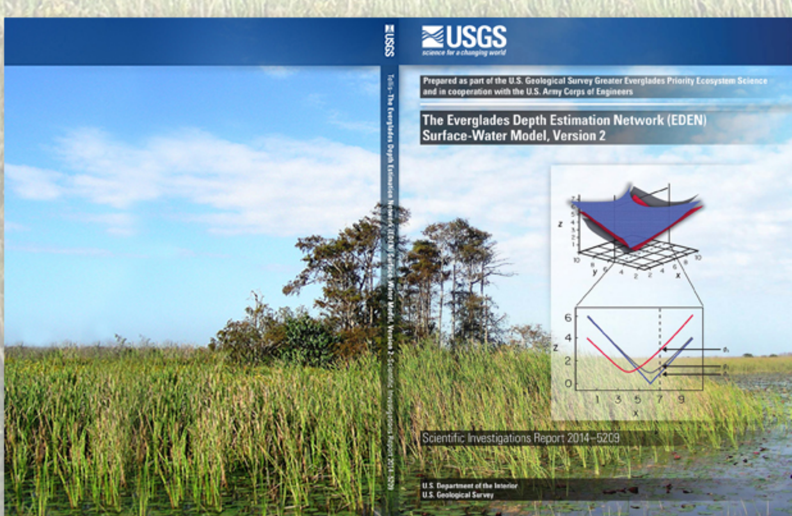

Cover: Photo showing Water Conservation Area 3A, Florida, and example of a radial basis function conceptual design in 2 and 3 dimensions (fig. 9*A*).

Photograph: Courtesy of Dr. Jim Heffernan, Duke University.

The Everglades Depth Estimation Network (EDEN) Surface-Water Model, Version 2

By Pamela A. Telis, Zhixiao Xie, Zhongwei Liu, Yingru Li, and Paul A. Conrads

Prepared as part of the
U.S. Geological Survey Greater Everglades Priority Ecosystems Science
and in cooperation with the
U.S. Army Corps of Engineers for the
Comprehensive Everglades Restoration Plan REstoration COordination and VERification Program

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U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors and Datums

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) and National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Acronyms and Abbreviations

ADAM	Automated Data Assurance and Management
BCNP	Big Cypress National Preserve
CERP	Comprehensive Everglades Restoration Plan
C&SF	Central and Southern Florida
CVE	cross-validation error
DEM	digital elevation model
EDEN	Everglades Depth Estimation Network
EDENapps	Everglades Depth Estimation Network applications
ENP	Everglades National Park
EVE	Explore and View Everglades Depth Estimation Network
FAU	Florida Atlantic University
FTP	file transfer protocol
GIS	geographic information system
GPS	global positioning system
HAED	high-accuracy elevation data
LE95	linear error of the 95th percent confidence
LOOCV	leave-one-out cross validation
MAE	mean absolute error
ME	mean error
MAP	Monitoring and Assessment Plan
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
NWIS	National Water Information System
PW	Pennsuco Wetlands
RBF	radial basis function
RECOVER	REstoration, COordination, and VERification
RSME	root mean squared error
SFWMD	South Florida Water Management District
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
V1	version 1
V2	version 2
WCA	Water Conservation Area
WCA1	Water Conservation Area 1
WCA2	Water Conservation Area 2
WCA3A	Water Conservation Area 3A
WCA3AN	Water Conservation Area 3A North
WCA3AS	Water Conservation Area 3A South
WCA3B	Water Conservation Area 3B

Acknowledgments

The authors extend a special thanks to Aaron Higer (U.S. Geological Survey, retired) who saw the need, early in the restoration process, for comprehensive system-wide hydrologic datasets for scientists involved with research and managers monitoring water levels in the Everglades. The authors are grateful for the contribution of Dr. Ikuko Fujisaki, Dr. John W. Jones, and Dr. James Beerens whose applications show how EDEN data contribute to advancing our understanding of the Everglades ecosystem. Most importantly, the authors thank the researchers, scientists, managers, and others who are using the EDEN data to help restore the Everglades.

The Everglades Depth Estimation Network (EDEN) Surface-Water Model, Version 2

By Pamela A. Telis[1], Zhixiao Xie[2], Zhongwei Liu[3], Yingru Li[4], and Paul A. Conrads[1]

Abstract

The Everglades Depth Estimation Network (EDEN) is an integrated network of water-level gages, interpolation models that generate daily water-level and water-depth data, and applications that compute derived hydrologic data across the freshwater part of the greater Everglades landscape. The U.S. Geological Survey Greater Everglades Priority Ecosystems Science provides support for EDEN in order for EDEN to provide quality-assured monitoring data for the U.S. Army Corps of Engineers Comprehensive Everglades Restoration Plan.

The EDEN surface-water model, version 2 (V2), interpolates water-level data from a network of 240 gages to generate gridded daily water-level surfaces for the freshwater domain of the Everglades. When these spatiotemporal continuous surfaces are combined with EDEN's digital elevation model of ground surface, derived hydrologic data provide scientists and water managers working in the Everglades with data necessary to analyze ecological and biotic responses to hydrologic changes in the Everglades. Derived datasets include water depth, recession rates, days since last dry, water-surface slopes, and hydroperiod. The V2 model includes enhancements from the previous model (version 1; V1) to accommodate changes in the water-level gage network, adjustments to water-level data, improved understanding of the flow dynamics (particularly near canals), and installation of an elevation benchmark network. Enhancements to the V2 model included

- Expansion of the EDEN domain: The model domain was expanded to include a part of southern Big Cypress National Preserve and northwestern Everglades National Park upstream of the marsh mangrove wetlands, thus completing the coastal connection along the southwestern boundary of the model; and
- Development of subdomain models: To account for insufficient water-control structure gage data at some subbasin boundaries, subdomain models were developed for five subdomains, and the resulting water-level surfaces were merged to generate the final water-level surface.

Model performance statistics show a general improvement in the V2 model as compared to the V1 model. Overall, the root mean squared error (RMSE) was reduced by 2.42 centimeters (cm) to 4.68 cm. In Water Conservation Area 3A North and Water Conservation Area 3B, the RMSE was reduced by 10.88 and 9.15 cm, respectively. In addition to evaluating model performance statistics, 2-cm water-level maps were generated and evaluated for irregular contours that would indicate a potential problem either with data input or water-level estimates.

Three applications of the EDEN-modeled water surfaces and other EDEN datasets are presented in the report to show how scientists and resource managers are using EDEN datasets to analyze biological and ecological responses to hydrologic changes in the Everglades. The biological responses of two important Everglades species, alligators and wading birds, to changes in hydrology are described. The effects of hydrology on fire dynamics in the Everglades are also discussed.

Introduction

Over the last 100 years, the Everglades, the Nation's largest freshwater wetland, was channelized, leveed, and drained to meet water-supply and flood-control requirements for the expanding urban and agricultural areas of southern Florida. In the 1990s, there was increased public interest to save what remained of the Everglades. The Federal Government, in collaboration with State and local agencies, developed a plan to restore the Everglades to its original function as a habitat for large wading bird colonies, alligators, and the diversity of flora and fauna assembled only in the Everglades. The final plan to restore the Everglades, the Comprehensive Everglades Restoration Plan (CERP), was signed into law in December 2000 (U.S. Army Corps of Engineers, 1999). The primary goal of the Plan is to restore the quantity, timing, and distribution of freshwater flow within the remaining

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[4] Auburn University

Everglades to more natural conditions and to bring back the diverse and abundant flora and fauna of the previously undisturbed wetlands.

The REstoration COordination and VERification (RECOVER) program, a component of the CERP, links science to decision-making and uses scientific methods and monitoring to evaluate and assess the CERP's performance, refine and improve the CERP with new data, and ensure that an ecosystem-wide perspective is maintained throughout the restoration process (RECOVER Leadership Group, 2012). The Monitoring and Assessment Plan (MAP) of the RECOVER program describes an integrated, system-wide monitoring and assessment plan and is the primary tool by which the RECOVER program will assess the performance of the CERP (RECOVER, 2004, 2009).

The Everglades Depth Estimation Network (EDEN) was initiated in 2006 with funding from RECOVER MAP and the U.S. Geological Survey (USGS) Greater Everglades Priority Ecosystems Science to provide consistent, documented, and readily available hydrologic and ground-elevation data for the Everglades (Telis, 2006; Everglades Depth Estimation Network [EDEN] for Support of Biological and Ecological Assessments, 2014c). Prior to EDEN, ecologists and biologists examining trophic- and landscape-level responses to hydrodynamic changes in the Everglades often estimated water levels in the Everglades from nearby gages, or they linearly interpolated water levels between gages. A region-wide, high-resolution surface-water modeling approach with Internet access to datasets was needed. Hydrology is an important factor in many of the conceptual ecological models used to illustrate the links among actions, stressors, and responses in the Everglades system. These models provide the basis for developing and testing cause-and-effect hypotheses and monitoring performance measures as CERP is implemented. Target users of EDEN data and products include biologists, wildlife-resource scientists managing habitat requirements for endangered species, fire ecologists, and water-resource managers monitoring water levels and depths to meet mandated regulation schedules.

To create daily water-level surfaces for the Everglades, EDEN integrates data from a network of 240 water-level gages collected by multiple agencies: Big Cypress National Preserve (BCNP), Everglades National Park (ENP), South Florida Water Management District (SFWMD), and USGS. The EDEN surface-water model, version 1, (Pearlstine and others, 2007; Liu and others, 2009) interpolated daily water-level surfaces gridded to 400-square-meter cells using the EDEN grid developed by Jones and Price (2007a) for the period January 1, 2000, to December 31, 2011. When these surfaces are combined with EDEN's digital elevation model (DEM) for ground surface (Jones and Price, 2007b; Xie and others, 2011; Jones and others, 2012), daily surfaces of water depth can be generated. To assist users in applying the EDEN datasets to their needs, a series of applications (EDENapps) were developed to view, extract, plot, and manipulate EDEN data to create other derived hydrologic data (Telis and Henkel, 2009).

Since its inception in 2006, there were changes in the EDEN water-level gage network, adjustments to water-level data, improved model schematization of the water-level gradients (particularly near canals and levees), and installation of a surveyed elevation benchmark network, all of which required revisions to the surface-water model created by Pearlstine and others (2007). For the purpose of this report, the EDEN surface-water model by Pearlstine and others (2007) is referred to as the version 1 (V1) model, and it was revised to develop the version 2 (V2) model documented here. Development of the V2 surface-water model was made in collaboration with Florida Atlantic University (FAU) through a Southern Florida Cooperative Ecosystem Studies Unit agreement for 2010–2012. Model revisions were completed by FAU; all data management, quality-assurance of hydrologic data, model schematization research and development, and model testing and review were completed by the USGS.

Purpose and Scope

The purpose of this report is to document the V2 model used to interpolate daily water-level surfaces for the freshwater part of the greater Everglades (fig. 1), including summary model performance statistics and examples of model applications. The differences between the V1 model and the V2 model also are explained.

An important part of the USGS mission is to provide scientific information for the effective management of the Nation's water resources. The techniques presented in this report demonstrate how existing gaging networks maintained by different agencies can be integrated and used as input to spatially extensive surface-water models. These models assist researchers and resource managers to better understand complex natural systems and, therefore, better manage the resources of these systems. The approach is readily applicable to other natural systems to support ecosystem restoration.

One of the six science directions outlined in the USGS science strategy for 2007–2017 (U.S. Geological Survey, 2007) is to provide scientific information for understanding ecosystems and predicting ecosystem change. The USGS collects hydrologic, biological, and other data using standardized methods to study the causes and consequences of ecological change. The USGS also interprets those data for policymakers and others who wish to predict how changes could affect natural resources and the public. The techniques presented in this report demonstrate how information can be extracted from existing USGS databases and integrated with other data networks to assist local, State, and Federal agencies in their efforts to restore the Everglades ecosystem. As a real-time surface-water model for a large hydrologic system, the EDEN surface-water model demonstrates how (1) a hydrologic model can be automated to produce daily results, (2) a multi-agency network of gages and databases can be integrated, and (3) model results can be easily disseminated to meet the needs of a broad range of end users.

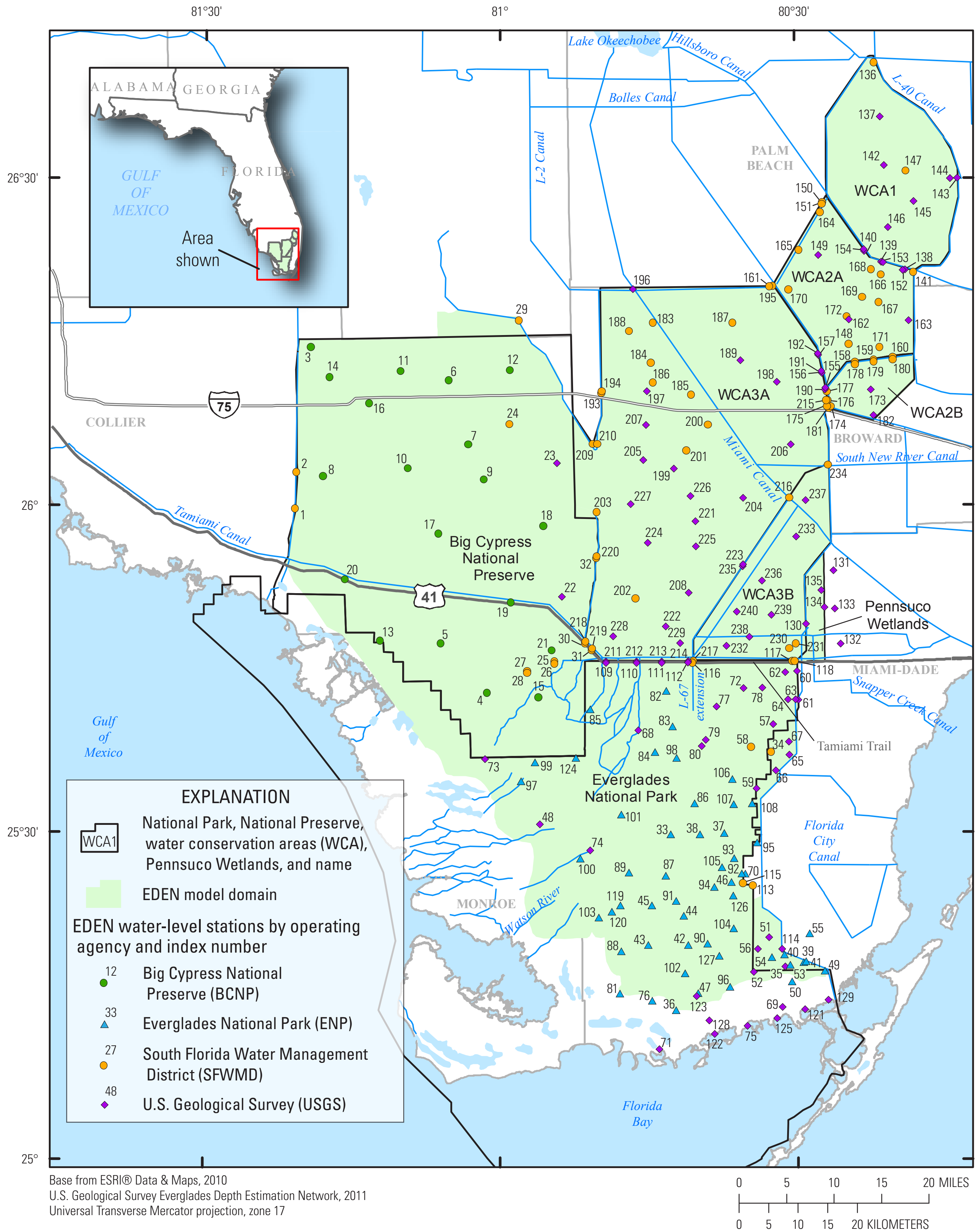

Figure 1. EDEN model domain and location of EDEN water-level gaging stations used in the EDEN surface-water model, version 2.

A second USGS science strategy priority for 2007–2017 is to provide research and monitoring for understanding global climate change and assessing its consequences. The USGS is uniquely positioned to improve understanding of (1) droughts, floods, and water availability under changing land use and climate and (2) coastal effects of sea-level rise. The EDEN model domain includes the freshwater marsh upstream of the oligohaline wetlands along the coast of Florida Bay and the southwest coast of the Gulf of Mexico (fig. 1). As sea levels rise, the hydrologic changes and ecological responses in the tidal wetlands and upstream freshwater marshes may be evident along this extremely low-gradient coastline. The EDEN daily water-level surfaces modeled for the period 2000 to 2014 form a hydrologic basis for assessing coastal impacts over time.

Description of the Study Area

The study area is the freshwater part of the Everglades and includes Water Conservation Areas 1, 2A, 2B, 3A, and 3B, parts of the Pennsuco Wetlands, and the freshwater parts of BCNP and ENP (fig. 1). The model domain includes the entire study area.

The Everglades are a large wetland area that overlies a broad platform of porous limestone that gently slopes from the southern end of Lake Okeechobee to the Florida Bay. Over a distance of 100 miles, the land slopes imperceptibly at an average of 1 inch per mile in a shallow, broad, swale-like channel that is 50 miles wide and mainly through a savannah of tall sedges and dwarf cypress trees (fig. 2). Before the hydrology of the Everglades was altered by development, the Everglades were predominantly covered for much of the year by a wide and shallow sheet of water that flowed from Lake Okeechobee in the north to the coastal bays surrounding the southern tip of the Florida peninsula (fig. 3). The predevelopment wetland supported seasonally abundant communities of fish and invertebrates that sustained wading bird super colonies in a mosaic of plant communities (Grunwald, 2006).

Historically, water levels in Lake Okeechobee rose in wet years and spilled over the banks along the southern edge to form the northern reaches of the Everglades. The predevelopment Everglades consisted of approximately 4 million acres of long-hydroperiod wetlands and covered most of the southern part of the Florida peninsula, which is surrounded by water on three sides. South Florida has a subtropical climate with two distinct seasons: during the wet season, June to October, average monthly rainfall ranges from 3.7 to 9.6 inches; during the dry season, November to May, average monthly rainfall ranges from 1.7 to 4.3 inches, and is largely associated with winter weather systems (Sobczak and others, 2011). Annual variations in average rainfall produce drought years when parts of the Everglades become dry and are subject to wildfires and wet years when most landscapes and vegetation communities are flooded and can remain flooded for months as a result of slow runoff rates (German, 2000).

The predevelopment landscape of the Everglades was dominated by sawgrass plains in the north and ridge and slough landscape in the center and south (Davis, 1943; fig. 2). The landscape pattern of tree island ridges and interconnecting sloughs combined with the dynamic hydrologic processes, including water storage and sheet flow, created diverse vegetation communities and habitats for native flora and fauna (Fling and others, 2004). Water depth and distribution in this wetland environment were determined by the highly variable seasonal and annual rainfall patterns, vegetation, and underlying topography. Historical measurements in the Everglades indicate that the primary flow velocity in the sloughs averaged 0.3 to 0.5 foot per day. Although debate remains, historical records indicate that sloughs were covered by water approximately 9 months of the year and some tree islands flooded for as much as 3 months each year (Fling and others, 2004).

Since the mid-1800s, many attempts to drain and convert Florida swamp land were made, largely for agriculture and later for urban development. Many had visions of southern Florida with its rich peat soil as being the breadbasket of the United States (Grunwald, 2006). The first congressional action that initiated draining the Everglades was the Swamp Land Act of 1850, which authorized the transfer of 200 million acres of Federal land to the State of Florida for drainage and conversion to farmland. Canals were used to drain water from the wetlands quickly and directly to the ocean. As the land drained and proved to be agriculturally productive, further drainage of swamp land was funded. Over time, draining the Everglades proved to be more difficult than expected. More canals had to be dug and deepened, and during wet years, the wetlands persisted and drained fields were flooded. Several thousand people drowned in floodwaters that could not be contained in Lake Okeechobee and the drainage canals during the unnamed hurricanes of 1926 and 1928 (Grunwald, 2006).

To respond to the public demands for flood protection in the 1930s, the Federal Government initiated a project with the State of Florida to control flooding around Lake Okeechobee. In 1948, following another devastating hurricane, the larger, more comprehensive Central and Southern Florida (C&SF) Project expanded the canal system, extended levees, and constructed water-control structures to provide flood control throughout south Florida. The C&SF Project created a compartmentalized Everglades consisting of a regulated system of water conservation areas (WCAs) with adjacent nationally protected lands designated as Big Cypress National Preserve and Everglades National Park (fig. 3). Today, water management in the Everglades centers around regulation schedules for (1) sustaining minimum flow requirements for ENP, (2) minimizing flood risk during hurricane season (June–October), and (3) maximizing water storage during the dry season (November–May) (Davis and Ogden, 1994).

