Surface-Water Exchange through Culverts beneath State Road 9336 within Everglades National Park, 2004-05

By Raymond W. Schaffranek, Marc A. Stewart, and Daniel J. Nowacki

Prepared as part of the
USGS Greater Everglades Priority Ecosystem Sciences and National Research Programs

in cooperation with the
South Florida Water Management District and Everglades National Park

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Conversion Factors, Acronyms, and Abbreviations

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
centimeter per second (cm/s)	0.3937	inch per second
cubic meter per second (m^3/s)	35.31	cubic foot per second
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
kilometer per hour (km/hr)	0.6214	mile per hour

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$°F=(1.8×°C)+32$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88)
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Acronyms and Abbreviations

ADV	Acoustic Doppler Velocity
CERP	Comprehensive Everglades Restoration Plan
DTW	Distance-to-water
ENP	Everglades National Park
ENU	East-north-up
EST	Eastern Standard Time
PVC	Polyvinyl chloride
SFWMD	South Florida Water Management District
SNR	Signal-to-noise ratio
USGS	U.S. Geological Survey
cm/s	centimeter per second
dB	decibels
μS/cm	microsiemens per centimeter
ppt	parts per thousand

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Abstract

The U.S. Geological Survey collected hydrologic data between June 2004 and December 2005 to investigate the temporal and spatial nature of flow exchanges through culverts beneath State Road 9336 within Everglades National Park. Continuous data collected during the study measured flow velocity, water level, salinity, conductivity, and water-temperature in or near seven culverts between Pa-hay-okee Overlook access road and Nine Mile Pond. The two culverts east of Pa-hay-okee Overlook access road flowed into Taylor Slough Basin from 87 to 96 percent of the study period, whereas flows through five culverts between Pa-hay-okee Overlook access road and Nine Mile Pond flowed into Shark River Slough Basin from 70 to 99 percent of the study period. Synoptic flow discharges measured at all culverts during three intensive field efforts revealed a net discharge into Taylor Slough Basin from Shark River Slough Basin through culverts between Royal Palm Road and Pa-hay-okee Overlook access road, and into Shark River Slough Basin from Taylor Slough Basin through culverts between Pa-hay-okee Overlook access road and Nine Mile Pond. Data collected during the study and presented in this report provided additional knowledge of the magnitude, direction, and nature of flow exchanges through the road culverts.

Introduction

Restoration of the predevelopment quantity, timing, and distribution of freshwater flows within the Everglades is a goal of the Comprehensive Everglades Restoration Plan (CERP). Engineering modifications and operational water-management practices altered the natural movement of water through the southern Florida ecosystem and affected the supply and distribution of available water to the southern Everglades and Florida Bay. Concerns exist that the main road through Everglades National Park (ENP) between Homestead and Flamingo, State Road 9336 (SR 9336), could affect the flow of freshwater into Florida Bay by adversely changing the nature of interbasin flow exchange between Shark River Slough and Taylor Slough (fig. 1). Natural flow exchanges between Shark River Slough Basin and the Taylor Slough Basin that borders northern Florida Bay occurred through 177 culverts spaced at approximately equal intervals beneath the road and two bridges near the ENP entrance.

Historic background provided by Craighead (1966), culvert flows intermittently measured in 1997 and 1998 by the U.S. Geological Survey (USGS) (Tillis, 2001), and water levels intermittently observed and recorded in 1997 by the National Park Service (Stewart and others, 2002) indicated that flow exchange through culverts beneath SR 9336 between Pa-hay-okee Overlook Road and Nine Mile Pond occurred from Taylor Slough Basin into Shark River Slough Basin. Synoptic measurements and observations were the basis of these conclusions; flows through the culverts were not continuously monitored and water levels were not continuously recorded to compute flows using culvert ratings.