The WCAs (figs. 1 and 3), completed in the 1960s, serve to modulate variations in hydrologic patterns, to recharge the region's principal drinking water aquifer, and to protect against saltwater intrusion along the coast. Water moves into the WCAs through gated water-control structures and flows generally southwestward where more gated structures release

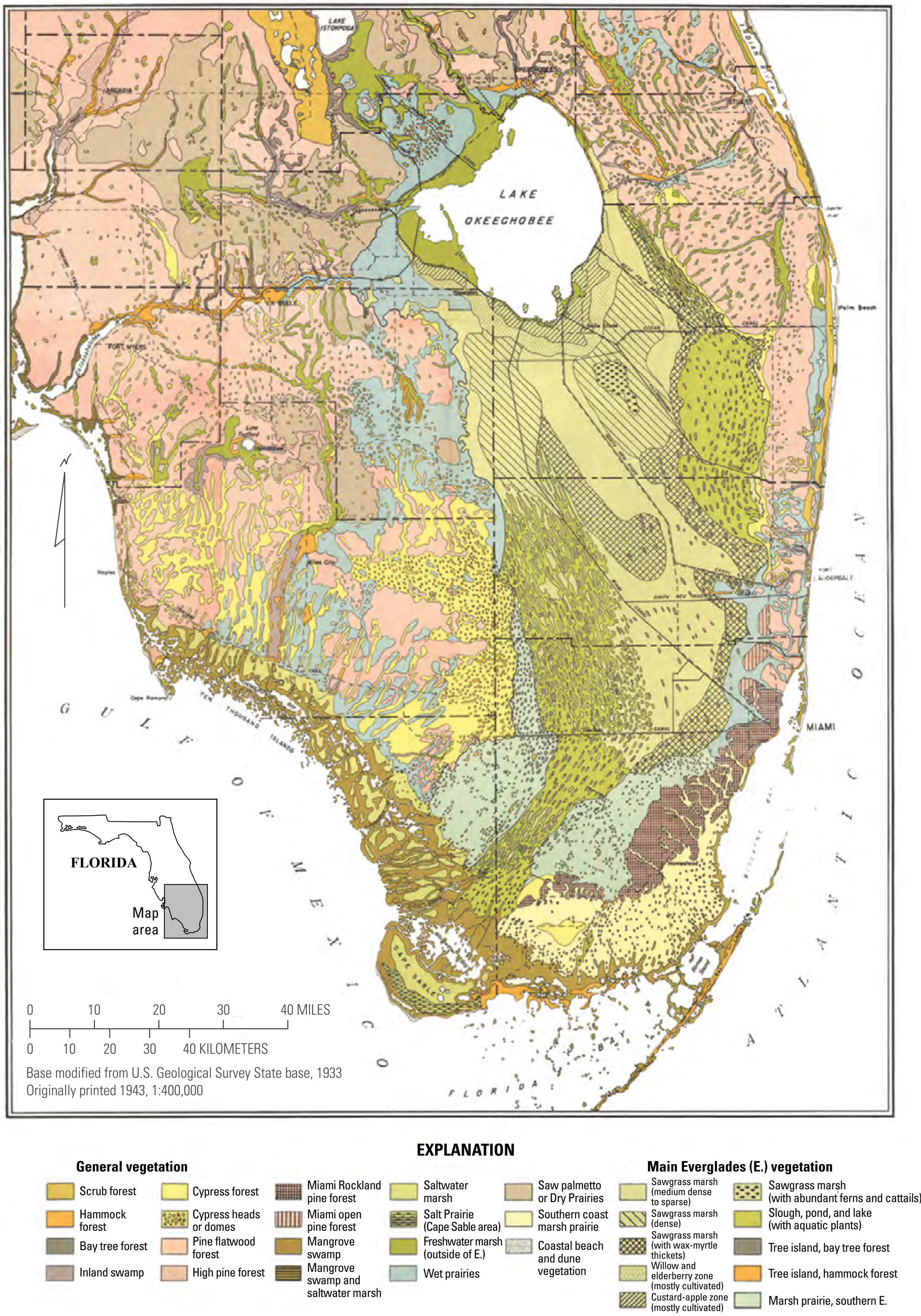

Figure 2. Vegetation map of southern Florida circa 1943 (modified from Davis, 1943).

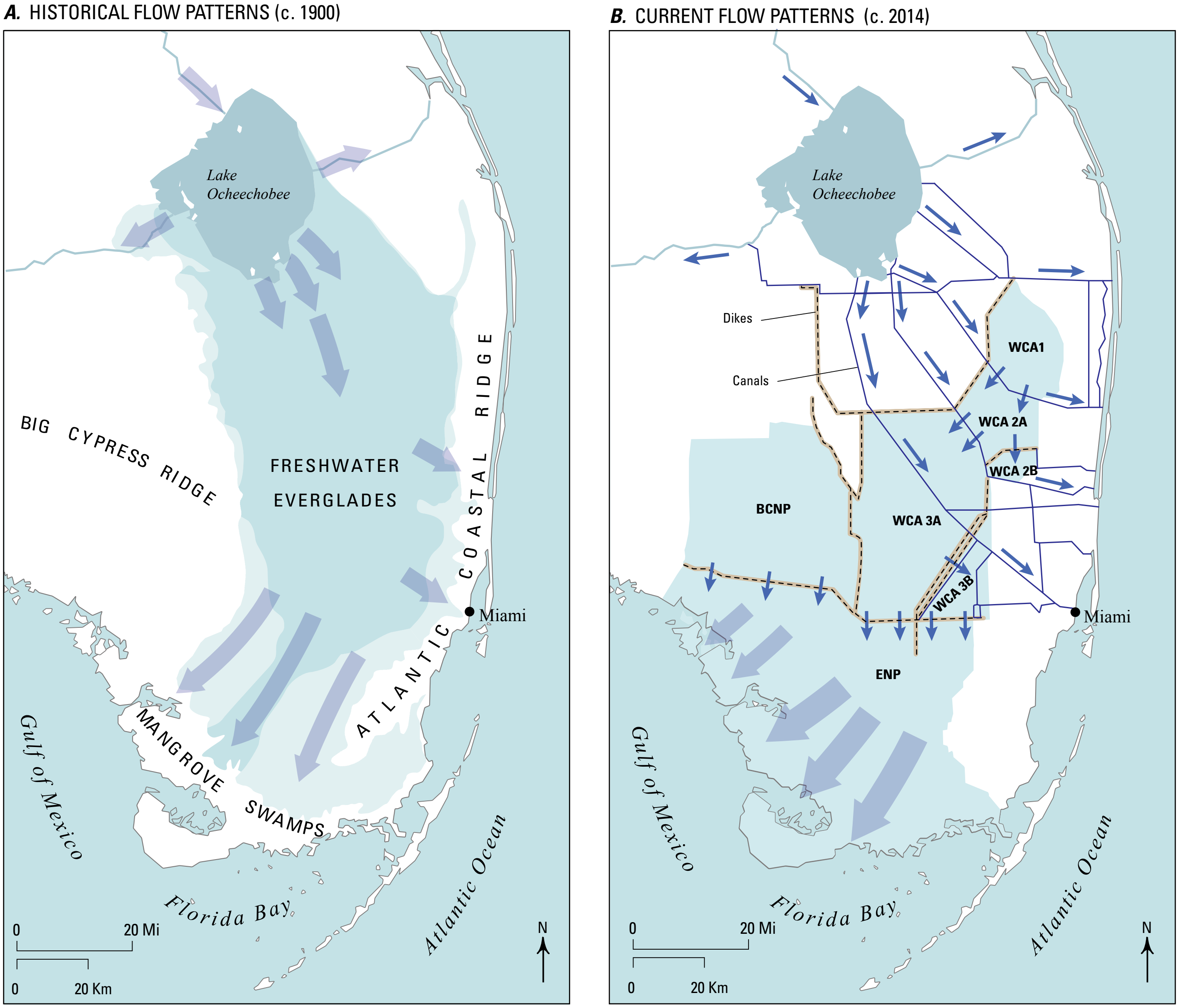

Figure 3. Everglades showing flow directions (*A*) before drainage (modified from Davis, 1943), and (*B*) after drainage and compartmentalization.

the water downstream until it reaches the Florida Bay and the Gulf of Mexico. Water levels in the WCAs and ENP are managed through water regulation schedules that dictate water levels within the WCAs based on current conditions, time of year, and minimum flow requirements.

Pennsuco Wetlands, an area between the heavily urbanized coastal areas and WCA3B, is managed to reduce overland seepage to the east and enhance groundwater recharge to a Miami-Dade County water-supply wellfield. Originally part of the Pennsylvania Sugar Company holdings in the 1920s, these wetlands are dominated by sawgrass marsh with scattered sloughs and areas infested with melaleuca trees, an invasive exotic tree species. Since the 1950s, limestone has been mined from the eastern part of the area known as the "Lake Belt" (Graham, 1951). In 1995, the SFWMD and the State of Florida began to buy lands in the Pennsuco Wetlands in order to protect it.

The BCNP was established in 1974 to preserve the distinctive natural areas that drained into Florida's southwest coastal fisheries and to provide habitat for several endangered flora and fauna, including the Florida panther. The BCNP, a seasonally flooded wetland, encompasses about 1,100 square miles and consists of an interwoven mosaic of ridges and sloughs that differ in elevation by only about 3 feet. Although the BCNP receives some surface-water inflow from the north, it is primarily a rain-driven watershed that flows in a southwesterly direction to the coast of the Gulf of Mexico (Sobczak and others, 2011).

ENP was established in 1947 primarily to preserve the unique flora and fauna of the area and to protect the primitive undeveloped natural conditions of the Everglades. ENP encompasses about 2,200 square miles and consists of freshwater sloughs, sawgrass marshes, wet prairies, pine and mangrove forests, and saline tidal flats. The topography is extremely low and flat with land-surface elevations ranging from sea level along the coasts of Florida Bay and the Gulf of Mexico to 6 feet above the North American Vertical Datum of 1988 (NAVD 88) in parts of the interior. In the predevelopment Everglades, the Shark River Slough carried more than 50 percent of the natural flow through the Everglades. Since the construction of the WCAs, water is delivered to ENP through a series of structures, culverts, and pump stations primarily along its northern and eastern borders with the goal of providing water for environmental benefit by simulating the rainfall-runoff patterns that occurred prior to construction of the upstream WCAs and other water-control structures.

Approach

Estimating systemwide water levels is requisite for evaluating ecological responses to changes in hydrologic behavior resulting from restoration changes in the Everglades. The focus of this study was to develop a model that simulates daily water levels for the freshwater part of the Everglades. The appropriate model schematization and model architecture must simulate the discontinuities in the water-surface elevation between the compartmentalized subbasins. The EDEN model domain is divided into eight subbasins represented by the five WCAs, BCNP, ENP, and Pennsuco Wetlands.

The general approach for modeling the water levels for the EDEN model domain was to:

1. Select water-level data for interpolation of daily water-level surfaces and for computation of model error, then update selected water-level data based on recent vertical elevation datum surveys.

2. Interpolate daily water-level surfaces by using five subdomain models.
   a. Interpolate water levels within four smaller subdomains by using selected gages in each subdomain.
   b. Interpolate water levels within the largest subdomain by using selected gages in the subdomain. Use water-level data at water-control structure gages and derived data at specific locations (or pseudogages) to model water levels along the boundaries with smaller subdomains and along selected levee-canal boundaries.
   c. Merge results of separately modeled subdomains.

3. Calibrate the interpolation model by testing the model for various combinations of model parameters and water-level conditions until cross-validation errors at gages were minimized.

4. Use two qualitative methods to guide model development and review calibrated model results.
   a. Evaluate contour maps to verify that resulting water-surface gradients were hydraulically defensible. Make adjustments to input gage data, such as corrections to datum conversion (National Geodetic Vertical Datum of 1929 [NGVD 29] to NAVD 88), if necessary.
   b. Compare difference maps to verify that changes made to the V1 model improved results in the V2 model.

5. Conduct model-error analysis by using water-level data at elevation benchmarks.
   a. Plot observed water levels at benchmarks versus residuals (modeled water level minus observed water level at a benchmark) to compare model results from the V1 and V2 models.
   b. Compute and compare model statistics of water-level residuals for V1 and V2 models.

6. Automate the data management, modeling, and accessibility of the model results, to the extent possible, to create an efficient process for the daily generation of near-real-time water-level surfaces for the Everglades.

Water-Level Data

Water-level data are collected from two principal networks for input to the V2 model and for testing of the V2 model. Data from a network of water-level gages are systematically measured water levels and are used by the model to estimate water levels in ungaged areas of the model domain. Water-level data collected at a network of elevation benchmarks provide independent measurements of water level away from gages and are used to measure the accuracy of the model at selected sites.

Water-Level Data Measured at Gages

Water-level data measured at the EDEN network of 240 gaging stations are used to model daily water-level surfaces. Gages in the EDEN network are operated and maintained by one of four agencies: BCNP, ENP, SFWMD, and USGS (fig. 1; appendix 1). In this report, gaging station names follow the naming convention used by EDEN and are generally similar to the names used by the operating agency. Real-time measurements of surface-water levels or shallow groundwater levels are collected generally every 15 minutes or 60 minutes and are transmitted hourly to the operating agency. In areas not adequately covered by real-time gages (gages with telemetry equipment), water-level data for several gages (gages without telemetry equipment) are provided on a monthly basis for the previous 30 days, and these data are used for modeling the provisional and final water-level surfaces.

The EDEN network of gages consists of (1) marsh gages that monitor surface water or shallow groundwater in the wetlands distant from levees and subbasin boundaries, (2) marsh structure gages located upstream or downstream of and near water-control structures where water is neither ponded nor directed into a canal and generally represents the water level in the adjacent marsh, (3) canal structure gages located upstream or downstream of and near a water-control structure where water is ponded or directed into a canal and the measured water level may vary slightly from the surrounding marsh, and (4) gages in rivers and canals distant from water-control structures. At water-control structures across levees that divide subbasins, gages are generally paired; the headwater gage records the water level on the upstream side of the structure, and the tailwater gage records the water level on the downstream side of the structure (fig. 4*A*). At water-control structures in canals, gages also are paired; the headwater gage records the water level on the upstream side of the structure for the predominant flow direction of the canal, and the tailwater gage records the downstream water level (fig. 4*B*). Water levels at water-control structures are managed to optimize the movement of water through the system of canals in the Everglades. Gages in rivers and canals also record, at times, rapidly changing water levels. Sheetflow conditions predominate at marsh gages; therefore, rapidly fluctuating water levels are uncommon.

Some existing gages in the Everglades are not used in the V2 model because they are not in hydraulic connection with the freshwater subbasins; for example, they are located in canals between levees that separate them from the marsh water levels. Gages that measure local hydraulic conditions and do not measure nearby marsh water levels also are excluded from the V2 model. For example, gages near pump stations may show local fluctuations that do not extend into the nearby marsh or extend less than the 400-meter grid spacing used in the V2 model.

Estimation of a water-level surface across the freshwater Everglades requires use of a consistent vertical datum because the differences between common vertical datums in south Florida can be about 1.5 feet. Historically, water-level gaging stations have been surveyed to the NGVD 29 to be consistent with the water-level schedules used to operate the C&SF Project. In 1973, the NGVD 29 was adjusted for changing sea levels. Inconsistencies in the vertical network were identified and never resolved for south Florida where extremely low-relief terrain and remote wetlands made traditional line-of-sight survey techniques difficult (U.S. Army Corps of Engineers, 2003). The NAVD 88 was developed by using improved satellite technology and generates more consistent water-level data across the greater Everglades than the previous datum, NGVD 29. The USGS high-accuracy elevation data (HAED) for measurements of ground elevation used to develop the EDEN ground-elevation model were collected during 1996–2007 using state-of-the-art differential global positioning system (GPS) technology and data processing techniques and are referenced to NAVD 88 (Desmond, 2003; Jones and others, 2012). For these reasons, all elevations and coordinates used in the V2 model are referenced to NAVD 88 and North American Datum of 1983 (NAD 83).

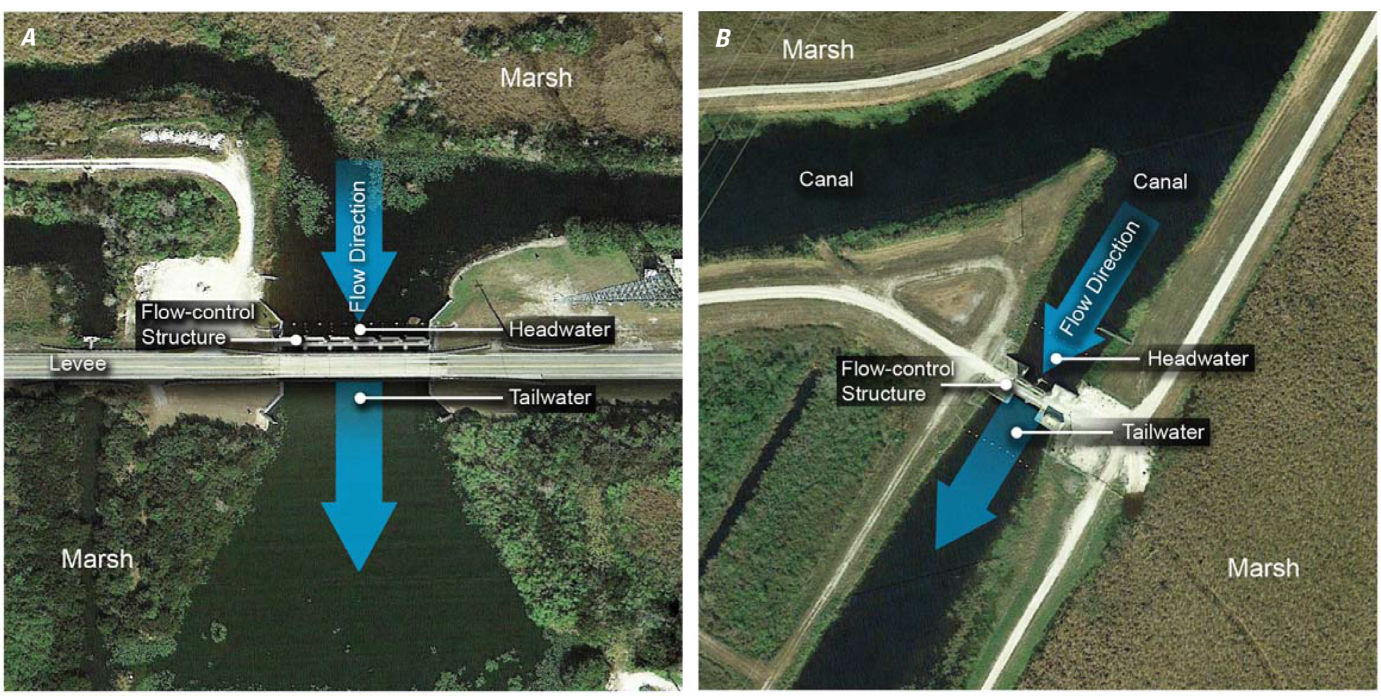

Figure 4. Types of gages at water-control structures used in the EDEN surface-water model showing (*A*) a plan view of a pair of headwater and tailwater gages across a levee that separates two subbasins; and (*B*) a plan view of a pair of headwater and tailwater gages in a canal adjacent to a subbasin boundary levee.

Water-Level Data Measured at Elevation Benchmarks

A network of 41 elevation benchmarks was installed by the U.S. Army Corps of Engineers (USACE) in the marshes of the Everglades and surveyed to NAVD 88 in 2009–2010 to provide points of known elevation independent from the existing water-level gages (fig. 5; appendix 2). Three of the benchmarks installed by the USACE were outside the EDEN domain and not used for the analysis. The benchmarks in the EDEN domain were combined with the 31 elevation benchmarks installed by the Florida Department of Environmental Protection in 2006 (Volin and others, 2008) to create a broadly distributed network of 69 elevation benchmarks to test and confirm the V2 model (fig. 6). Of the eight subbasins in the EDEN model domain, only the Pennsuco Wetlands subbasin has no benchmarks. Manual measurements of water levels in 2009–2011 at the benchmark locations provide independent measures of water level for comparison with EDEN model results. The number of measured water levels at a single benchmark ranges from 1 to 18 measurements.

Data Limitations

As with any modeling effort, the reliability of the model is dependent on the quality and completeness of the input datasets and the range of measured conditions used to calibrate the model. Selected days during 2004–2008 are used for the calibration period and provide a range of water-level conditions corresponding to low and high water associated with dry and wet seasons, respectively, and the longer interannual variability common in south Florida. The water-level gages used in the model were selected from an existing network of gages operated by multiple agencies to meet unique and often dissimilar agency missions, with a spatial density and distribution that has evolved over time. Gages are constructed and added to the EDEN network while others are defunded and discontinued. Records for gages added to the network in 2006 were hindcasted back to 2000 using methods of Conrads and Roehl (2007). When gages are discontinued, the data for those gages are evaluated to determine if the data for the gage will be estimated for future use in the model or removed from the model.

The water levels at some gages fall below land surface during the dry season. The reliability of the data under dry conditions varies based on the gage construction and the site conditions that control the hydraulic connection between surface water and groundwater near the gage. Some gages are constructed to measure water levels up to 3 feet below land surface, while other gages cannot measure water levels that recede below land surface in the vicinity of the gage. When the water level is below land surface, gages may (1) correctly record the shallow groundwater level in the subsurface, (2) record residual water in the gaged well not hydraulically connected to the shallow groundwater, or (3) simply record the bottom of a gaged well that is dry. The accuracy of the data in these circumstances usually cannot be determined. Therefore, surface-water-gage data recorded below the land surface is of unknown quality. Several of the water-level gages in the EDEN network are shallow groundwater gages and were constructed to accurately measure water levels above and below land surface. The accuracy of data at these gages is considered satisfactory when below ground level. Groundwater gages are identified in appendix 1.

Figure 5. An elevation benchmark (left) and measurement of water-level elevation (right). From Volin and others (2008).

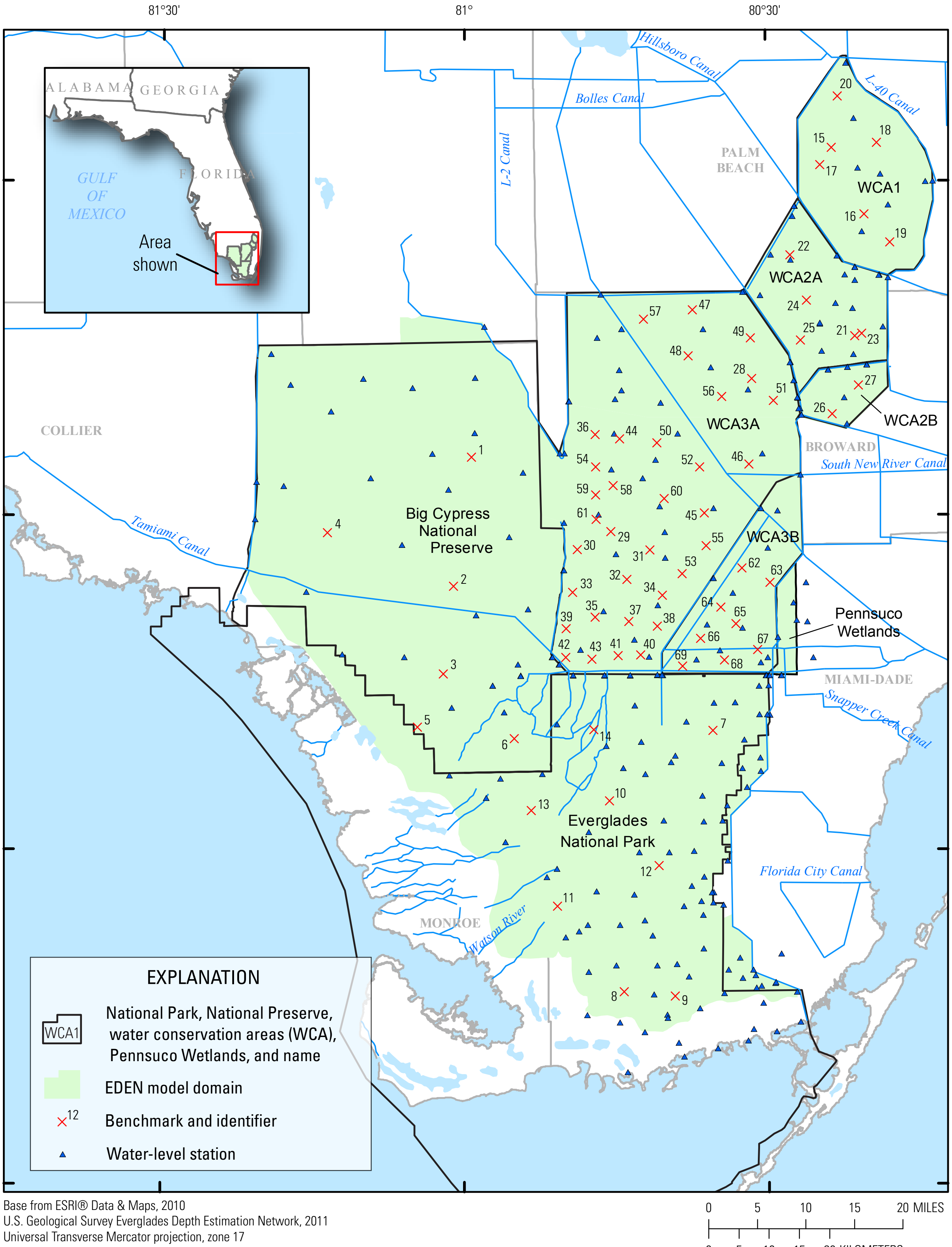

Figure 6. Location of elevation benchmarks in the Everglades.

Estimation of Water-Level Surface Using the EDEN Surface-Water Model, Version 2

The EDEN surface-water model simulates water levels in the freshwater part of the Everglades by using data from a network of gaging stations that measure and record water levels throughout the model domain (fig. 7). The V2 model was developed by using geoprocessing tools available in Esri ArcGIS 9.3.1 and written in Python programing language. To assist EDEN target users, the model provides water level and water depth output in centimeters. Water levels at gages measured in feet are converted to centimeters in the model input formatting program.

Model Domain

The V1 and V2 model domains include eight subbasins separated, in part or completely, by canals and levee systems that have gated water-control structures and culverts. Water levels across these boundaries are not continuous, and subdomain models are used to model these abrupt changes in water level along these boundaries. The exception is along the northern boundary between WCA3A and BCNP where an open marsh allows water to move between the basins (fig. 1).

The V1 model domain was based on a map from the 2004 CERP Monitoring and Assessment Plan (RECOVER, 2004) that showed the extent of wetlands in the greater Everglades within the CERP study area. For the V2 surface-water model, the model domain was expanded to include a part of southern BCNP and northwestern ENP that is upstream of the marsh mangrove wetlands identified on the vegetation maps by Davis (1943) (fig. 2). Adding this area south of the Tamiami Trail to the EDEN model domain fills in the missing freshwater marsh and connects the freshwater wetlands of the Everglades to the oligohaline wetlands along the coast of Florida Bay and the southwest coast of the Gulf of Mexico (fig. 8).

Model Grid

To use EDEN data layers most effectively, Jones and Price (2007a) developed a geographic data layer to index ground elevation and other surface characteristics for the greater Everglades region. For simplicity of design and use, the EDEN domain was subdivided into a large number of equal-sized squares (“cells”) that in total are referred to as the “EDEN grid.” The EDEN model domain consists of more than 57,000 cells of 400-meter by 400-meter resolution to agree with the Airborne Height Finder system sample spacing (Desmond, 2003; Jones and others, 2012). Once the grid database is developed (Jones and Price, 2007a), some of the characteristics of the grid, such as the size of the cells, its origin, area of Florida it is designed to represent, and individual grid cell identifiers, cannot be changed.

Each grid cell is assigned various information based on the EDEN surface-water model, ground-elevation model, and other spatial information. For example, a grid cell is assigned a daily water level, ground elevation (from the ground-elevation model), and computed water depth and hydroperiod attributed to the grid cell. Using gridded datasets to post-process, subset, analyze, and distribute large datasets is easier and more efficient than using other dataset formats and, therefore, benefits scientists and water-resource managers who access and use the EDEN datasets.

Radial Basis Function

The radial basis function (RBF) method is a series of exact interpolation techniques; that is, the surface must go through each measured sample value. RBFs are conceptually similar to fitting a rubber membrane through measured sample values while minimizing the total curvature of the surface. RBFs are used for calculating smooth surfaces from a large number of data points and produce good results for gently varying surfaces, such as low-gradient land-surface elevation and water-level surfaces. The technique is not appropriate when large changes in the surface occur within a short distance (ArcGIS Resources, 2013). The shape of the surface between measured points can be mathematically predicted in different ways, such as RBF regularized spline and RBF multiquadric. Palaseanu and Pearlstine (2008) developed the interpolation for the EDEN daily water-level surface for the V1 model by using the RBF multiquadric method. They tested other interpolation methods and reported that an RBF multiquadric produced lower statistical errors, such as the variance of the prediction error and the standard error of the estimated mean bias, and, overall, performed better at interior border conditions, such as canals and levees.

The interpolation of a surface through measured data values using the RBF multiquadric method requires calibration of several model parameters, including the shape parameter, the number of neighbors used, and the size and angle of rotation of the search neighborhood. When the shape, or smoothing, parameter is small, the resulting interpolated surface has the minimum curvature forming a cone-shaped basis function with a generated surface that is ‘tight’ around the data points. As the shape parameter increases, the curvature of the function flattens until the basis function is almost flat (Kansa and Carlson, 1992; Golberg and others, 1996; Johnston and others, 2001).

The search neighborhood defines the neighborhood shape, size, and the constraints of the points within the neighborhood that will be used for the interpolated surface. Spatial autocorrelation among the points assumes that nearby points are more similar than distant points. The specified shape and size of the neighborhood, therefore, restricts how far and how many measured points are used for the interpolation. The shape of the search neighborhood is dictated by the spatial autocorrelation of the data. For data with no directional

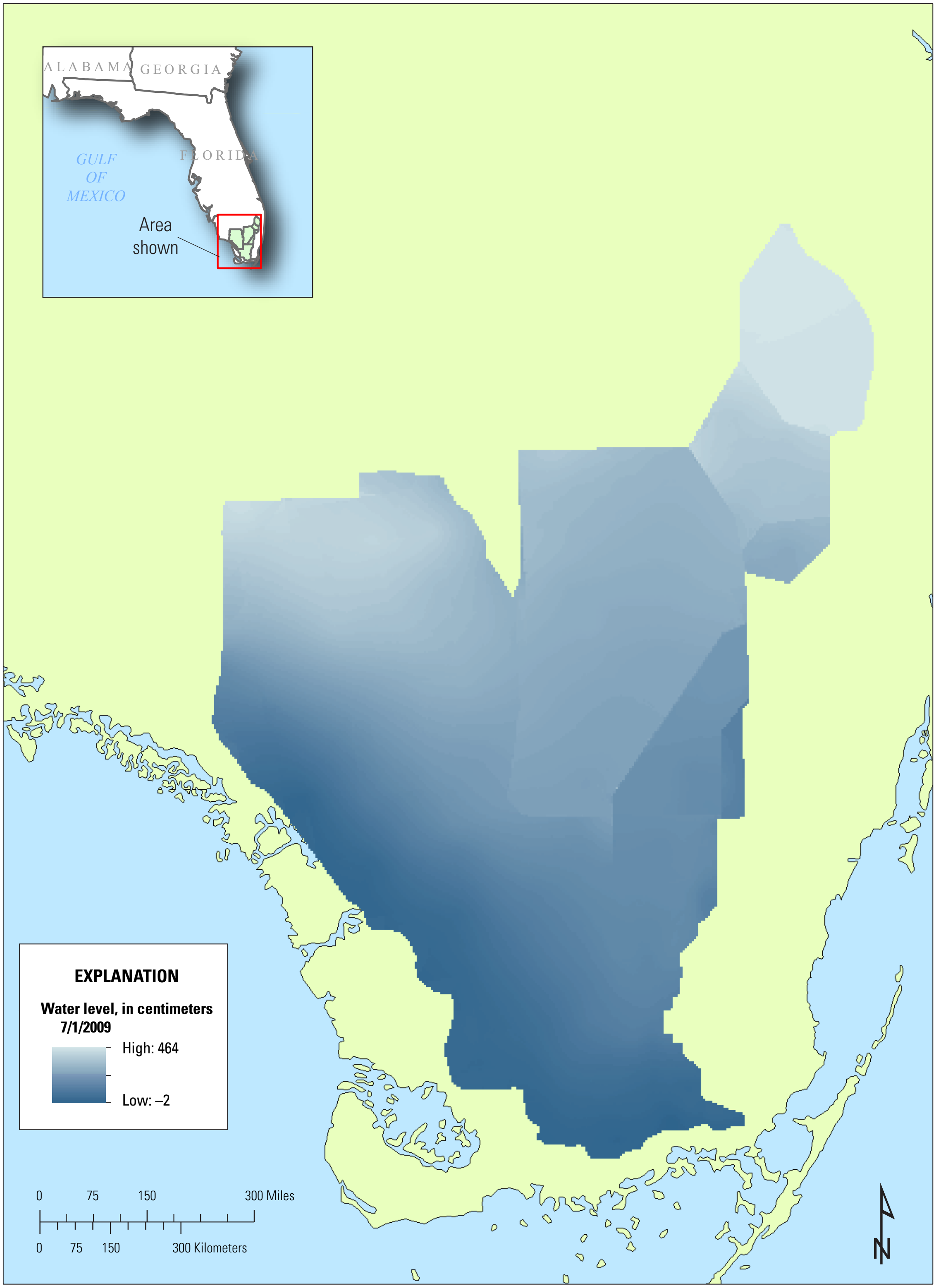

Figure 7. Water-level surface for July 1, 2009, obtained by using the EDEN surface-water model, version 2.

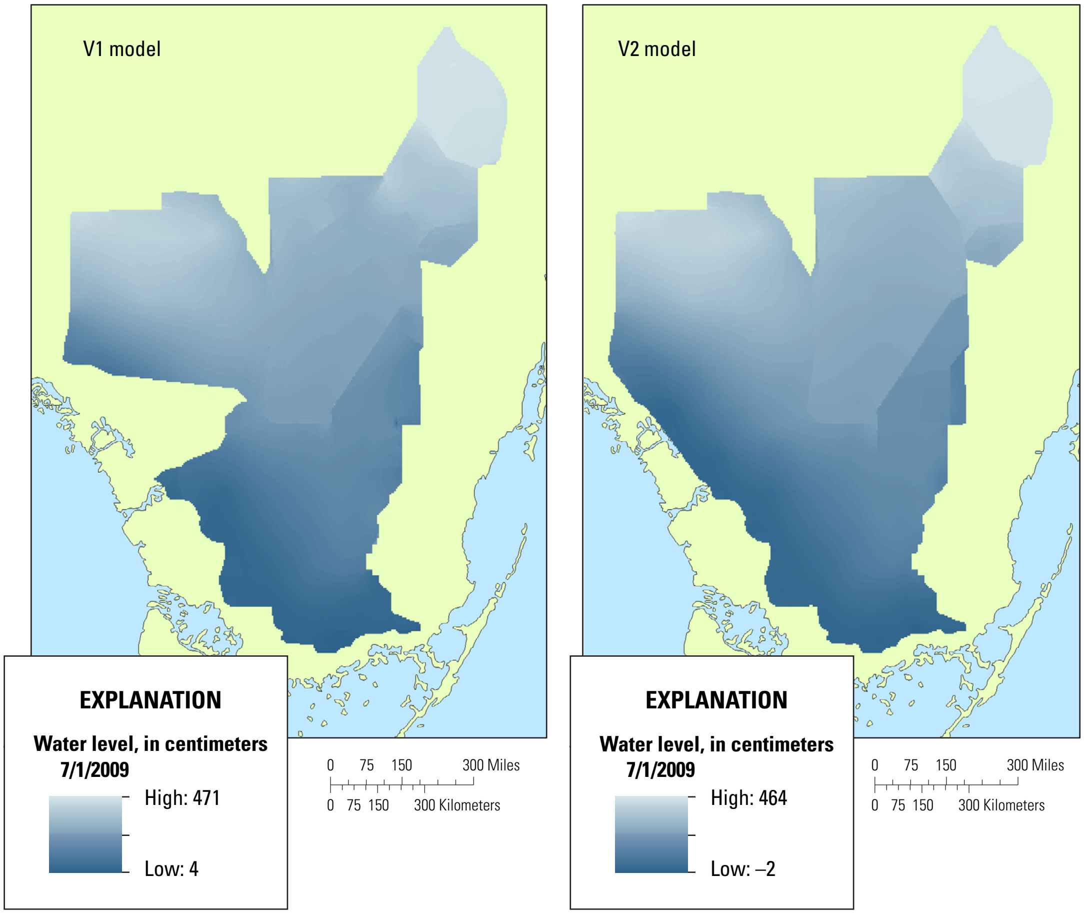

Figure 8. The domains of the EDEN surface-water model, versions 1 and 2, and examples of daily water-level surfaces. The version 2 model was expanded to include parts of southern Big Cypress National Preserve and northwestern Everglades National Park.

autocorrelation, the ideal shape of the search neighborhood is a circle. For data with directional autocorrelation, the ideal shape of the search neighborhood is an ellipse adjusted by an angle to align the major axis parallel to that direction. The size of the search neighborhood is defined by the linear distance of the radius of the circle or the major and minor semiaxes of the ellipse. Once the shape is defined, a maximum and minimum number of measured points, or neighbors, are defined for use in the interpolation. To avoid bias in a particular direction, the circle or ellipse, can be divided into sectors from which an equal number of points are selected (fig. 9; ArcGIS Resources, 2013).

Pearlstine and others (2007) tested surfaces based on 22 different sets of model parameters for water levels for wet, dry, and average conditions. Based on the analysis of the model errors, the final RBF parameters for the V1 model are listed in table 1.

Table 1. Model parameters used for calibration of the EDEN surface-water model, version 1.

Type	Values
Shape parameter	16.77
Maximum number of neighbors	1
Minimum number of neighbors	1
Sector type	8
Angle (degrees)	350
Major/minor semiaxes (meters)	31,000/30,000

Revisions to the Water-Level Gage Data

The confidence in the water-level surfaces depends on the selection of gages and the accuracy of their data because the EDEN surface-water model interpolates between water levels at gages. Based on a review of the V1 model results and comparison with field observations, several revisions to the input gage datasets were tested and implemented for the V2 model (table 2; fig. 10). Changes were made to 76 gages in the V2 model. Thirty-two gages were added to the input gage dataset because they were recently constructed or determined to be useful for interpolating the water-level surface. Twenty-nine gages were deleted from the input gage dataset because

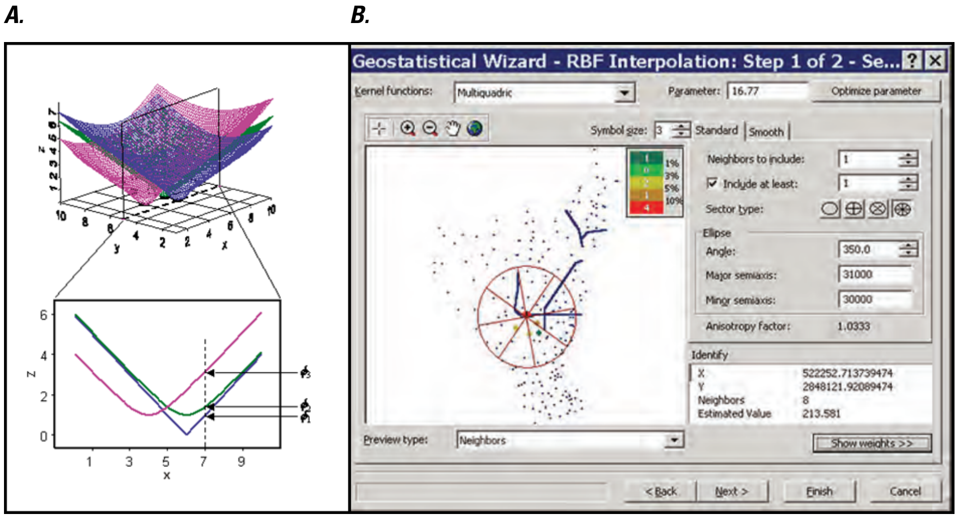

Figure 9. Example of (*A*) a radial basis function conceptual design in 2- and 3-dimensions and (*B*) a screenshot for calibration of radial basis function interpolation.

they were recently discontinued or were determined to not represent water levels in the freshwater marsh. Vertical datums were revised for 11 gages, and the locations of two gages, S142_H and S142_T (index numbers 215 and 176, respectively) were updated (fig. 10).

Review of 2-centimeter (cm) contour maps of the daily water-level surfaces showed two gages, 3ANE and Site_8C (index numbers 187 and 143, respectively) that consistently recorded water levels higher or lower than those from nearby gages and data collected at benchmark sites (fig. 10). Review of historical data at these sites indicates that reference elevations at these gages may not be correct perhaps because the gage elevation has changed over time. The datum for 3ANE has been questioned for a number of years, and the funding has not been available to re-survey the gages. Because no known hydraulic conditions could explain the water-level differences, a slight adjustment was made to the water levels at this gage. An approximate 0.16-foot discrepancy exists between the water level at Site_8C and the USGS-measured water levels (Michael Waldon, U.S. Fish and Wildlife Service, oral commun., January 10, 2010). The adjustments at these two sites improve the data at these gages until more accurate vertical datum surveys are conducted. To estimate the water level on the downstream side of the Tamiami Trail at the southern end of the L-67 extension canal-levee system, data for a “pseudogage” (pNP202NESRS1, a virtual gage, not an actual gage) were generated for use along this boundary. The V2 model averages water-level data at two nearby gages, NP202 and NESRS1 (index numbers 83 and 77, respectively; fig. 1), to estimate water level at this pseudogage location for use in the model.

Although all of the operating agencies are currently (2014) undergoing a multi-year effort to convert gaging equipment, data processing programs, and archive databases to reference NAVD 88, water-level data at some gages continue to be collected and referenced to NGVD 29. Prior to input to the V2 model, all data referenced to NGVD 29 are converted to NAVD 88 by using conversion values obtained from the operating agencies. These conversion values are based on surveys using traditional line-of-sight techniques from points of known elevation or on satellite-based GPS surveys. When survey data do not exist, the Corpscon version 6.0.1 program (U.S. Army Corps of Engineers, Geospatial Center, 2004) developed by USACE is used to model the conversion value. Corpscon is a program that interpolates the difference between ground elevation in NAVD 88 and NGVD 29 for a given location specified by latitude and longitude. Further refinement is achieved by using the Corpscon Vertcon version 2.5 grid modified by the USACE Jacksonville District to incorporate the CERP vertical control network established during 2001–2002 (Rory Sutton, U.S. Army Corps of Engineers, written commun., 2005). When new surveys are conducted, conversion values are updated and used in interpolation of subsequent water-level surfaces.