In 2004, the USGS began continuous monitoring of flow velocities, water levels, salinities, conductivities, and water temperatures at selected culverts to document the temporal nature of interbasin flow exchanges between the Shark River Slough and Taylor Slough basins. The study included projects within the Greater Everglades Priority Ecosystem Sciences and National Research Programs of the USGS in cooperation with the South Florida Water Management District (SFWMD) and ENP. The objectives of the study were to: (1) collect continuous data to document the nature of temporal flow exchanges through selected road culverts for a full wet season; and (2) analyze available ancillary data (for example, water levels, rainfall, wind speeds, storm tracks, and so forth) to determine mechanisms that could affect these flow exchanges. Data collected during this study supported modeling efforts within the region and helped managers make informed decisions about the movement of water within the southern Everglades wetlands that border northern Florida Bay.

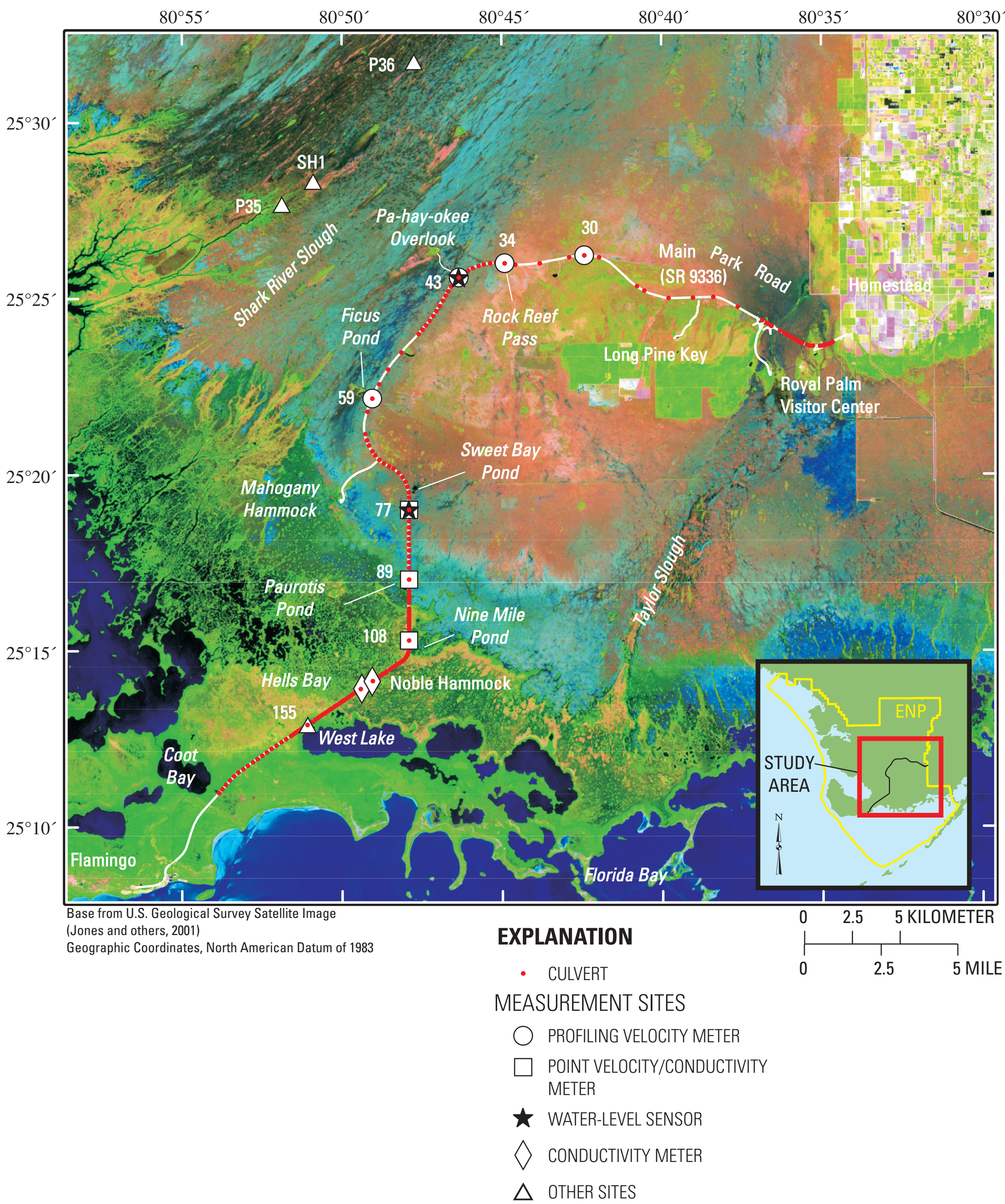

Figure 1. Satellite image of the southern Everglades, including monitoring locations along State Road 9336 within Everglades National Park (ENP).