Subdomain Models

The V1 model interpolates the entire domain as a single model unit using measured water-level data at water-control structure gages and derived data at specified locations (or pseudogages) along boundaries to model the water-level discontinuities between the subbasins separated by levees.

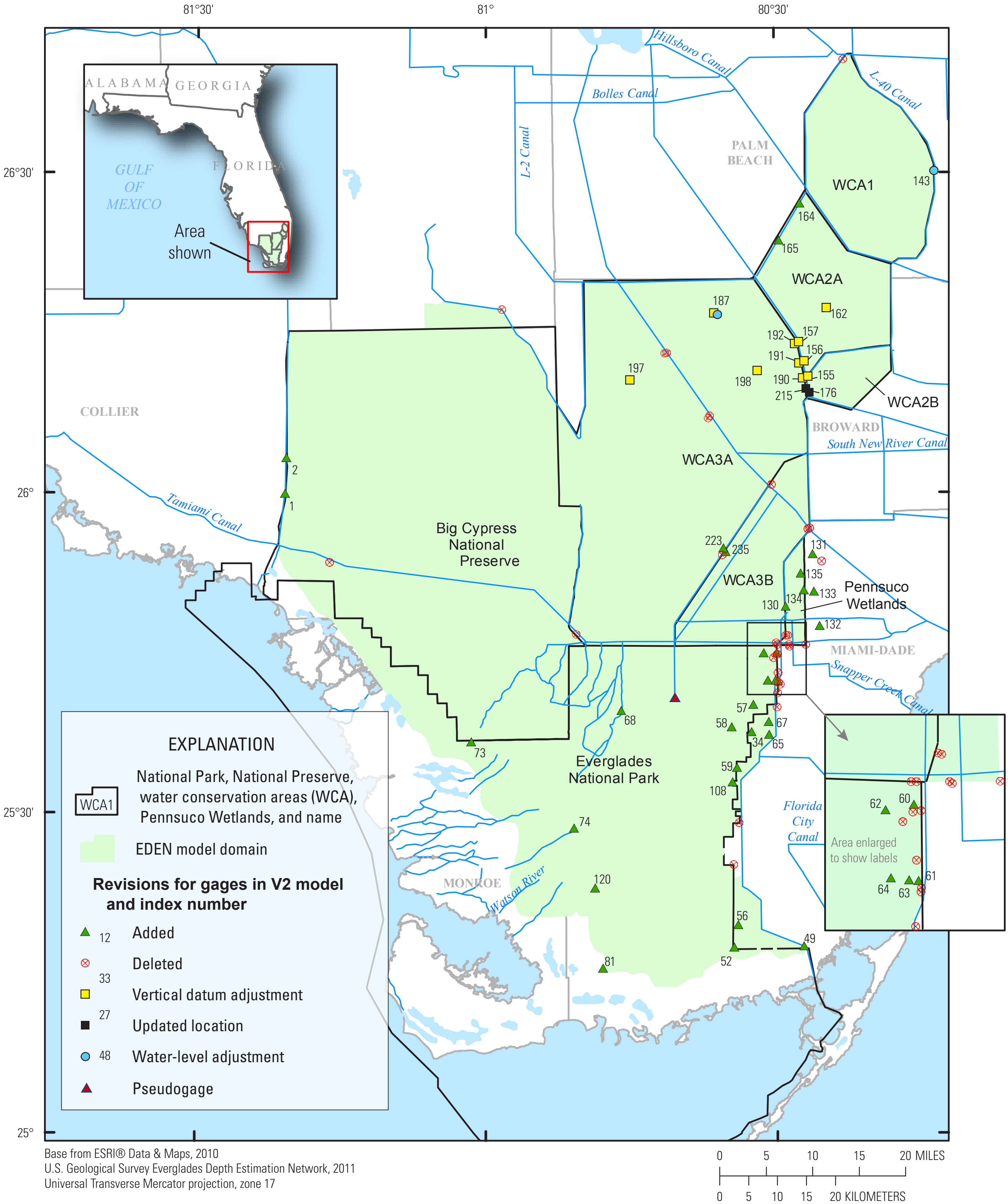

Figure 10. Location of gages adjusted, deleted, or added for use in the EDEN surface-water model, version 2.

Table 2. Updates made to the gage data used in the EDEN surface-water model, version 2.

[V2, version 2; NA, not applicable]

Index number on figure 1	Gage/station name	Subbasin	Update for V2 model
1	BARW4	Big Cypress National Preserve	Added
2	BARW6A	Big Cypress National Preserve	Added
NA	BCA8	Big Cypress National Preserve	Deleted
NA	S190_H	Big Cypress National Preserve	Deleted
34	ANGEL	Everglades National Park	Added
49	EP1R	Everglades National Park	Added
52	EVER5A	Everglades National Park	Added
56	G-1251	Everglades National Park	Added
57	G-3272	Everglades National Park	Added
58	G-3273	Everglades National Park	Added
59	G-3437	Everglades National Park	Added
60	G-3574	Everglades National Park	Added
61	G-3575	Everglades National Park	Added
62	G-3576	Everglades National Park	Added
63	G-3577	Everglades National Park	Added
64	G-3578	Everglades National Park	Added
65	G-3626	Everglades National Park	Added
67	G-596	Everglades National Park	Added
68	G-620	Everglades National Park	Added
NA	L31N_1	Everglades National Park	Deleted
NA	L31N_3	Everglades National Park	Deleted
NA	L31N_4	Everglades National Park	Deleted
NA	L31N_5	Everglades National Park	Deleted
NA	L31N_7	Everglades National Park	Deleted
NA	L31NN	Everglades National Park	Deleted
NA	L31NS	Everglades National Park	Deleted
73	MO-214 (previously LO1)	Everglades National Park	Added
74	MO-215 (previously SH1)	Everglades National Park	Added
NA	NESRS3	Everglades National Park	Deleted
81	NMP	Everglades National Park	Added
NA	pNP202NESRS1	Everglades National Park	Programmed pseudogage
108	RG3	Everglades National Park	Added
NA	S175_T	Everglades National Park	Deleted
NA	S332D_T	Everglades National Park	Deleted
120	SR1	Everglades National Park	Added
NA	G119_H	Pennsuco Wetlands	Deleted
NA	G119_T	Pennsuco Wetlands	Deleted
130	G-1488	Pennsuco Wetlands	Added

Table 2. Updates made to the gage data used in the EDEN surface-water model, version 2.—Continued

[V2, version 2; NA, not applicable]

Index number on figure 1	Gage/station name	Subbasin	Update for V2 model
131	G-3567	Pennsuco Wetlands	Added
132	G-3676	Pennsuco Wetlands	Added
133	G-3761	Pennsuco Wetlands	Added
134	G-3818	Pennsuco Wetlands	Added
135	G-975	Pennsuco Wetlands	Added
NA	NWWF	Pennsuco Wetlands	Deleted
NA	S380_H	Pennsuco Wetlands	Deleted
NA	G301_T	Water Conservation Area 1	Deleted
143	Site_8C	Water Conservation Area 1	Water level adjusted
155	S11A_H	Water Conservation Area 2A	Vertical datum adjusted
156	S11B_H	Water Conservation Area 2A	Vertical datum adjusted
157	S11C_H	Water Conservation Area 2A	Vertical datum adjusted
162	SITE_17	Water Conservation Area 2A	Vertical datum adjusted
164	WC2AN1	Water Conservation Area 2A	Added
165	WC2AS1	Water Conservation Area 2A	Added
176	S142_T	Water Conservation Area 2B	Location updated
187	3ANE	Water Conservation Area 3A North	Vertical datum adjusted
187	3ANE	Water Conservation Area 3A North	Water level adjusted
190	S11A_T	Water Conservation Area 3A North	Vertical datum adjusted
191	S11B_T	Water Conservation Area 3A North	Vertical datum adjusted
192	S11C_T	Water Conservation Area 3A North	Vertical datum adjusted
NA	S339_H	Water Conservation Area 3A North	Deleted
NA	S339_T	Water Conservation Area 3A North	Deleted
197	SITE_62	Water Conservation Area 3A North	Vertical datum adjusted
198	SITE_63	Water Conservation Area 3A North	Vertical datum adjusted
215	S142_H	Water Conservation Area 3A South	Location updated
NA	S340_H	Water Conservation Area 3A South	Deleted
NA	S340_T	Water Conservation Area 3A South	Deleted
223	SITE_69W	Water Conservation Area 3A South	Added
NA	S151_T	Water Conservation Area 3B	Deleted
NA	S31_H	Water Conservation Area 3B	Deleted
NA	S335_H	Water Conservation Area 3B	Deleted
NA	S335_T	Water Conservation Area 3B	Deleted
NA	S336_H	Water Conservation Area 3B	Deleted
NA	S336_T	Water Conservation Area 3B	Deleted
NA	S337_T	Water Conservation Area 3B	Deleted
NA	SITE_69	Water Conservation Area 3B	Deleted
235	SITE_69E	Water Conservation Area 3B	Added

Pearlstine and others (2007) referred to the model input files containing the list of water-control structure gages as canal files; however, canals are not always present at the boundaries. Water levels at pseudogages are estimated by linear interpolation between the water-control structure gages. The pseudogages are located every 200 meters (656 feet) and create track data, which are densely sampled preferential lines of data along water-level discontinuities that prevent data in the adjacent subbasin from influencing the model water surface on the other side of the levee (fig. 11). Subsequent review of the water-control structure gages used by Pearlstine and others (2007) indicated that some of the gages do not measure water levels in hydraulic connection with marsh water levels and the interpolation of these data produces inaccurate modeled water levels near the subbasin boundaries. At some locations, insufficient gage data exist to adequately define the water levels at these boundaries.

In the V2 model, water levels across the model domain are calculated separately for five subdomains and merged to create a single map of water levels (fig. 12). Water-level data at water-control structure gages and derived data create track data that are used to model water levels in the largest subdomain (WCA2A, WCA3A, WCA3B, BCNP, and ENP) along the subdomain model boundaries and along several levee-canal boundaries (fig. 11). No derived data for pseudogages to create track data were used in the four smaller subdomain models along the subdomain boundaries because sufficient water-control structure gage data do not exist. The smaller subdomain models interpolate a water-level surface using gages in each subdomain to the subdomain boundaries. The modeled water surface for all five of the subdomains uses the same RBF interpolation and parameters described in the description of parameter calibration for the EDEN V2 model. The data used for the development of the track data along the subdomain boundaries are no longer handled separately in “canal files” as was done in the V1 model. The V2 model uses data for these locations in the input files based on the model schematization and models the water-level surface at the boundary similarly to the V1 model.

To integrate the water-level surfaces from subdomain models, a subset of the EDEN grid is created for each of the five subdomain models, which allows the resulting subdomain modeled surfaces to be easily merged into a single surface for the entire domain. Then, the V2 model uses gage data to interpolate the water-level surfaces for each of the subdomains. Finally, the subdomain surfaces are merged to a single modeled surface.

The Pennsuco Wetlands has only six gages, and they are unevenly distributed (fig. 13). Gages G-975 and G-3818 are real-time gages; therefore, data for these gages are available for generating daily real-time water-level surfaces. Data for the other four non-real-time gages are estimated for use in the real-time water-level surface modeling, and measured data at these gages are available for generating only the quarterly provisional and annual final water-level surfaces. A minimum of four gages are needed to generate the daily water-level surfaces for the Pennsuco Wetlands:

1. one of either gages G-975 or G-3567, and
2. one of either gages G-3818 or G-3761, and
3. gage G-3676, and
4. gage G-1488.

If measured or estimated data for the minimum number of gages are not available on a particular day, the subbasin is not modeled, and no water-level surface is generated for that day.

Summary of the Differences Between Versions 1 and 2 of the EDEN Surface-Water Model

Three principal changes were made to the V1 surface-water model to develop the V2 model. Each change is briefly described as follows.

- The model domain for the V1 model based on the 2004 CERP Monitoring and Assessment Plan (RECOVER, 2004) was expanded to include a part of the southern BCNP and northwestern ENP that is upstream of the marsh mangrove wetlands. This spatial extent incorporates the freshwater marsh upstream of the oligohaline wetlands completing the coastal connection along the southwestern boundary of the model.
- Model input gage data were revised for several gages based on a review of the V1 model results and comparison of field observations:
  - Added 32 gages,
  - Deleted 30 gages,
  - Revised headwater and tailwater location for one pair of water-control structure gages,
  - Revised vertical datum conversions for 11 gages,
  - Adjusted water levels at 2 gages, and
  - Estimated 1 marsh pseudogage.
- Five subdomain models interpolate water-level surfaces, which are then merged into a single surface for the entire model domain. Data at water-control structures and derived data at pseudogages similar to those used in the V1 model were revised and only used along the subdomain boundaries in the largest subdomain. The remaining four subdomain models (WCA1, WCA2B, WCA3B, and Pennsuco Wetlands) interpolate a water-level surface using gages in each subbasin.

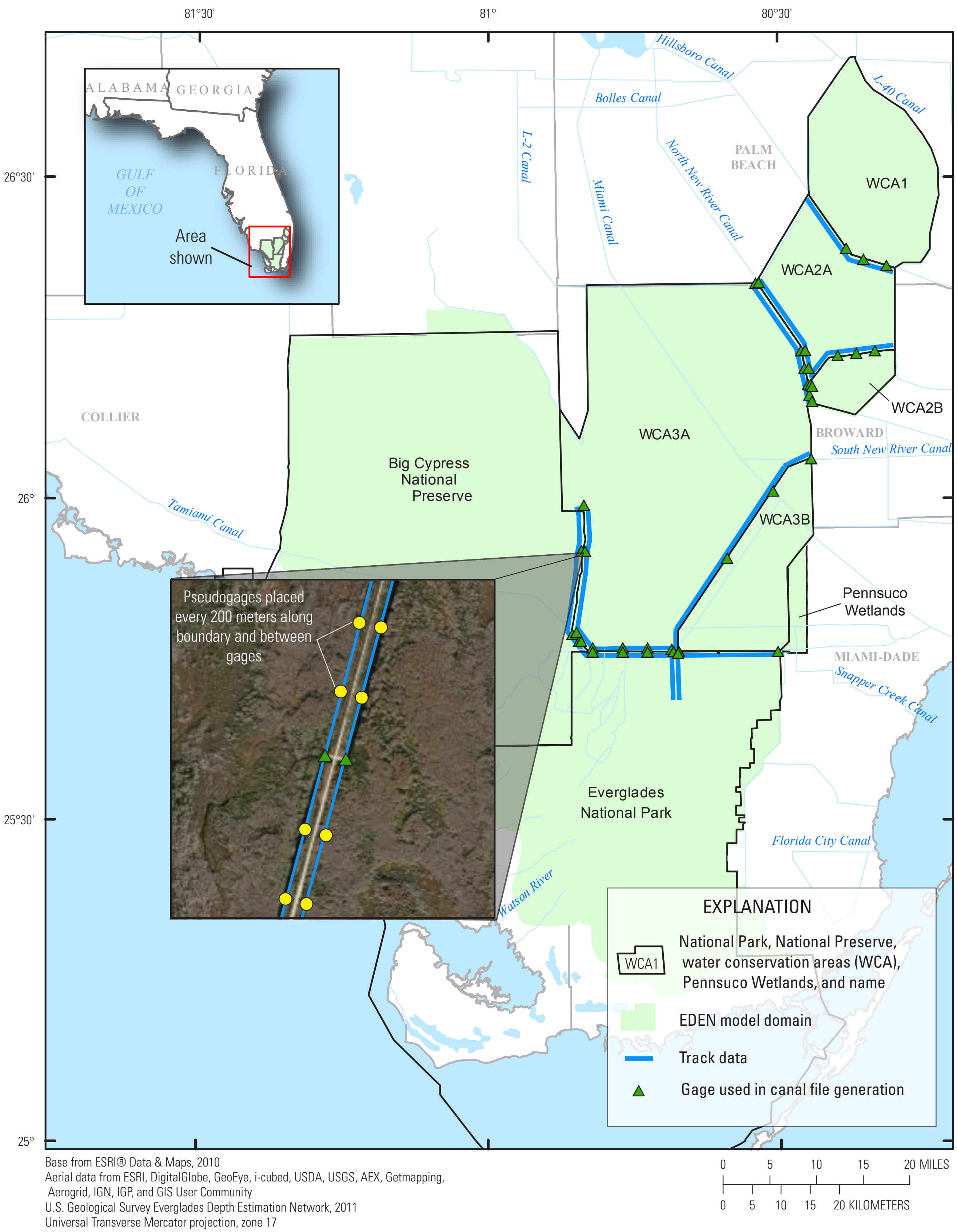

Figure 11. Location of pseudogages where track data are used to constrain water-surface discontinuities between Big Cypress National Preserve, Everglades National Park, and the Water Conservation Areas in the EDEN surface-water model, version 2.

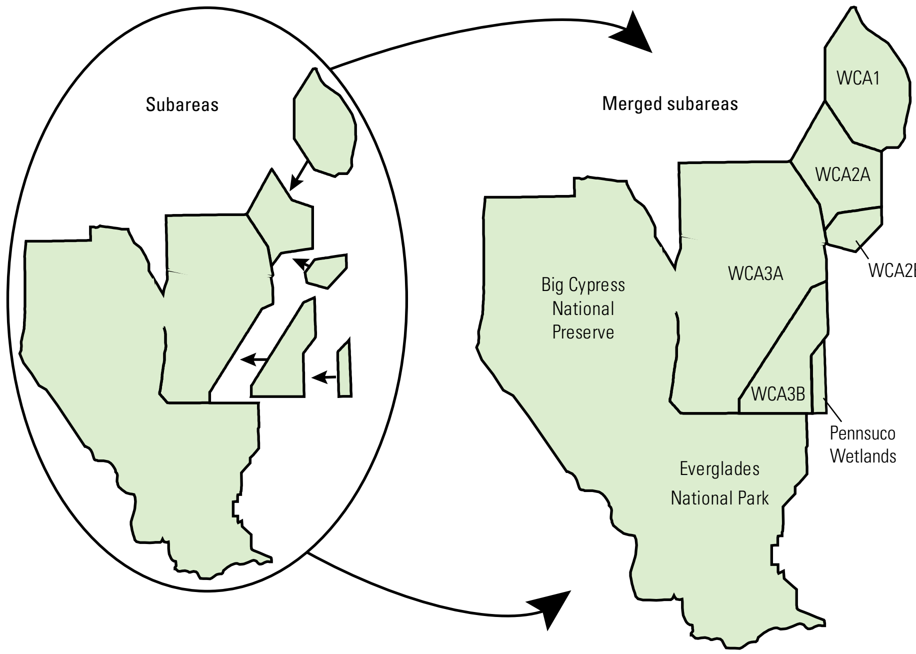

Figure 12. Five subdomain models merged to generate a single modeled surface used in the EDEN surface-water model, version 2.

Calibration of EDEN Surface-Water Model, Version 2

The EDEN V2 model interpolates points with known water levels through a low-gradient model domain that is complicated by compartmentalization by canals and levees. The calibration of the EDEN V2 model is an iterative process of adjusting model parameters until the model output results meet the modeling objectives (Nix and others, 1999). The calibration objective for the EDEN V2 model was to determine the combination of model parameter coefficients that minimized the model error for the range of water-level conditions from dry to wet years.

For the EDEN V2 model, cross validation was used to minimize the model error at the 198 marsh and marsh-structure gages in the model domain. Cross validation is a method for estimating generalized errors based on re-sampling of the model input data to evaluate how well future data will be predicted (Nix and others, 1999). The error at the marsh and marsh-structure gages is determined by computing the cross-validation error (CVE) which is the difference between the measured water level and the modeled water level from a model run without the gage input data. Goutte (1997) demonstrated that leave-one-out cross validation (LOOCV), the cross-validation technique used for calibrating the EDEN V2 model, is superior for small datasets compared to split-sample validation where some portion of the input data is removed prior to calibration and later used to test the model. LOOCV uses all available data for calibrating the model.

Table 3. Model parameters used for calibration of the EDEN surface-water model, version 2.

[Values in bold font are the final parameters used in the V1 model by Pearlstine and others, 2007]

Type	Values
Shape parameter	0, 10, **16.77**, 20, 30, 40, 50, 100, 150, 200, 500, and 1000
Maximum number of neighbors	**1**, 2, 3, 4, 5, 6, 7, and 8
Minimum number of neighbors	**1**, 2, 3, 4, 5, 6, 7, and 8
Sector type	1, 4, 4 with 45 degrees offset, and **8**
Angle (degrees)	0, 10, 20, 30, 40, …, **350**, 360
Major/minor semiaxes (meters)	**31,000/30,000**, 57,813/30,385 (1 standard deviation)

Calibration of the EDEN V2 model involved thousands of model runs. The multi-quadratic radial basis function, the interpolation scheme used in the EDEN V2 model, is parameterized with six model parameter coefficients. The coefficient values considered for calibration are listed in table 3. Testing all of the possible combinations of coefficients in table 3 could result in hundreds of thousands of model runs. Each combination of model parameter coefficients needed to be evaluated over a range of hydrologic conditions. Nine days representing different hydrologic conditions were selected to represent each of three hydrologic conditions: dry, wet, and average conditions (table 4). The dry season of 2004 was drier than normal,

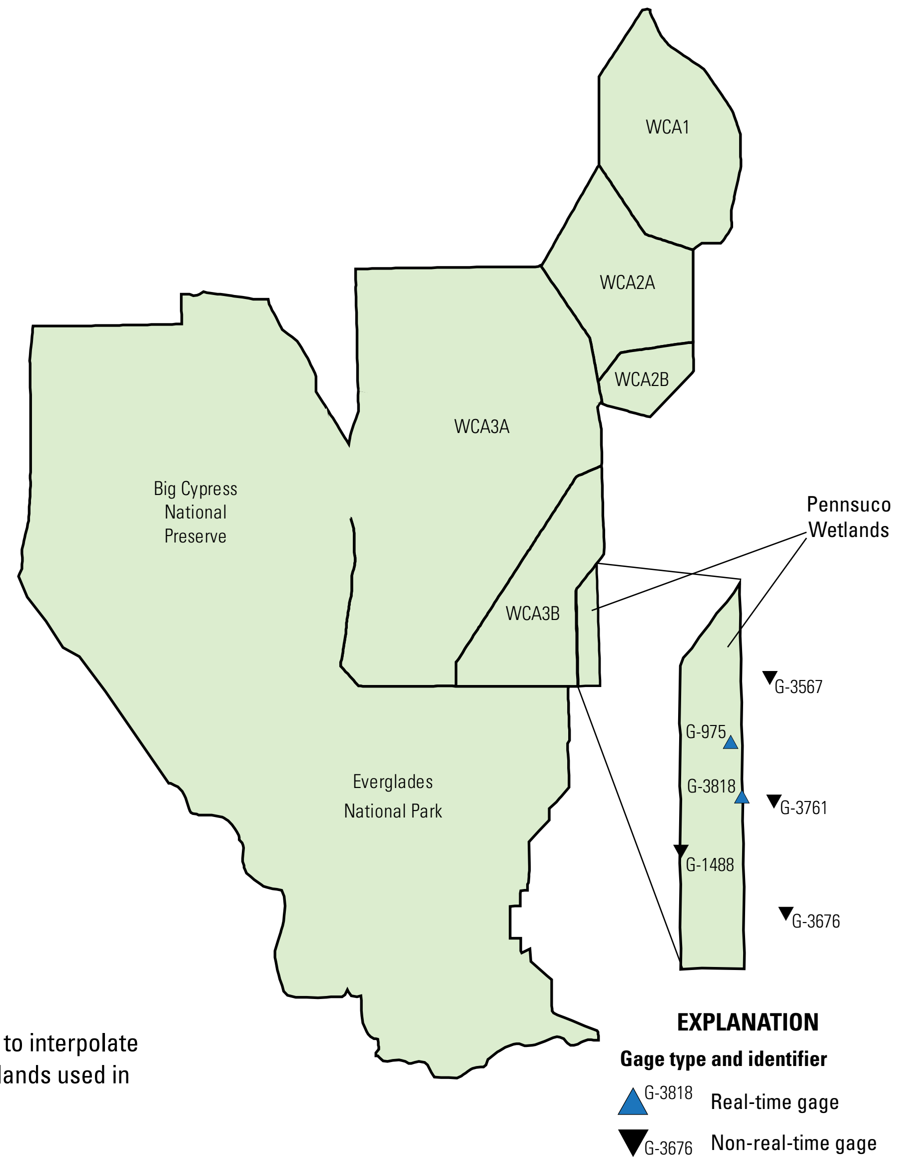

Figure 13. Gages used in subdomain model to interpolate daily water-level surfaces for Pennsuco Wetlands used in the EDEN surface-water model, version 2.

Table 4. Days selected for EDEN surface-water model, version 2, model parameter calibration and hydrologic conditions for each day.

Year	Dry	Wet	Average
2004	6/1/2004	10/1/2003	2/8/2004
2007	6/1/2007	10/1/2006	1/15/2007
2008	6/10/2008	9/30/2008	8/1/2008

resulting in lower than normal low-water conditions. The wet season of 2008 was wetter than normal, resulting in higher than normal high-water conditions. Water levels in 2007 were typical of an average year.

To constrain the number of combinations of the six model parameter coefficients, the coefficient values used in the V1 model were used as default values. The sensitivity of the coefficients was determined by using the CVE values computed at the marsh and marsh-structure gages. The calibration started with the shape parameter, maximum and minimum number of neighbors, sector type, angle, and major/minor semiaxes (table 3). Using the LOOCV technique to compute the CVEs for 1 combination of coefficients for 1 day involved 195 model runs—one run with all the gages and 194 runs systematically removing 1 of the marsh and marsh-structure gages to compute the CVE.

Three types of error statistics were computed to summarize the CVEs at the 194 gages; mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE). Each error statistic measures a different characteristic of model performance. The ME measures the average magnitude of the errors at gages where positive and negative errors indicate an over- or underprediction bias by the model. MEs near zero can be misleading because positive and negative differences can be important, but can add together to produce a near-zero value, thus canceling each other. The MAE measures the average magnitude of the errors at gages without considering their direction, thereby eliminating the canceling effect of the ME. The RSME also measures the magnitude of the errors at gages rather than the direction of the discrepancies; however, large errors are given more weight when the differences are squared, averaged, and then taken to the square root. The RMSE can be useful in indicating the presence of large errors. The greater the difference is between the RMSE and MAE, the greater the variance in the individual errors. Gages at canal structures, in canals, and in rivers were not used in the analysis. Each gage and gage's type are listed in appendix 1 (online at *http://dx.doi.org/10.3133/sir20145209*).

The result of the calibration process for the V2 model showed that the combination of model coefficients for the V2 model that minimize the CVEs was the same combination as used in the V1 model. The error statistics for the V1 and V2 models for marsh and marsh-structure gages in the model domain (grouped by subbasin) are listed in table 5. WCA3A was divided into two subareas. WCA3A is a large subbasin with many water-level gages distributed broadly across the area, with a substantial difference in hydrologic conditions from north to south. The northern part of WCA3A often dries out during the dry season, whereas the southern part of the subbasin is influenced by backwater from the canal and levee system along the southern boundary. For these reasons, error statistics were computed separately for WCA3A North and WCA3A South.

Comparison of error statistics for the V1 and V2 model results for wet, dry, and average conditions shows that the V2 model consistently generates more accurate results in all subbasins of the model domain except in WCA2B and WCA3B. The error statistics for WCA1 and WCA2A show the greatest improvement when using the V2 model, indicating that the data input changes and the subdomain model configuration improve the modeled water-level surface for these subbasins. Other areas with slight improvement using the V2 model revisions include BCNP and ENP.

Error statistics for the CVEs for gages in WCA2B and WCA3B are higher for the V2 model than for the V1 model. Both of these subbasins are small and have a less dense network of marsh gages than other subbasins. One explanation may be linked to the use of the canal files in the V1 model that added numerous data points, measured and derived, along the subbasin boundaries. The effect of removing a gage during the CVE analysis is likely less in the V1 model because track data along the subbasin boundaries is used. Without the track data along the boundary for WCA2B and WCA3B, the cross-validation errors for WCA3B using the V2 model are higher, indicating that removal of a single marsh gage has a relatively larger impact on the calculated surface than when using the V1 model. The model-error analysis using water levels measured at benchmarks can be used to compare the accuracy of the two models.

Two qualitative methods were used to guide model development and review of the calibrated model results. Evaluation of contour maps identified potentially erroneous input data while comparison of difference maps verified improvements from the V1 model results. Each of these methods is described in more detail in the following sections.

Evaluation of Contour Maps

Contour maps of modeled water-level surfaces at 2-cm intervals were examined for selected days each year from 2000 to 2010 to verify that modeled water levels and resulting water-surface gradients are hydraulically defensible and consistent with the input data. When contour maps based on the V2 model results are compared with the V1 model results, differences in contours help verify that water-level surfaces are improved for the V2 model. The high resolution provided by the 2-cm contour intervals highlights areas of the model domain where input data may be incorrect or missing, where boundaries at subdomain models do not adequately represent hydraulic conditions, and where water-level gradients may not be consistent with current knowledge of sheet flow in the marshes.

Review of the contour maps guided development of the model and evaluation of the input data and helped identify geographic areas where further analysis or data collection is necessary to improve the estimation of daily water levels. Water-level surfaces generated by the V1 and V2 models were contoured with 2-centimeter contours for a part of the EDEN domain for July 23, 2009 (fig. 14). Five areas highlighted in figure 14 show examples of notable improvements in the V2 model results when compared with the V1 model results:

- Use of subdomain models and selection of appropriate water-control structure gages between WCA2A and WCA3A produce a water surface for area A (fig. 14) that more accurately represents the discontinuous water surface between these subbasins. This is seen in the difference between the contours in the two WCAs with steeper water-level gradients in WCA2A and smaller gradients in WCA3A.

- In area B (fig. 14), two sets of gages, S339_H, S339_T, S340_H, and S340_T (fig. 10; table 2), record water levels at water-control structures along the Miami Canal, which runs generally northwest to southeast through WCA3A. These four gages were removed from the V2 model. The local water-level differences at these structures and water levels recorded at their headwater and tailwater gages likely do not extend into the adjacent marsh as represented in the V1 model results. These two sets of headwater and tailwater gages have been removed from the model input files used for the V2 model.

- Area C (fig. 14) shows that extending data at water-control structure gages and derived track data along the southern boundary between WCA3A and BCNP (fig. 11) improved the water-level surface at this levee-canal boundary where discontinuous water levels occur.

Table 5. Cross-validation errors (in centimeters) at gages for the EDEN surface-water model, versions 1 and 2, for dry, wet, and average conditions by subbasin.

[N, number of observations; MAE, mean absolute error; ME, mean error; RMSE, root mean squared error; V1, version 1; BCNP, Big Cypress National Preserve; ENP, Everglades National Park; WCA, Water Conservation Area; V2, version 2; PW, Pennsuco Wetlands; Error statistics for the version 1 model were not computed for Pennsuco Wetlands]

Dry Season																
	June 1, 2004					June 1, 2007					June 10, 2008					
Model	Type	N	MAE	ME	RMSE	Type	N	MAE	ME	RMSE	Type	N	MAE	ME	RMSE	
V1 model	BCNP	28	26.48	–1.08	34.82	BCNP	28	23.12	–0.57	27.25	BCNP	28	26.74	–4.66	34.37	
	ENP	66	10.93	2.12	15.09	ENP	66	7.22	0.34	9.61	ENP	66	11.06	2.40	17.28	
	WCA1	9	14.67	–3.46	17.29	WCA1	9	19.52	–13.19	27.23	WCA1	9	11.37	–8.08	18.62	
	WCA2A	20	22.61	–6.08	28.59	WCA2A	20	18.51	–4.83	23.19	WCA2A	20	21.14	–2.81	28.88	
	WCA2B	6	15.03	12.02	18.05	WCA2B	6	31.43	20.27	46.28	WCA2B	6	11.56	8.09	13.52	
	WCA3A North	14	14.42	4.95	19.33	WCA3A North	14	21.39	1.99	24.73	WCA3A North	14	13.65	3.91	18.39	
	WCA3A South	21	9.08	–5.49	10.97	WCA3A South	21	10.49	–7.17	12.38	WCA3A South	21	4.90	–3.19	6.00	
	WCA3B	11	6.84	–5.19	9.05	WCA3B	11	8.05	–3.61	10.16	WCA3B	11	7.75	–2.83	9.81	
	All	175	14.89	–0.42	21.20	All	175	14.10	–1.43	20.01	All	175	14.01	–0.55	21.41	
V2 model	BCNP	27	25.95	–0.50	33.11	BCNP	27	22.47	–1.77	31.03	BCNP	27	26.18	–5.90	32.74	
	ENP	83	12.55	1.60	17.75	ENP	83	6.19	0.19	7.91	ENP	83	9.44	1.62	15.09	
	PW	6	14.37	7.39	19.39	PW	6	10.40	6.60	14.65	PW	6	14.97	9.55	19.97	
	WCA1	7	19.27	–13.91	23.33	WCA1	7	18.53	–12.27	20.88	WCA1	7	12.72	–9.50	14.99	
	WCA2A	22	15.19	–7.49	20.69	WCA2A	22	14.78	–7.70	19.25	WCA2A	22	15.76	–6.71	22.13	
	WCA2B	7	14.84	14.84	18.50	WCA2B	7	28.36	20.64	45.46	WCA2B	7	16.00	12.73	19.38	
	WCA3A North	13	13.50	3.73	18.24	WCA3A North	13	19.78	2.21	22.28	WCA3A North	13	12.58	2.84	18.10	
	WCA3A South	22	5.70	–3.77	7.29	WCA3A South	22	10.17	–5.06	13.27	WCA3A South	22	3.96	–2.31	5.14	
	WCA3B	11	8.51	1.01	9.49	WCA3B	11	8.94	2.49	10.56	WCA3B	11	8.49	4.97	10.70	
	All	198	14.12	–0.09	20.12	All	198	12.20	–0.80	18.76	All	198	12.49	–0.26	18.98	

Table 5. Cross-validation errors (in centimeters) at gages for the EDEN surface-water model, versions 1 and 2, for dry, wet, and average conditions by subbasin.—Continued

[N, number of observations; MAE, mean absolute error; ME, mean error; RMSE, root mean squared error; V1, version 1; BCNP, Big Cypress National Preserve; ENP, Everglades National Park; WCA, Water Conservation Area; V2, version 2; PW, Pennsuco Wetlands; Error statistics for the version 1 model were not computed for Pennsuco Wetlands]

	Wet Season														
	October 1, 2003					October 1, 2006					September 30, 2008				
Model	**Type**	**N**	**MAE**	**ME**	**RMSE**	**Type**	**N**	**MAE**	**ME**	**RMSE**	**Type**	**N**	**MAE**	**ME**	**RMSE**
V1 model	BCNP	28	21.34	–1.62	27.23	BCNP	28	19.08	–1.92	26.08	BCNP	28	18.92	–1.06	24.44
	ENP	66	6.69	1.40	12.84	ENP	66	6.08	1.27	10.77	ENP	66	7.24	1.66	14.24
	WCA1	9	22.04	0.68	28.44	WCA1	9	8.98	–7.70	22.22	WCA1	9	4.44	–2.82	8.03
	WCA2A	20	26.75	–1.27	37.59	WCA2A	20	22.90	1.31	32.52	WCA2A	20	24.03	–2.14	34.36
	WCA2B	6	28.78	25.09	34.86	WCA2B	6	16.22	16.22	20.16	WCA2B	6	27.49	26.97	37.85
	WCA3A North	14	11.27	8.16	14.45	WCA3A North	14	7.47	3.00	9.43	WCA3A North	14	6.40	2.02	7.68
	WCA3A South	21	8.11	–3.80	13.00	WCA3A South	21	6.11	–3.75	9.67	WCA3A South	21	5.41	–4.30	8.33
	WCA3B	11	12.36	0.97	16.60	WCA3B	11	13.12	2.46	18.34	WCA3B	11	15.38	2.69	20.89
	All	175	13.76	1.28	21.91	All	175	11.13	0.43	18.77	All	175	11.81	0.80	20.00
V2 model	BCNP	27	15.31	–3.31	20.34	BCNP	27	15.79	–3.38	21.31	BCNP	27	16.04	–2.51	20.56
	ENP	83	6.43	0.81	9.03	ENP	83	5.79	0.50	7.63	ENP	83	6.16	1.09	8.66
	PW	6	8.48	8.48	15.72	PW	6	11.53	9.11	17.43	PW	6	9.20	7.83	15.50
	WCA1	7	8.77	–7.38	15.16	WCA1	7	9.51	–7.75	15.37	WCA1	7	8.24	–6.51	13.73
	WCA2A	22	18.93	–5.86	29.05	WCA2A	22	14.13	–3.00	22.60	WCA2A	22	15.69	–5.79	27.40
	WCA2B	7	37.10	35.68	44.53	WCA2B	7	26.67	26.67	29.87	WCA2B	7	43.55	43.55	50.61
	WCA3A North	13	9.15	7.61	12.47	WCA3A North	13	6.05	2.03	8.21	WCA3A North	13	3.94	0.40	5.67
	WCA3A South	22	7.15	–2.82	11.52	WCA3A South	22	5.65	–2.46	10.64	WCA3A South	22	6.07	–3.64	12.84
	WCA3B	11	21.70	15.17	30.44	WCA3B	11	22.53	16.65	30.14	WCA3B	11	29.27	20.62	40.39
	All	198	11.36	1.52	18.62	All	198	10.05	1.15	16.12	All	198	11.18	1.79	19.70

Table 5. Cross-validation errors (in centimeters) at gages for the EDEN surface-water model, versions 1 and 2, for dry, wet, and average conditions by subbasin.—Continued

[N, number of observations; MAE, mean absolute error; ME, mean error; RMSE, root mean squared error; V1, version 1; BCNP, Big Cypress National Preserve; ENP, Everglades National Park; WCA, Water Conservation Area; V2, version 2; PW, Pennsuco Wetlands; Error statistics for the version 1 model were not computed for Pennsuco Wetlands]

	Average Condition														
	February 8, 2004					January 15, 2007					August 1, 2008				
Model	Type	N	MAE	ME	RMSE	Type	N	MAE	ME	RMSE	Type	N	MAE	ME	RMSE
V1 model	BCNP	28	16.32	–1.96	23.41	BCNP	28	18.46	–1.80	25.50	BCNP	28	18.40	–1.87	24.15
	ENP	66	8.21	1.40	13.00	ENP	66	7.20	1.99	12.08	ENP	66	5.18	0.11	7.32
	WCA1	9	30.89	–9.32	47.60	WCA1	9	8.90	–8.17	22.29	WCA1	9	8.78	–7.63	20.15
	WCA2A	20	22.24	3.35	34.19	WCA2A	20	26.09	–1.09	35.02	WCA2A	20	16.96	4.76	26.58
	WCA2B	6	13.42	2.08	15.01	WCA2B	6	18.47	17.54	23.04	WCA2B	6	12.85	12.69	15.28
	WCA3A North	14	7.30	3.80	9.49	WCA3A North	14	10.64	5.53	14.78	WCA3A North	14	5.82	1.71	8.32
	WCA3A South	21	8.94	–4.37	13.56	WCA3A South	21	6.14	–3.86	9.94	WCA3A South	21	3.46	–1.51	4.50
	WCA3B	11	10.06	0.26	13.66	WCA3B	11	7.89	–0.44	10.53	WCA3B	11	9.89	2.42	14.16
	All	175	12.59	–0.01	21.22	All	175	11.82	0.47	19.47	All	175	9.23	0.43	15.61
V2 model	BCNP	27	14.97	–2.91	21.09	BCNP	27	17.25	–2.74	24.37	BCNP	27	16.04	–2.81	20.87
	ENP	83	6.33	0.39	7.98	ENP	83	5.04	0.31	6.57	ENP	83	5.60	0.75	7.53
	PW	6	15.88	9.17	23.35	PW	6	21.05	8.90	27.82	PW	6	14.04	8.41	19.84
	WCA1	7	10.42	–8.90	17.08	WCA1	7	9.55	–8.25	15.27	WCA1	7	9.11	–8.00	14.05
	WCA2A	22	14.43	–1.37	23.29	WCA2A	22	17.19	–5.12	25.75	WCA2A	22	9.12	0.43	16.51
	WCA2B	7	16.99	9.84	18.94	WCA2B	7	24.86	24.86	30.38	WCA2B	7	18.62	18.62	20.15
	WCA3A North	13	5.76	2.40	7.90	WCA3A North	13	9.60	4.60	14.42	WCA3A North	13	4.01	0.60	6.98
	WCA3A South	22	6.06	–2.32	9.21	WCA3A South	22	4.83	–1.90	7.88	WCA3A South	22	4.26	–1.38	8.07
	WCA3B	11	17.50	13.94	23.99	WCA3B	11	14.04	10.50	19.57	WCA3B	11	21.26	16.54	28.95
	All	198	9.77	0.60	15.25	All	198	10.18	0.72	16.70	All	198	8.87	1.41	14.27

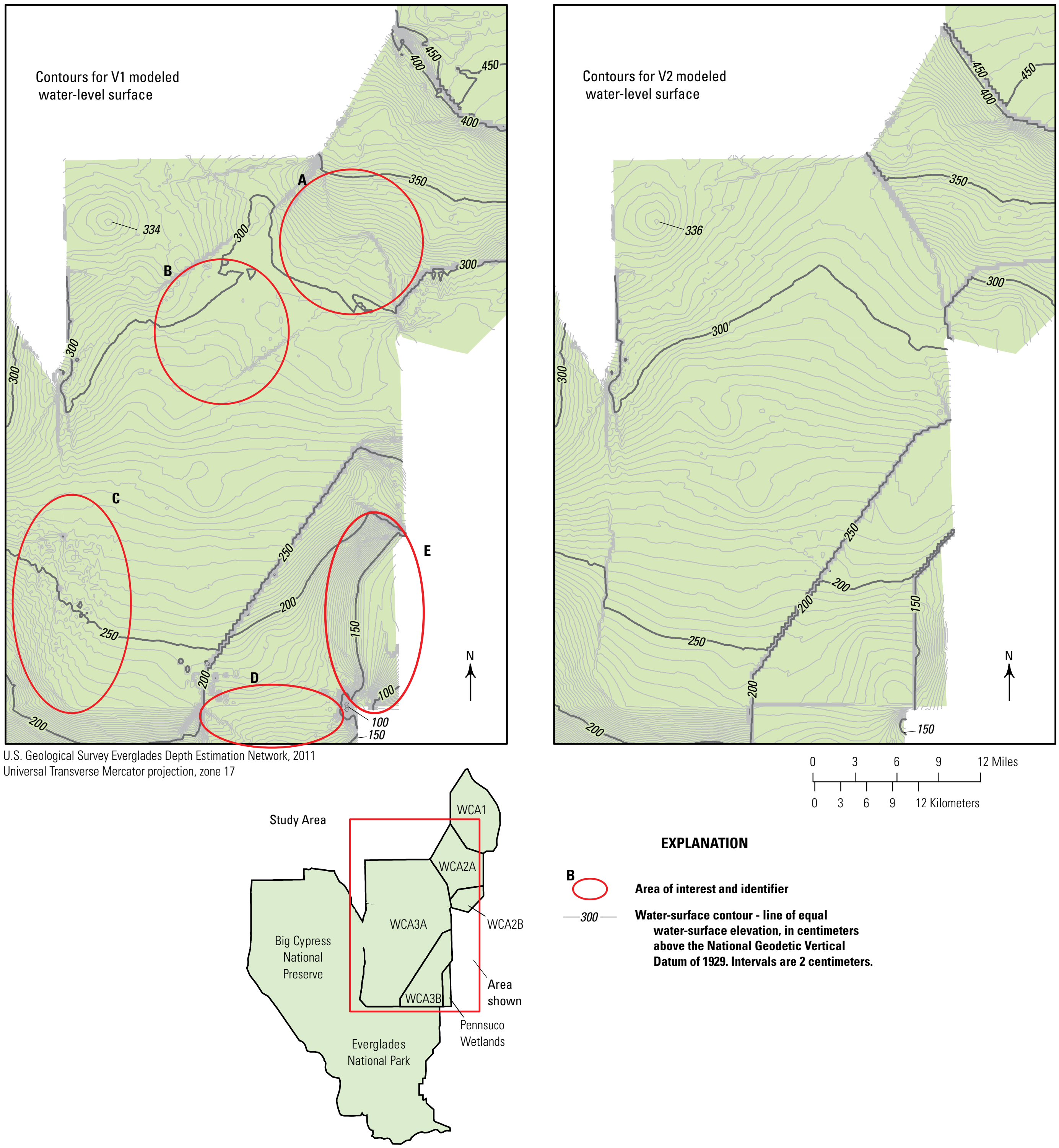

Figure 14. Water-level surfaces for July 23, 2009, showing 2-centimeter contours for the EDEN surface-water model, versions 1 and 2.