Purpose and Scope

The purposes of this report are to: (1) describe the hydrologic data collected between June 2004 and December 2005; (2) document the methods and techniques used to collect and analyze the data; and (3) provide digital files containing data from select culverts. The digital files include data pertaining to flow velocity, water level, salinity, conductivity, and water temperature collected at seven culverts (fig. 1 and table 1). Discrete sets of data were collected for flow velocity, water level, and conductivity at all culverts between Royal Palm access road and West Lake during three intensive field efforts.

Description of Study Area

The study area encompassed a section of SR 9336 within the ENP known as the Main Park Road that extended a distance of about 60 km from the ENP entrance near Homestead to Flamingo (fig. 1). The eastern extent of the Main Park Road traversed the northern boundary of Taylor Slough near its headwaters. Two bridges and approximately fifteen culverts between the ENP entrance and Royal Palm access road (fig. 1) accommodated the primary inflow into Taylor Slough. The Main Park Road between the Royal Palm Road and Pa-hay-okee Overlook access road (fig. 1) is bordered by pinelands interspersed with small glades. South of the Pa-hay-okee Overlook, the Main Park Road followed the approximate basin boundary between Taylor and Shark River Sloughs (Stewart and others, 2002). Natural flow exchanges between the Taylor Slough and Shark River Slough basins conveyed water through 155 2-foot-diameter culverts, spaced at approximately equal intervals between Royal Palm Road and Coot Bay (fig. 1) (Stewart and others, 2002). Continuous hydrologic data collected at seven culverts between culvert 30 in the pineland forest area to culvert 108 near Nine Mile Pond (fig. 1) spanned a distance of approximately 32 km. Three discontinuous sets of hydrologic data were collected from culverts observed to convey flow between Royal Palm Road and West Lake (fig. 1).

Acknowledgments

Ami Riscassi, Shane Ploos, and Edward Simonds from the USGS provided initial reconnaissance help and performed fieldwork throughout the study. Kevin Kotun, Everglades National Park, provided ancillary data from the hydrologic monitoring network. The SFWMD provided contractors who obtained vertical datum control information at the culvert measurement locations.

Table 1. Geodetic coordinates, locations, monitored parameters, and nearby landmarks for monitoring culverts within Everglades National Park (ENP) during 2004-05.

[Culverts are listed from northeast to southwest beneath State Road 9336; see figure 1 for locations. USGS, U.S. Geological Survey; WT, water temperature]

USGS station identifier	Culvert number	Geodetic coordinates, North American Datum of 1983		Distance from ENP entrance along State Road 9336 (kilometers)	Monitored parameters	Nearby landmarks
		Latitude	Longitude			
252614080422500	30	25°26′14″	80°42′24″	14.69	Profile velocity	Pinelands area
252600080445400	34	25°26′00″	80°44′54″	19.02	Profile velocity	Rock Reef Pass
252537080462000	43	25°25′36″	80°46′20″	21.61	Profile velocity Water level	Pa-hay-okee Overlook Road
252211080490300	59	25°22′10″	80°49′02″	29.44	Profile velocity	Ficus Pond
251901080475400	77	25°19′01″	80°47′54″	36.25	Point velocity Water level Conductivity & WT	Sweet Bay Pond
251702080475400	89	25°17′02″	80°47′54″	39.90	Point velocity Conductivity & WT	Paurotis Pond
251518080475500	108	25°15′18″	80°47′54″	43.09	Point velocity Conductivity & WT	Nine Mile Pond

Data Collection

Data collected during this study included continuous flow velocity, water level, salinity, conductivity, and water temperature. Data collected at 30-minute intervals used Acoustic Doppler Velocity (ADV) meters that measured flow velocity within a culvert or near the end of a culvert. Submerged pressure sensors near the end of selected culverts monitored water levels at 15-minute intervals. Sensors deployed near the ADV meters at the culvert ends measured salinity, conductivity, and water temperature at 30-minute intervals. Data were recorded by the ADV meters and by the sensors; these data were downloaded during intermittent site visits. Geodetic coordinates of the monitoring sites, types of parameters monitored, approximate distances of the sites from the ENP entrance, and identifying landmarks near the sites are listed in table 1 by culvert number or site name.