- In the V1 model surface, area D (fig. 14) does not show the discontinuity in water surfaces between WCA3B and ENP. The V2 model shows the discontinuity with the differences in the distances between contours.
- The contours for area E (fig. 14) in WCA3B from the V1 model show that the preferential flow path (perpendicular to the contours) is to the east toward the Pennsuco Wetlands. The V2 model shows the preferential flow path in WCA3B to be to the south toward ENP.

Comparison of Difference Maps

To ensure that revisions to the V2 model and updates to the input data produce improved water-level surfaces compared with the V1 model, water-level-surface difference maps were visually reviewed for expected changes in the modeled water levels. The difference maps were generated by subtracting the V1 modeled surface from the V2 modeled surface for a given day, then shaded to indicate the range of differences in water level (fig. 15). This qualitative evaluation allows areas of change to be easily identified and verified with model or data revisions. Four areas highlighted in figure 15 show where the V2 model results differ from the V1 model results:

- Large differences between the V1 and V2 models in area A (fig. 15) result from extending data at water-control structure gages and derived data at pseudogages along the downstream (southern) side of the WCA2A/WCA3A boundary to prevent gages in WCA2A from being incorrectly used for generating water-level surfaces in WCA3A. Other subbasin boundaries show similar differences resulting from use of subdomain models and revisions to data at water-control structure gages and derived data at pseudogages.
- The differences in WCA3B and Pennsuco Wetlands in area B (fig. 15) result from the use of subdomain models for both of these subbasins and the addition of marsh gages in Pennsuco Wetlands.
- Differences between the V1 and V2 models in area C (fig. 15) result from removal of some gages and addition of others to better represent water levels in eastern ENP. The deleted gages near water-control features, such as gates and canals, measure locally fluctuating water levels that cannot be represented at the EDEN 400-meter grid scale.
- The difference between the V1 and V2 models in area D (fig. 15) results from the addition of a gage upstream of the coastal marsh mangrove wetlands in northwestern ENP. The fluctuations in water levels were not well modeled in the V1 model because of the sparse distribution of gages in this area.

Model-Error Analysis Using Water Levels at Benchmarks

Measured water levels at the network of elevation benchmarks in the model domain were compared with simulated water levels to compute the model error of the calibrated V2 model. This statistical analysis provides a quantitative measure of the model's ability to simulate water levels in the Everglades. Between April 2007 and October 2010, 274 field-measured water levels were collected at the network of 72 benchmarks in the marshes of the greater Everglades (fig. 6; appendixes 2 and 3 [online at *http://dx.doi.org/10.3133/sir20145209*]). Most of these measurements were collected during the wet season and were greater than the average water level based on the V2-modeled water-level surfaces; therefore, the error analysis of the model using benchmark data is based primarily on above-average water-level conditions.

Modeled water levels corresponding to water levels measured at the benchmarks were extracted from the daily water-level surfaces by using the EDEN xyLocator program (Everglades Depth Estimation Network (EDEN) for Support of Biological and Ecological Assessments, 2013). Appendix 3 lists the differences between the measured water levels and modeled water-level surfaces, by benchmark. The scatter plots of the differences, or residuals, and the measured, or observed, water levels indicate that the modeled water levels from the V1 and V2 models have strong agreement with the observed water levels throughout the range of the measured water levels (fig. 16). The water-level differences between modeled and measured water levels for the V2 model range from –18.3 cm to +18.8 cm, whereas differences for the V1 model are –45.0 cm to +44.4 cm. For the V2 model, 85.5 percent of the modeled water levels at benchmarks are within 5 cm of the measured water levels, whereas 81.2 percent of modeled water levels are within 5 cm of measured water levels for the V1 model (table 6; fig. 17). Only 6.9 percent of water-level differences at benchmarks are greater than +/-10 cm for the V2 model, compared to 11.8 percent for the V1 model.

Graduated symbol maps were created to illustrate the largest difference between measured and modeled water levels for the V1 and V2 models for each benchmark (figs. 18 and 19, respectively). For benchmarks with both positive and negative differences, symbols for the largest positive and negative differences are shown. Although the differences in some subbasins are similar for both models, several areas show reduction in the residuals using the V2 model. For example, differences in the southern part of WCA3B are reduced and within 5 cm of the V2 modeled water-level surface.

Statistical measures of the EDEN model accuracy were computed by using the differences between measured and modeled water levels at benchmarks (table 7; fig. 20). Although most error statistics for the V1 and V2 models are similar, error statistics for the V2 model indicate a closer fit than for the V1 model for WCA3A North and WCA3B. This closer fit is largely attributable to the revision of the gage data in northern WCA3A and use of a subdomain model for

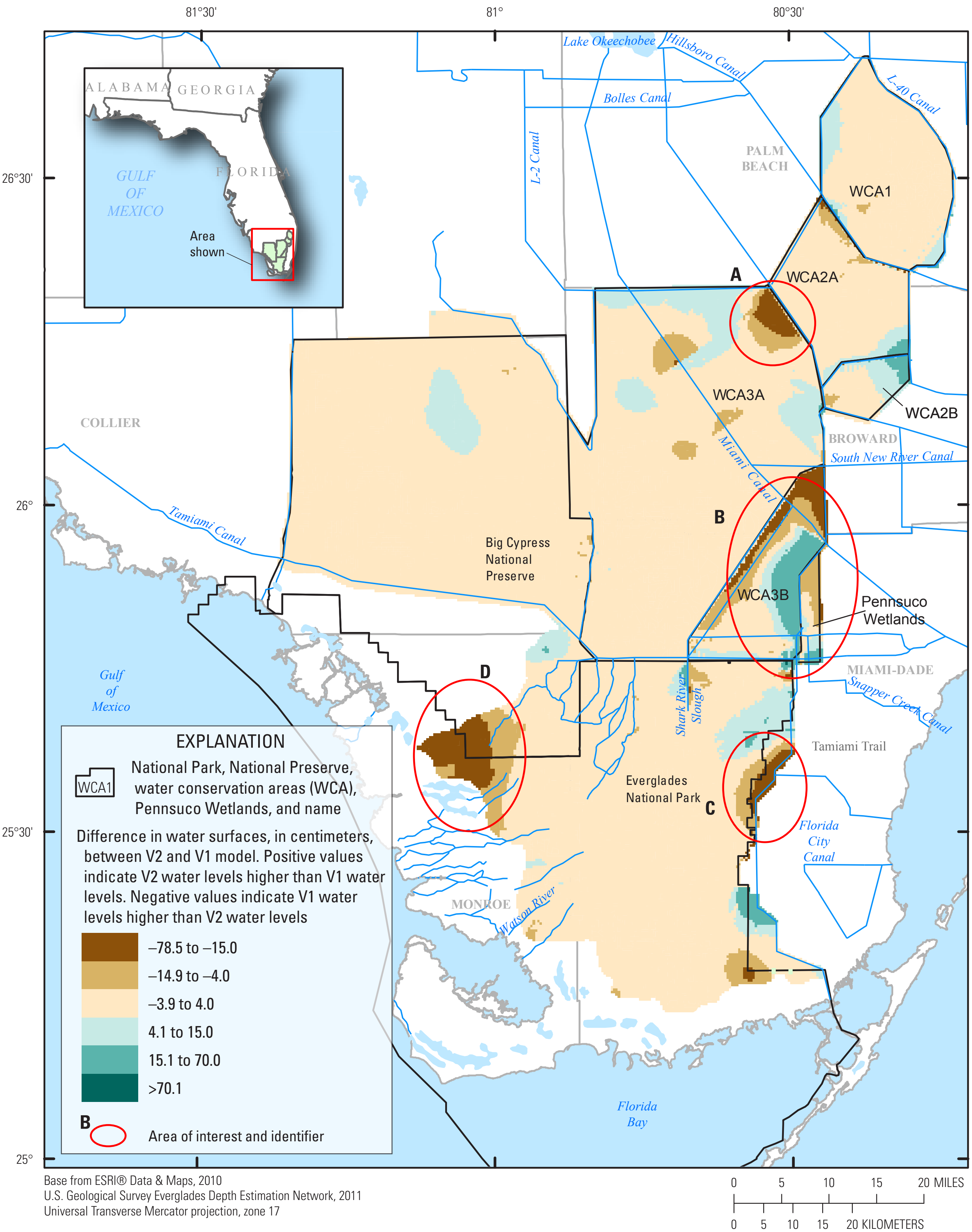

Figure 15. Differences (in centimeters) in water-level surfaces on July 23, 2009, for the EDEN surface-water model, versions 1 and 2.

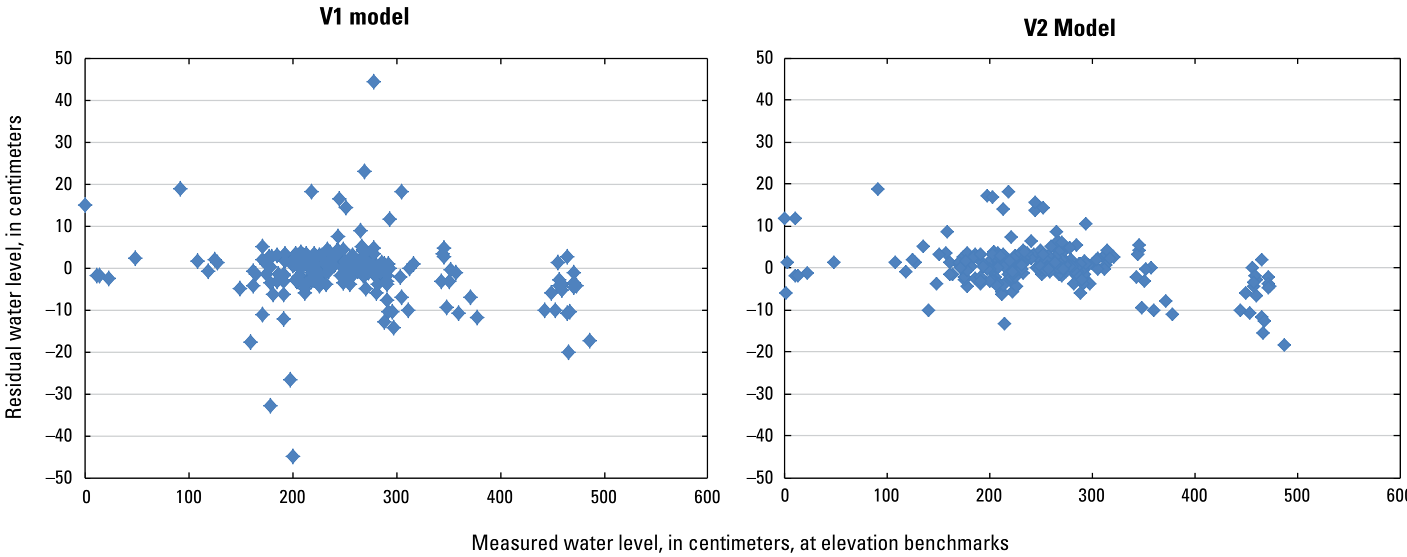

Figure 16. Residuals (EDEN modeled water level minus measured water level) and measured water levels at elevation benchmarks based on the EDEN surface-water model, versions 1 and 2, results.

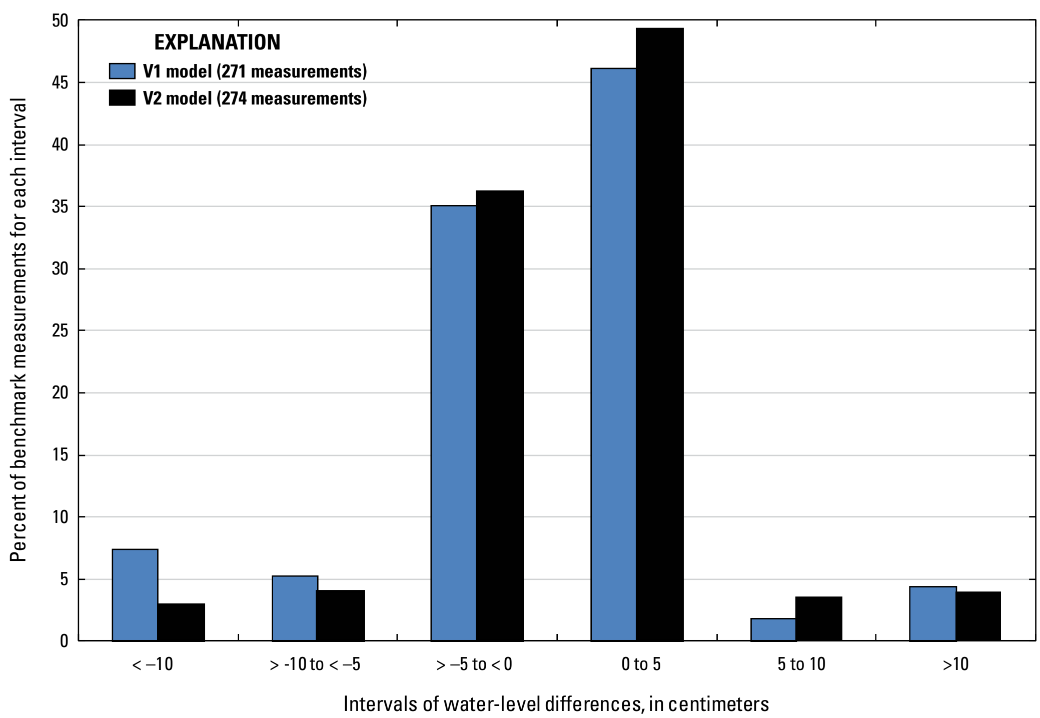

Figure 17. Differences between measured and modeled water levels at benchmarks for the EDEN surface-water model, versions 1 and 2, and the percent of benchmark measurements in each interval. Water-level difference equals modeled water level minus measured water level.

Table 6. Differences between measured and modeled water levels at benchmarks for the EDEN surface-water model, versions 1 and 2, and the percent and number of benchmark measurements for each interval. Water-level difference equals modeled water level minus measured water level.

[V1, version 1; V2, version 2]

EDEN Model (total number of benchmark measurements)	Intervals of water-level differences, in centimeters	Percent of benchmark measurements for each interval	Number of benchmark measurements for each interval
V1 model (271)	< –10	7.4	20
	–10 to <–5	5.2	14
	–5 to <0	35.1	95
	0 to 5	46.1	125
	>5 to 10	1.8	5
	>10	4.4	12
V2 model (274)	< –10	2.9	8
	–10 to <–5	4.0	11
	–5 to <0	36.2	99
	0 to 5	49.3	135
	>5 to 10	3.6	10
	>10	4.0	11

WCA3B. Error statistics for the BCNP show that both models of this subbasin provide poorer fits than for the other subbasins. Contributing factors may be the less-dense network of gages in the BCNP and the more complex topography and flow paths. During average- and low-water conditions, BCNP has more discontinuities in the water surface, and some areas become hydrologically isolated; thus, water levels are not represented accurately by nearby gages.

An approach used to evaluate the accuracy of modeled surfaces, such as DEMs, is to compute the linear error at the 95th percent confidence (LE95) of the data and report those errors that are greater than the confidence interval (Gesch, 2013). A similar approach was used to evaluate the V1 and V2 models. The LE95 metric is an implementation of the U.S. National Standard for Spatial Data Accuracy, which states that the “reporting standard in the vertical component is a linear uncertainty value, such that the true or theoretical location of the point falls within +/- of the linear uncertainty value 95% of the time” (Federal Geograpic Data Committee, 1998). The LE95 can be calculated directly from the RSME:

$$LE95 = 1.96 * RMSE.$$

The LE95 was computed for the subareas in the model (table 7) and applied to the V1 and V2 model error list in appendix 3. Measurements greater than the LE95 interval are in bold font. The majority of the differences are less than the 95th percent confidence interval, indicating that the errors are not statistically significant. The number of errors greater than the LE95 was reduced from 14 in the V1 model to 8 in the V2 model. All other measurements are within the LE95 and therefore fall within the range of the model uncertainty.

Generating Daily Water-Level Surfaces with the EDEN Surface-Water Model, Version 2

The EDEN surface-water model simulates daily water-level surfaces by using the median values of water-level data from gages in the model domain. To reduce the influence of missing or incorrect hourly data, the V1 model used the daily median. The input water-level data for the V2 model is preprocessed using the Automated Data Assurance and Management (ADAM) software (Daamen and others, 2010). The ADAM software is a Microsoft Excel-based program developed by USGS and Advanced Data Mining International, LLC. The software program uses empirical models and filters to quality assure measured data; missing data are estimated at each EDEN gage by using linear regression models (Petkewich and Conrads, 2013). For each gage, at least three linear regression equations were developed, and an order of precedence was established for the regression equations to be used to fill a data gap. The ADAM software has greatly reduced, if not eliminated, the use of erroneous data in the V2 model. The V2 model continues to use the daily median values, which now closely approximate the daily mean values on most days.

EDEN’s daily water-level surfaces are generated automatically or manually based on the quality of the input water-level data. Real-time water-level surfaces are generated daily by an automated process using real-time water-level data that have received little or no review by the operating agencies. The ADAM software removes and estimates erroneous data and fills missing data. Provisional and final water-level surfaces for each day are manually generated quarterly

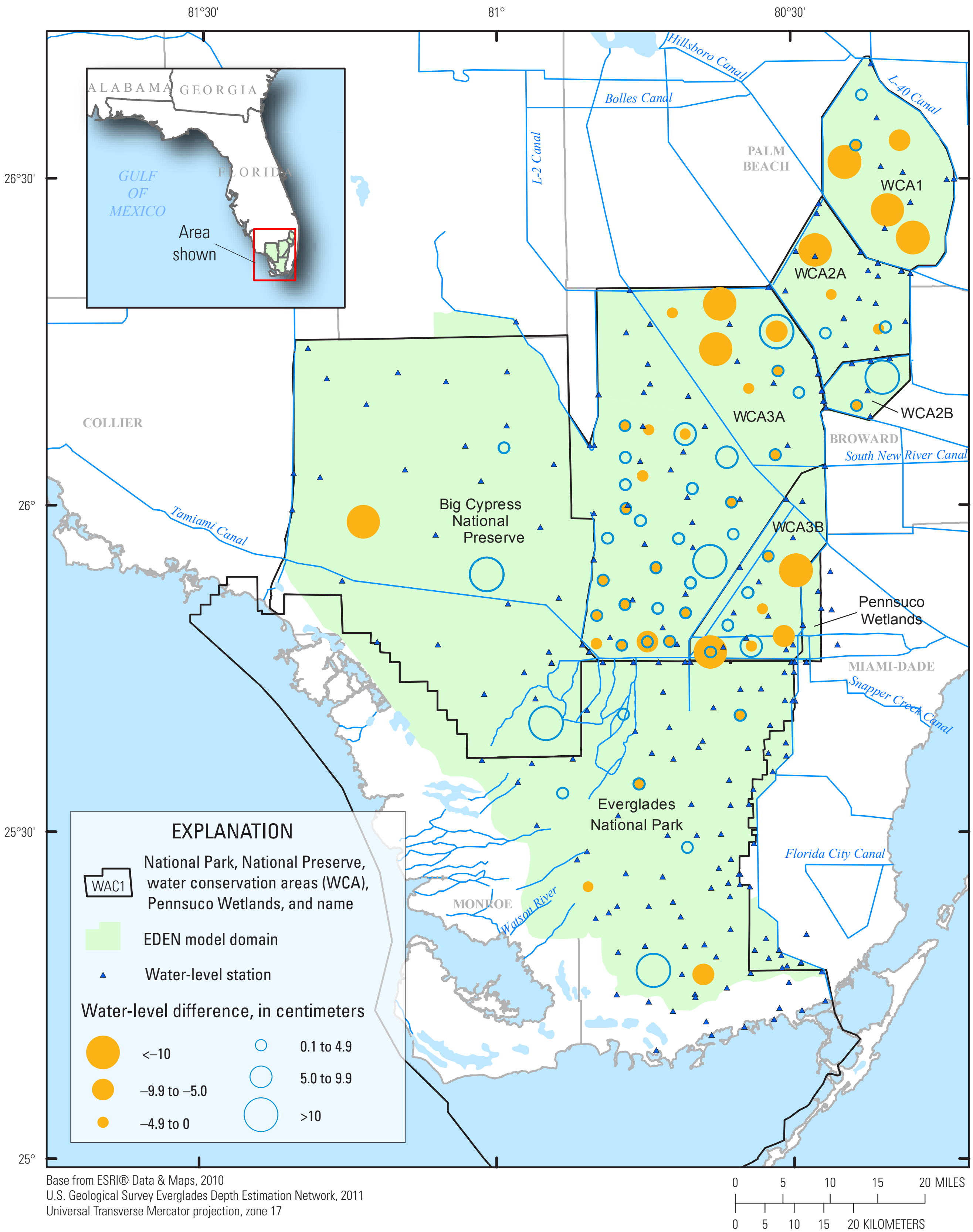

Figure 18. Differences (modeled minus measured, in centimeters) between the EDEN surface-water model, version 1, modeled water level and the measured water level at each benchmark. Positive differences indicate that the modeled water level at the benchmarks are higher than the measured water level. Negative differences indicate that the modeled water level at the benchmark are lower than the measured water level. If differences at a benchmark are both positive and negative, the largest positive and largest negative differences are shown.

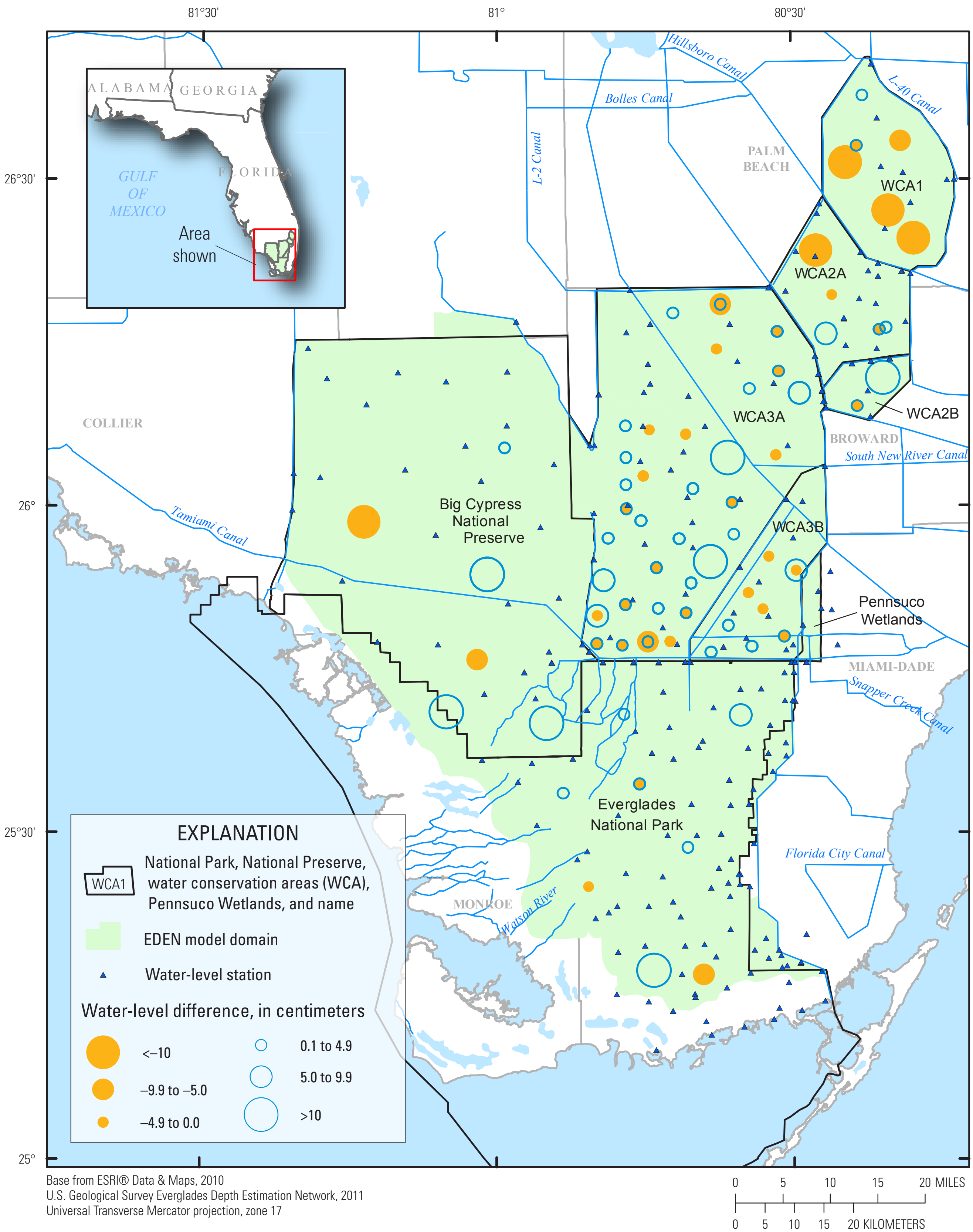

Figure 19. Differences (modeled minus measured, in centimeters) between the EDEN surface-water model, version 2, modeled water level and the measured water level at each benchmark. Positive differences indicate that the modeled water level at the benchmarks are higher than the measured water level. Negative differences indicate that the modeled water level at the benchmark are lower than the measured water level. If differences at a benchmark are both positive and negative, the largest positive and largest negative differences are shown.

Table 7. Error statistics for water-level differences at the benchmarks (modeled minus measured, in centimeters) for the EDEN surface-water model, versions 1 and 2, for the entire domain and by subbasins.

[MAE, mean absolute error; ME, mean error; RMSE, root mean squared error; LE95, 95th confidence interval; V1, version 1; BCNP, Big Cypress National Preserve; ENP, Everglades National Park; WCA, Water Conservation Area; V2; version 2; No benchmarks are located in the Pennsuco Wetlands]

EDEN Model	Type	Number of benchmark measurements	Minimum water level	Maximum water-level difference	Standard deviation	MAE	ME	RMSE	LE95
V1 model	BCNP	8	–13.93	16.47	10.94	9.64	4.61	11.22	21.99
	ENP	15	–6.25	18.96	6.11	3.85	2.03	6.24	12.23
	WCA1	18	–20.10	2.6	5.87	6.86	–6.42	8.59	16.84
	WCA2A	13	–11.87	4.82	5.49	4.51	–2.75	5.95	11.66
	WCA2B	4	–1.71	11.71	6.1	4.1	2.92	6.04	11.84
	WCA3A North	19	–14.14	44.45	14.38	9.61	0.16	14	27.44
	WCA3A South	162	–5.91	18.29	3.25	2.22	0.69	3.31	6.49
	WCA3B	32	–44.97	5.06	11.03	6.73	–5.2	12.04	23.60
	All	271[1]	–44.97	44.45	7.1	4.02	–0.46	7.1	13.92
V2 model	BCNP	9	–13.18	17.1	11.29	9.6	3.21	11.12	21.80
	ENP	17	–5.79	18.75	6.01	4.47	3.11	6.61	12.96
	WCA1	18	–18.31	1.84	5.44	6.72	–6.51	8.39	16.44
	WCA2A	13	–11.15	5.53	5.72	4.62	–2.12	5.89	11.54
	WCA2B	4	–2.1	10.59	6.01	3.85	1.78	5.5	10.78
	WCA3A North	19	–5.81	6.5	3.13	2.34	0.68	3.12	6.12
	WCA3A South	162	–6.1	18.27	3.26	2.13	0.94	3.39	6.64
	WCA3B	32	–4.3	8.67	2.92	2.33	–0.31	2.89	5.66
	All	274[1]	–18.31	18.75	4.68	3.01	0.37	4.68	9.17

[1] Three benchmarks are located in the area added to the expanded V2 model domain.

and annually, respectively, using water-level data that have been reviewed and edited by the operating agencies. For some agencies, the quarterly datasets are final, while for others, these datasets are preliminary. The annual final water-level surfaces use the final, approved data from the operating agencies. The ADAM software is used to verify the final data and estimate missing data. The data are loaded into the EDEN database for each process that generates water-level surfaces (either daily real-time, quarterly provisional, or annual final). The EDEN database serves as the primary storage of the gage data and links to a common online platform for users to extract data and view hydrographs for the EDEN gages.

File Transfer Protocol (FTP) is used throughout the process of generating water-level surfaces to transfer data and other files between databases, programs, and servers where, for example, data are processed for input to the EDEN surface-water model and the model generates the daily water-level surfaces. The FTP transfers are automated in the generation of the daily real-time water-level surfaces, but some of these transfers are manually initiated for the generation of quarterly provisional and annual final water-level surfaces for each day.

Automated Model Simulation

A series of automated scripts retrieve, transfer, and format data and then generate the EDEN real-time daily water-level surfaces (fig. 21). Data from the real-time water-level gages in the EDEN network are transmitted one or more times per day via radio or satellite telemetry to the operating agencies' data servers and stored in their databases; DBHydro (SFWMD), DataForEver (ENP), and National Water Information System (NWIS; USGS). Data from gages operated by BCNP (BCA1 through BCA20) are stored in DBHydro through a partnership with the SFWMD. On a daily basis, the real-time hourly data for the previous day are transferred from the agency databases to a USGS server and used to generate real-time daily water-level surfaces.

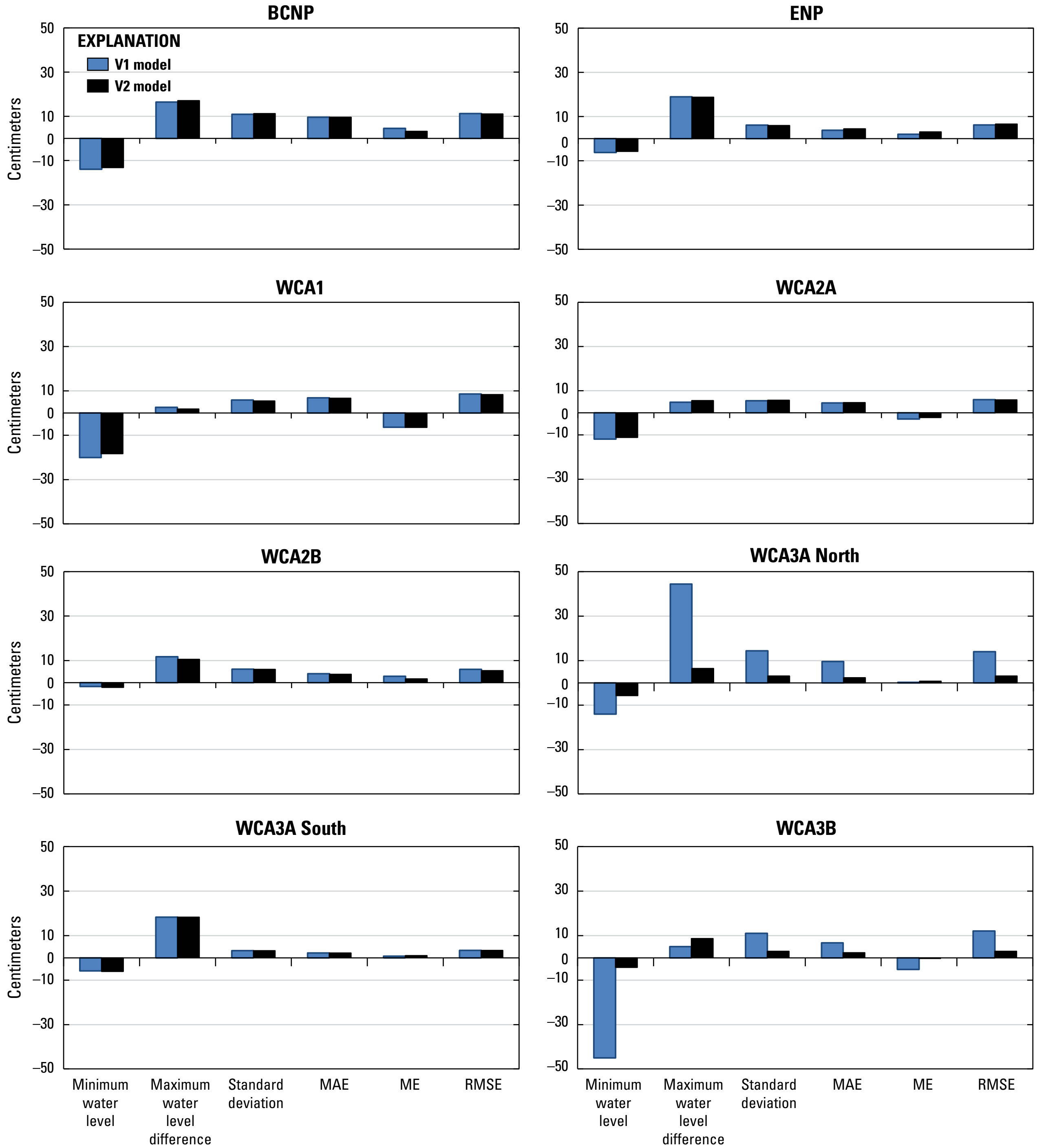

Figure 20. Error statistics for water-level differences at the benchmarks (modeled minus measured, in centimeters) for the EDEN surface-water model, versions 1 and 2, by subbasin. [MAE, mean absolute error; ME, mean error; RMSE, root mean squared error; BCNP, Big Cypress National Preserve; ENP, Everglades National Park; PW, Pennsuco Wetlands; WCA, Water Conservation Area]

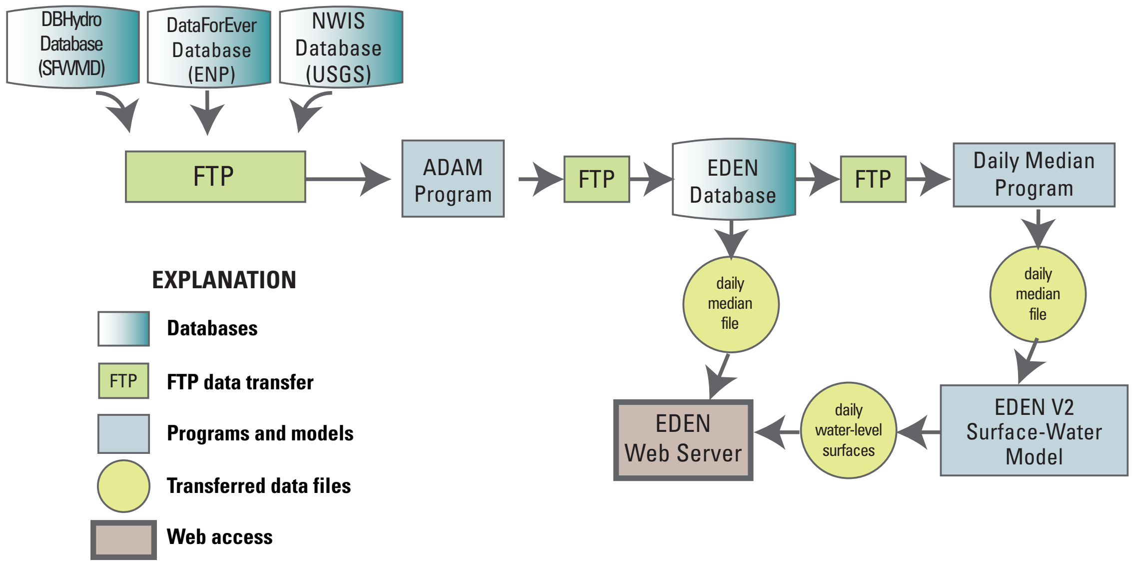

Figure 21. Schematic diagram showing flow of data and generation of EDEN-modeled water-level surfaces.

Each morning, a script transfers the gage data provided by the SFWMD and ENP and combines them with USGS gage data from NWIS. To prepare datasets for use in the surface-water model, the measured hourly water-level data are loaded into the ADAM software and quality assured. The quality-assured datasets are then automatically loaded into the EDEN database.

As the quality-assured datasets for each gage are loaded into the EDEN database, water-level values are identified as measured or estimated. In the rare situation where the ADAM software cannot estimate missing data, a flag for missing data is stored in the database. Using the quality-assured data, a script generates the daily median file for that day which lists all the gages used in the model, the daily median water level converted from feet to centimeters for each gage, and whether the value is measured, estimated, missing, or records dry conditions (fig. 22). Knowing which gages and what type of data are used to generate a particular water-level surface is useful to users with specific confidence limits or quality-assurance requirements or for identifying day-to-day differences in the surfaces. The daily median file is posted with the water-level surface for each day on the EDEN Web site. A script processes the Daily Median program, which formats the data for input to the V2 model. Each afternoon, scripts transfer this daily median file and initiate the V2 model to generate the daily real-time water-level surface using data transferred from the operating agencies earlier that day.

Batch Model Simulations

Quarterly provisional and annual final water-level surfaces for each day are generated by manually processing and transferring the input datasets and running the V2 model. The quarterly provisional water-level surfaces for each day are processed as follows: January through March, April through June, July through September, and October through December. To provide operating agencies with time to quality assure the water-level data, the quarterly provisional datasets are retrieved 45 days after the end of each quarter. Data for the gages operated by SFWMD and USGS are retrieved directly from their databases, DBHydro and NWIS, respectively. Data for gages operated by ENP are compiled by their staff and transferred to the USGS. After quality assurance of the data through ADAM, the quarterly provisional water-level datasets for all EDEN gages are loaded into the EDEN database overwriting the daily real-time data.

Similar to the automated model simulation for single daily real-time water-level surfaces (fig. 21), the datasets are quality-assured through ADAM, loaded into the EDEN database, and input into the V2 model. This processing is manually initiated by EDEN staff and generates quarterly provisional water-level surfaces for 3 months.

For annual final water-level surfaces, operating agencies provide final and approved water-level data for the gages in June or July for the previous water year (October through September). Similar to the batch, or manual, model simulation for the quarterly datasets, the data processing and modeling of the 1-year water-level surfaces are manually initiated by EDEN staff.

As with the daily real-time water-level surfaces, daily median files for each day are generated for both quarterly provisional and annual final water-level surfaces. The daily median file lists all of the gages used in the model for that day and is posted along with the daily water-level surface on the EDEN Web site (Everglades Depth Estimation Network (EDEN) for Support of Biological and Ecological Assessment, 2014a)

Agency	Station	X	Y	Daily median water level (cm, NAVD 88)	Date	Data type
NPS	RG3	542685	2825294	56	20130324	D
NPS	SP	520390.8	2808007.5	–11	20130324	D
NPS	SPARO	517147	2846252	139	20130324	E
NPS	SR1	518962.8	2806906.2	–16	20130324	D
NPS	TMC	512822.5	2832943.7	70	20130324	D
NPS	TSB	539496.7	2809627.6	9	20130324	D
NPS	TSH	537180.1	2799430.9	–3	20130324	O
SFWMD	3A10	525980.1	2906666.3	302	20130324	O
SFWMD	3A11	525605.1	2899897.8	286	20130324	D
SFWMD	3A12	532417.2	2894468.1	272	20130324	O
SFWMD	3AN1W1	525972.6	2896545.5	282	20130324	O
SFWMD	3ANE_GW	539459.1	2906638.9	272	20130324	O
SFWMD	3ANW_GW	521937.2	2905238.3	314	20130324	O

EXPLANATION

Agency	**Operating agency for gage**—NPS, SFWMD, or USGS
3	**EDEN station name**
X	**UTM Northing coordinate**—UTM, zone 17N, NAD 83
Y	**UTM Northing coordinate**—UTM, zone 17N, NAD 83
Daily Median Water Level (cm, NAVD 88)	**Daily median water level for gage**—For date specified, in centimeters
Date = date of water level (YYYYMMDD)	**Date of water level**—YYYYMMDD
Data type	**Type of data collected at the gage for the day**— "O" for observed or measured data, "M" for missing data, "E" for estimated data, and "D" for dry conditions at the gage

Figure 22. Example of daily median water-level file output from the EDEN database.