Instrumentation

The instruments used for this study included three types of flow-velocity meters manufactured by SonTek/Yellow Springs Instruments (YSI). The SonTek/YSI Argonaut Shallow Water (Argonaut-SW®), Argonaut Acoustic Doppler Velocimeter (Argonaut-ADV®), and FlowTracker® (*http://www.sontek.com*, accessed December 5, 2007) function used the acoustic Doppler shift principle. The Doppler shift determined flow velocity from measurements between transmitted acoustic signals and their reflections from particles suspended in the moving water.

The Argonaut-SW® is a fixed-mounted instrument consisting of a waterproof housing, internal data logger, acoustic signal processor, and three acoustic transducers (fig. 2). The Argonaut-SW® unit does not have an internal compass or an internal power supply. A pair of transducers oriented uniformly at 45 degrees from the vertical measured the two horizontal (x and y) components of flow velocity. A third transducer oriented in the vertical measured the depth of water above the instrument. The Argonaut-SW® measured and computed the mean horizontal velocity components in depth increments, defined as cells, throughout the water column. The accuracy of the Argonaut-SW® is specified as ±1.0 percent of measured velocity, ±0.5 cm/s, and ±1.0 percent of measured level, ±0.3 cm (SonTek, 2000).

The Argonaut-ADV® unit, a fixed-mounted instrument, consisted of processing electronics, an internal data recorder, a battery pack, a magnetic compass, and a tilt sensor all housed in a waterproof canister (fig. 3). The canister attached to a probe with a central down-looking acoustic transmitter at the end and three acoustic receivers secured by arms positioned in 120-degree arcs around the transmitter. The sample volume of the Argonaut-ADV® meter was a cylinder about 0.6 cm in diameter and 0.9 cm in height located 10 cm from the acoustic transmitter. The Argonaut-ADV® meter measured velocity with ±1.0 percent accuracy (SonTek, 2000).

The FlowTracker® ADV meter, a self-contained portable instrument, consisted of a handheld unit with a display screen, an internal data logger, a processor, and a power supply (fig. 4). Acoustic transducers are configured on a side-facing probe attached to the handheld unit by a flexible cable. The probe consisted of three receivers positioned in 120-degree arcs around a central acoustic transmitter. The sample volume of the FlowTracker® was located 10 cm from the acoustic transmitter. The FlowTracker® probe was mounted on a standard USGS wading rod for field use. The FlowTracker® measured velocity with ±1.0 percent accuracy (SonTek, 2000).

Pressure sensors manufactured by Global Water Instrumentation (*http://www.globalw.com*, accessed December 5, 2007) monitored water levels. The Global Water WL-15® recorders were self-contained sensors powered by a 9-volt battery and consisted of a processing module, date logger, and pressure transducer with a venting tube and cabling that connected the transducer and processing electronics (fig. 5). The WL-15® recorder measured water levels with 0.2-percent accuracy of its full range scale, which was ±0.0018 m over a 1.7 to 21.1 °C temperature range for the 0.91-m-range scale (Global Water instrumentation, Inc., 2002).

Probes manufactured by Sea-Bird Electronics (*http://www.seabird.com*, accessed December 5, 2007) and integrated with the Argonaut-ADV® units measured conductivity and water temperature (fig. 3). The MicroCAT SBE 37-SI® meter measures conductivity with a resolution of 0.1 µS/cm (microsiemens per centimeter) and an accuracy of 3.0 µS/cm, and temperature with a resolution of 0.0001 °C and an accuracy of 0.002 °C (Sea-Bird Electronics, Inc., 2005).

Probes manufactured by YSI measured salinity, conductivity, and water temperature. The YSI model 600 OMS® salinity meter contained an internal data recorder and measured salinity with a resolution of 0.01 ppt and an accuracy of ±1 percent or 0.1 ppt, whichever was greater (Yellow Springs Instruments, Inc., 2002). The unit measured temperature with a 0.01 °C resolution and ±0.15 °C accuracy, and conductivity with a 1 µS/cm resolution and ±0.5 percent accuracy (Yellow Springs Instruments, Inc., 2002).

Flow Velocity

Argonaut-SW® meters profiled flow velocities at culverts 30, 34, 43, and 59 and measured flow velocities at a fixed point using Argonaut-ADV® units at culverts 77, 89, and 108 (fig. 1). The Argonaut-SW® meters were bottom mounted about 3 m inside the Taylor Slough end of culverts 30, 34 and 59, and 3 m inside the Shark River Slough end of culvert 43. The Argonaut-ADV® units deployed within 5 m of the Shark River Slough side of SR 9336 at culverts 77, 89, and 108.

The Argonaut-SW® meters mounted inside culverts 30, 34, 43, and 59 recorded an average flow velocity for the water column and up to two cell velocities dependent on the flow depth within the culvert. However, parts of the water column could not be measured from the bottom of the culvert to

Figure 2. (A) Argonaut-SW® in dry culvert 43 and cable providing communication of data; and (B) camouflage fiberglass box. End of the cable with the communication port is housed in the fiberglass box with the 12-volt power supply.