Internet Access to Model Output

Model output of daily water-level surfaces is available on the EDEN Web site (Everglades Depth Estimation Network (EDEN) for Support of Biological and Ecological Assessment, 2014a) in three different formats: JPEG, NetCDF, and GeoTiff. A quick-view JPEG map (thumbnail) for real-time surfaces allows users to quickly assess hydrologic conditions without downloading data. For example, field scientists can quickly determine if water levels are near target conditions for sampling or other field work. The NetCDF data format (.nc files) more efficiently supports large array-oriented datasets than the commonly used Esri Grid format. Users with Esri ArcGIS installations (version 9.2 or higher) can import the NetCDF files into Esri ArcMap and easily animate EDEN surfaces. The standard GeoTiff file format can be used with multiple geospatial programs for viewing EDEN daily water-level surfaces. For ease of downloading, the daily water-level surface files, in either NetCDF or GeoTiff format, are bundled in zip files by quarter and by year. Each daily water-level surface has an associated daily median file that lists the daily median water-level value and data type (such as measured, estimated, missing, or dry) for each gage used in the surface-water model for that day. The real-time water-level surfaces are posted daily and are updated quarterly and annually with provisional and final water-level surfaces, respectively (fig. 23).

Water-level data, location data, and other information for gages used in the surface-water model can be accessed through an interactive map showing the locations of the gaging stations in the EDEN network on the EDEN Web site. The Station Information page for each gage lists the operating agency, location, data links, and other information such as ground elevation and vegetation type in the vicinity of the gage. Through data links, the Explore and View EDEN (EVE)

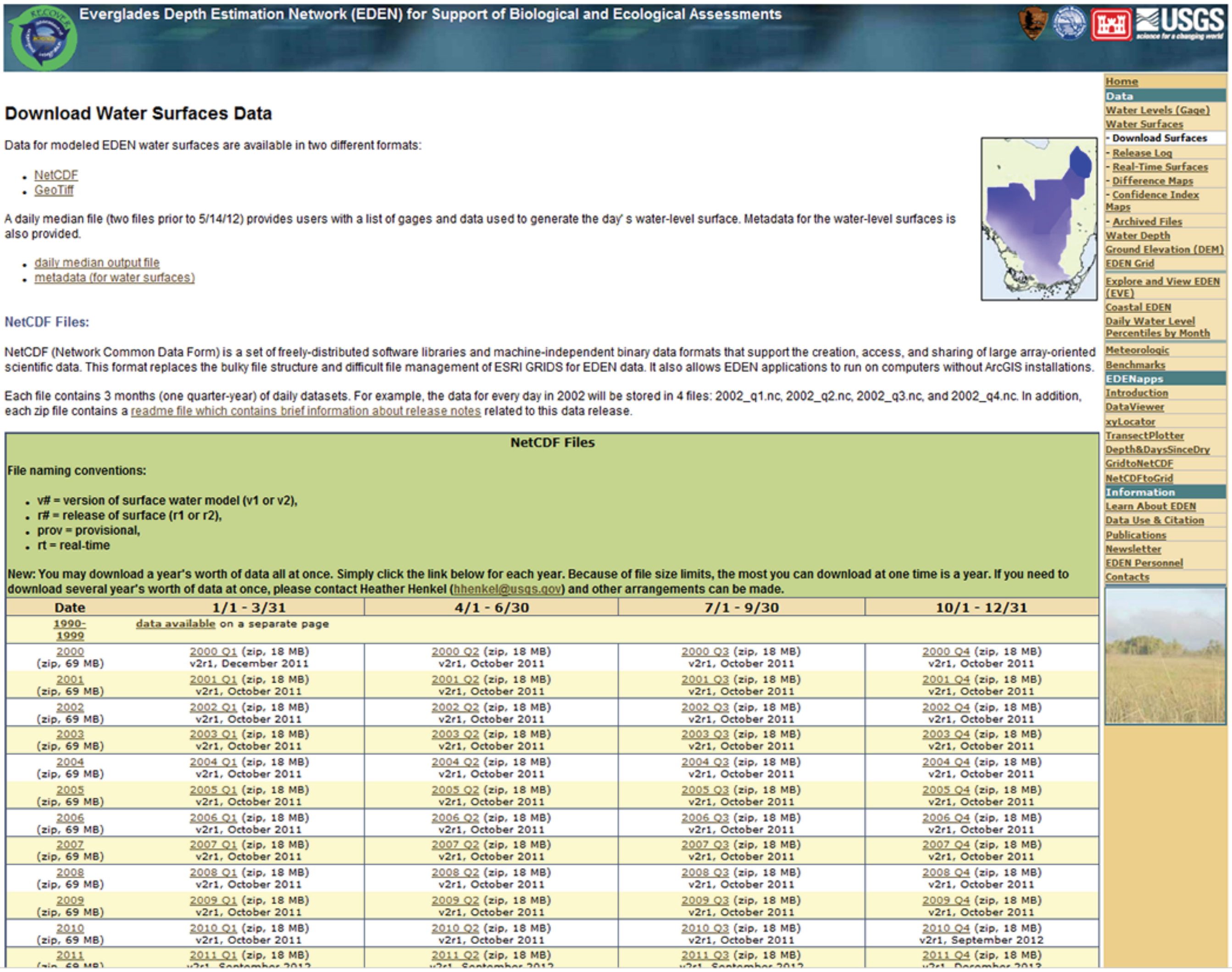

Figure 23. Example of a Web page showing EDEN daily water-level surfaces available for download by users.

graphical interface software provides users access to hourly and daily water levels and other data such as salinity, water temperature, rainfall, and evapotranspiration at gages. EVE allows users to retrieve, plot, and view data from gages for multiple parameters.

A set of EDEN application tools (EDENapps) was developed to make data in the daily water-level surfaces more accessible by allowing users to view, extract, plot, and manipulate the data (Everglades Depth Estimation Network (EDEN) for Support of Biological and Ecological Assessment, 2014b; Telis and Henkel, 2009). By combining the daily water-level surfaces with the ground-elevation model and using the EDENapps, extensive hydrologic datasets, including water depth, hydroperiod, computation of days since last dry (number of days since water level was below land surface), water-surface slope, surface animations of water elevation and water depth over time, and transects of water depth animated over time, are made available to scientists and other interested users.

Applications of the V2 Model

Three applications of EDEN-modeled water-level surfaces and other EDEN datasets demonstrate how scientists and resource managers are using EDEN to analyze biological and ecological responses to hydrologic changes in the Everglades. Examples 1 and 2 describe the biological responses of two important Everglades species, alligators and wading birds, to changes in hydrology. The third example discusses how hydrology affects fire dynamics in the Everglades.

Body Condition of the American Alligator as a Function of Everglades Water Depth

Fujisaki and others (2009) examined correlations between the body condition, an indicator of animal health, of American alligators in the Everglades and surface-water depths at their capture locations. When water levels in marshes recede at the end of the dry season (May), prey becomes concentrated and feeding opportunities increase for alligators. Water depth is generally higher in the fall making it more difficult to find and capture widely dispersed prey. Therefore, researchers hypothesized an inverse relation between alligator body condition and water depth in the Everglades. Body condition based on length and mass is a measure of the relative fatness of the animals and indicates how well the animals are coping with their environment.

Alligators were captured and measured for length and mass during nighttime spotlight surveys during 2000–2006 in the Shark River Slough, an extensive long-hydroperiod area of the ENP (fig. 24). At each location where animals were caught, daily water depths for 90 days (the capture day and 89 days prior) were extracted from the daily EDEN-modeled water-level-surface data. Body condition was correlated with water depth at the time of capture, and water depth during 10-day intervals prior to capture.

The relation between body condition of alligators and water depth varied by size class, season, and sex. Consistently higher mean body condition indicator values were observed in spring for all size classes and sexes, when water levels are annually at their lowest levels. Prey are concentrated in low water conditions, increasing foraging success by alligators. Negative correlations between the body condition indicator value and water depth in fall were consistent with the hypothesis that higher water levels, following the wet season, make foraging more difficult for alligators in the Everglades.

Understanding the correlations between body condition of alligators and hydrologic patterns that are key factors affecting prey availability and abundance is important for conservation of this species in the Everglades. The results of this application of the EDEN data and V2 model indicate that water-management practices may be critical for alligators in the Everglades because water depth can affect animal health in a relatively short period of time (within 90 days).

Habitat Selection of White Ibises and Great Egrets as a Function of Hydrologic Features in the Everglades

Beerens and others (2011) examined how White Ibises and Great Egrets in the Everglades adjust their habitat selection in response to varying food availability. The White Ibis is a tactile species that requires highly concentrated prey, whereas the Great Egret is a visual feeder and requires lower prey concentrations. Differing foraging strategies may account for the dissimilar population trends from the 1930s to 2001 when White Ibis populations declined about 87 percent while Great Egret populations increased about 270 percent. During this time, substantial hydrologic changes occurred in the Everglades that affected habitat and prey availability of wading bird species.

Using the EDEN water-level surfaces generated daily by the EDEN surface-water model, Beerens and others (2011) calculated daily recession rates, days since last dry, and hydroperiod for their study area. Positive recession rates indicated receding water, and negative recession rates indicated rising water.

Foraging habitat selection responses of ibises and egrets were compared for 2 years, 2006 and 2007, with different hydrologic conditions and associated prey availability. Hydrologic conditions in 2006 were characterized by generally high water levels preceding the dry season, a rapid water-level recession, few reversals (brief increases in water levels, creating conditions where prey can disperse) in the recession period, and above-average prey availability. These conditions are considered favorable for foraging and nesting by wading birds; therefore, 2006 was considered a “good year.” In contrast, 2007 was considered a “poor year” because the dry season was preceded by low marsh water levels and a rapid water-level recession rate with several reversals that resulted in lower prey availability.

The study results indicated that ibises always showed higher selectivity for water depth than egrets, and both species showed higher selectivity for water depth during 2006, the “good year,” than during 2007, the “poor year” (fig. 25). The findings indicate that the range of water depths and the recession pattern may be critical to support healthy wading bird populations in the Everglades. Using EDEN’s real-time data, habitat suitability can be assessed daily as water depth and prey availability changes over the breeding season. In addition, biological models developed by researchers based on these findings allow evaluation of restoration scenarios using hydrologic data output for restoration models.

Influence of Everglades Water Depth and Variability on Post-Fire Landscape Dynamics

Jones and others (2013) used EDEN water-level and ground-elevation data to document the influence of hydrology on post-fire landscape dynamics in the Everglades. To explore the relation among water level, hydroperiod, and fire ecology, the researchers needed the appropriate hydrologic variables to test their hypothesis that wetland water levels prior to, during, and following a fire are likely to influence burn severity and post-fire vegetation dynamics (fig. 26).

For each studied fire, several hydrologic variables were derived from the EDEN ground-elevation model and EDEN daily water-level maps: maximum and minimum daily water depth during the year of the fire, mean daily water depth during the year of the fire and each of the following 5 years, and maximum and minimum daily water depth between the fire date and green-up date, which is the date when satellite images show initial green vegetative growth in the burn scar. By using these datasets along with the fire and green-up dates, plausible explanations were established for relations among landscape dynamics, hydrology, and management practices.

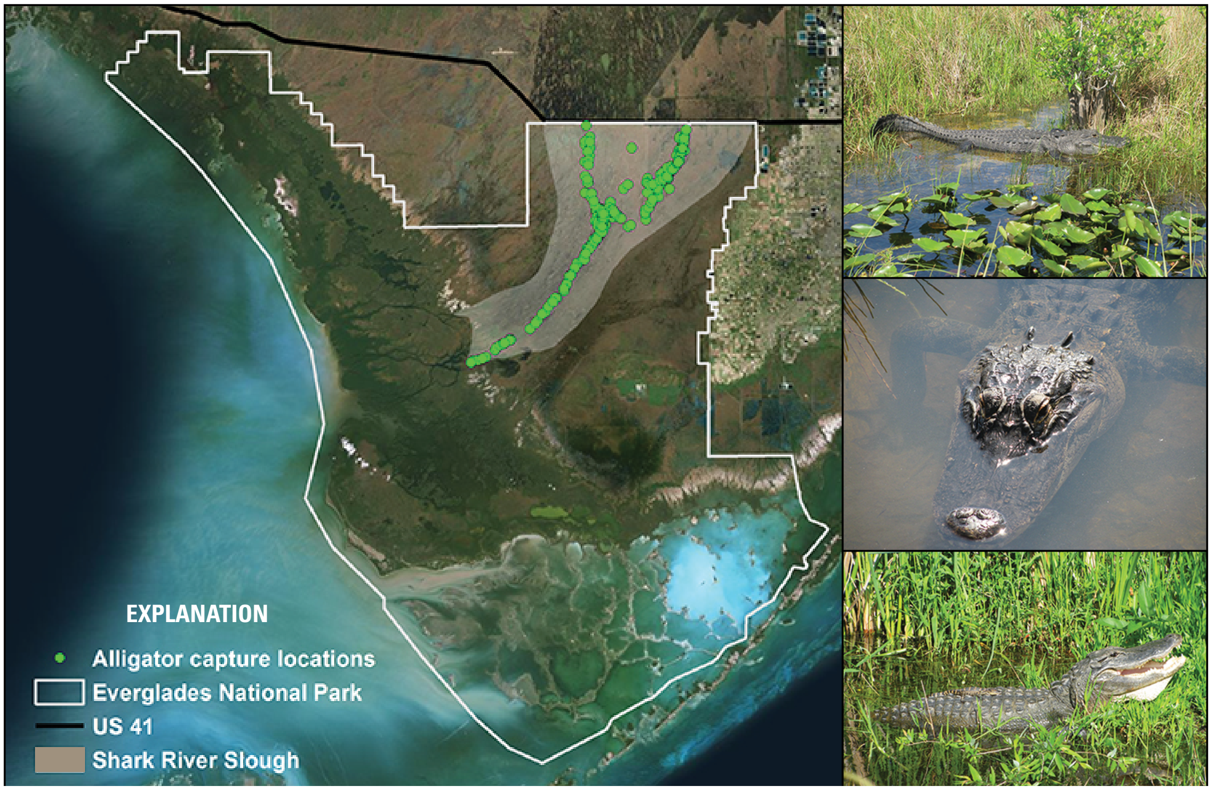

Figure 24. Capture locations of American alligators (left) in the Shark River Slough (modified from Fujisaki and others, 2009). Photos (right) of alligator habitat, courtesy of Ikuko Fujisaki and John Butler, University of Florida.

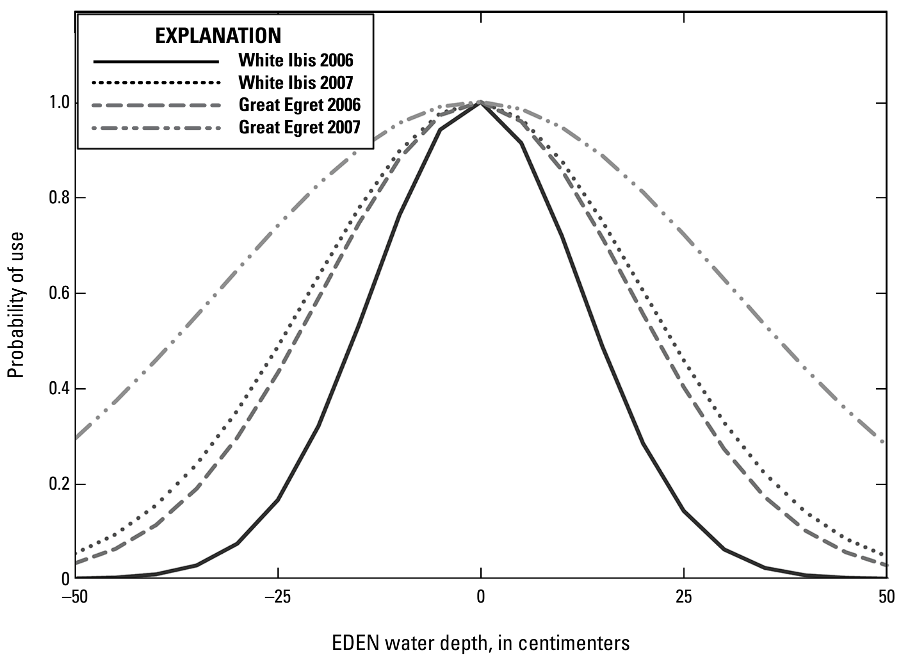

Figure 25. Probability of wildlife use for foraging by White Ibis and Great Egret relative to EDEN-modeled water depths. Modified from Beerens and others (2011).

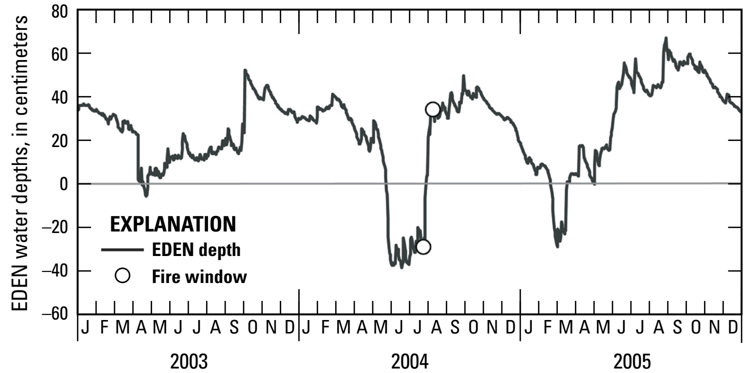

Figure 26. Three-year hydrograph of EDEN-modeled water depths at the centroid of a fire that occurred between July 25 and August 10, 2004. Modified from Jones and others (2013).

The factors of water depth and variability were important in explaining length of time for a burned area to return to pre-burn condition (PBC) where the scar edges can no longer be clearly delineated. Burned areas in ENP where the maximum water depth during the year of the fire was less than or equal to 17.45 cm occurred at higher elevations and had shorter hydroperiods than areas of lower elevation. For these higher elevation areas, fire scars returned to PBC in 2.9 years on average, more rapidly than wetter fire-scarred areas. These results suggest that drier conditions foster more rapid growth and therefore support more frequent burning. Fires in wetter conditions and fires in drier locations that experience large fluctuation in water depth take longer to return to PBC, usually 2.9 to 7.7 years. These data can be useful to management when decisions need to be made about how often and where to use controlled fires and about when and how to suppress wild fires in the Everglades.

Summary

Hydrology is the basis of many of the Everglades restoration hypotheses, and there is a need for region-wide high-resolution hydrologic datasets with Internet access for scientists and water-resource managers. The Everglades Depth Estimation Network (EDEN) surface-water model integrates data from a network of gages operated by multiple agencies and generates daily water-level surfaces, at a consistent datum, for the freshwater part of the Everglades. When combined with EDEN's digital elevation model for ground surface, derived hydrologic data such as water depth, recession rates, days since last dry, water-surface slopes, and hydroperiod are computed.

The second version (V2) of the EDEN model uses water-level data from 240 gages to generate data for real-time, provisional, and final water-level surfaces for the Everglades based on the quality of the input water-level data. The quality-assurance software removes and estimates erroneous data and fills in missing data. The EDEN database serves as the primary storage of the quality-assured data and is linked to a common platform for users to extract and plot gage data and download daily water-level surfaces.

The reliability of the model is dependent on the quality and completeness of the input datasets and the range of measured conditions used to calibrate the model. Since the model was calibrated in 2012, several gages have been discontinued as a result of operating agencies' funding reductions. The accuracy and confidence of the EDEN surface-water model depends on a spatially broad distribution of gages with a density that can adequately represent the wide range of water levels that occurs during the extreme wet and dry seasons throughout the Everglades. Reducing the current network of gages in the Everglades may result in less reliable model results that support the needs of scientists, managers, and other users.

Field-measured water levels at a network of elevation benchmarks in the Everglades were compared to modeled results to analyze model error of the V2 model. This statistical analysis provides a quantitative measure of the model's ability to simulate water levels in the Everglades. The water-level differences at benchmarks range from -18.3 cm to +18.8 cm; however, 85.5 percent of the modeled water levels are within 5 cm of the measured value, and only 6.9 percent of the modeled water levels are more than ±10 cm of the measured value.

To assist users in applying the EDEN datasets to their needs, a series of tools, or applications (EDENapps), were developed to view, extract, plot, and manipulate EDEN data to create other derived hydrologic data. By combining the daily water-level surfaces with the ground-elevation model and using the EDENapps, users can obtain extensive hydrologic data, including water depth, hydroperiod, computation of days since last dry, water-surface slope, surface animations of water elevation and water depth over time, and transects of water depth animated over time.

Three applications of the EDEN surface-water model results and other EDEN datasets are discussed in this report to demonstrate how scientists and resource managers are using EDEN to analyze biological and ecological responses to hydrologic changes in the Everglades. One application correlated simulated water levels from the V2 model with body condition data for alligators. Results indicate that water depth affects animal condition in the short term. In the second application, scientists who study foraging behaviors of wading birds in wetland habitats used change in hydrology as a surrogate for habitat and food availability. In the third application, EDEN water-level and ground-elevation data were used to document the influence of hydrology on post-fire landscape dynamics. These applications highlight how water management practices can affect the health and sustainability of the flora and fauna of the Everglades.

The EDEN modeled water-level surfaces and related datasets may be useful in identifying and monitoring hydrologic and ecological responses to modifications of the water delivery system from the Everglades restoration or future climate change. Long periods of record at some gages are essential for documenting changes in flow volume, timing, and distribution. Scientists and water managers working in the Everglades require the system-wide hydrologic data to correlate and assess effects of these changes.

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