A

B

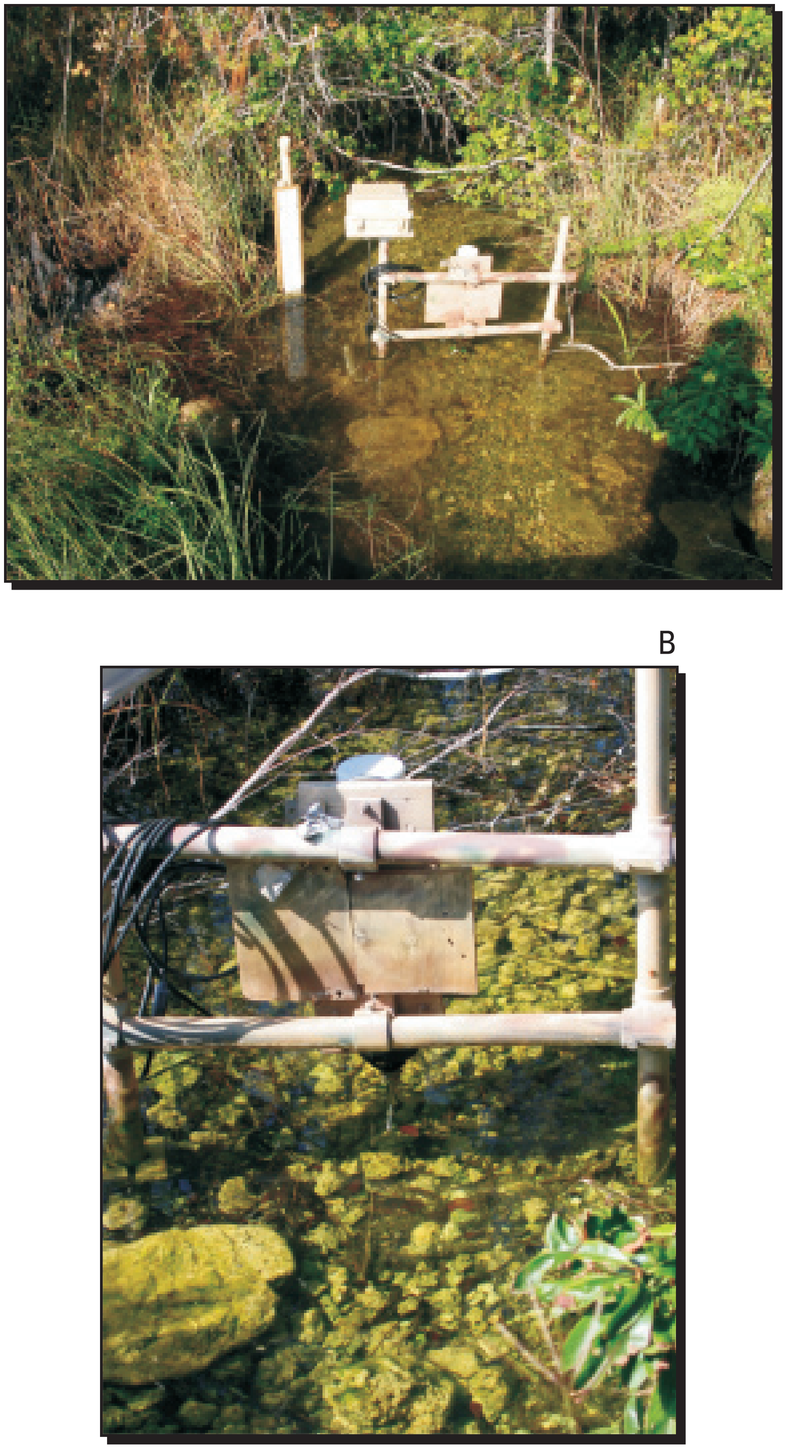

Figure 3. Distant and closeup views of the Argonaut-ADV® at (A) culvert 77 and (B) culvert 89. The ADV was in the middle of the piped mount system which created a rigid frame. The gray enclosure housed the communication cable. The Global Water pressure sensor was mounted to the PVC pipe shown in the background (see figure 5 for an enlarged view of this setup). The Sea-Bird conductivity meter was underwater on the left side next to the pipe.

Figure 4. FlowTracker-ADV® meter mounted on wading rod to measure data at (A and B) culvert 34 and (C and D) culvert 77. The instrument interface was a handheld unit.

Figure 5. Installed Global Water Instrumentation pressure sensor. The polyvinyl chloride (PVC) pipe behind the staff plate housed the pressure sensor.

the top of the Argonaut-SW® meter and the acoustic blanking distance above the top of the meter. The Argonaut-SW® meter measured the depth when flow inside the culvert was deeper than 17 cm and measured velocity when flow inside the culvert was deeper than 28 cm. A 30-minute sampling frequency with an averaging interval of 2 minutes determined the mean flow velocity. Measured mean flow velocity multiplied by the culvert flow area provided the discharge for each sample interval; measured flow depth and the culvert geometry provided the culvert flow area. Discharges computed from the Argonaut-SW® data compared favorably to discharges computed from FlowTracker® velocities and culvert flow depths measured concurrently during site visits.

Rigid frames supported Argonaut-ADV® meters that were suspended vertically in scour pools at the west ends of culverts 77, 89, and 108. The acoustic sample volumes of the probes positioned at a fixed depth in the water column measured the acoustic sample volumes. All Argonaut-ADV® meters had a velocity range setting of ±15 cm/s and recorded data in east-north-up (ENU) coordinates. Mean three-dimensional ENU velocity components were recorded during periodic intervals rather than continuously in order to extend battery life and storage space. Mean velocity components were determined using a 30-minute sampling frequency with an averaging interval of 2 minutes. Mean velocity, standard deviation, and signal-to-noise ratio (SNR) data were recorded for each ENU velocity component every 30 minutes. The SonUtils program, provided by SonTek/YSI, produced plots of signal strength, standard deviation, and diagnostic parameters throughout the study to verify meter performance.

Portable FlowTracker ADV® meters collected profiles of flow velocities at the seven culverts where continuous monitoring occurred during intermittent site visits and at other culverts during three synoptic surveys.

Water Level

The WL-15® recorders, installed within 5 m of both sides of SR 9336 at culverts 43 and 77, measured water levels. The WL-15® recorder was encased in a 5.1-cm diameter polyvinyl chloride (PVC) pipe with a slotted section at the end. The slotted end of the PVC pipe was driven into the peat and firmly secured to a metal pipe driven into the bedrock. During site visits, WL-15® readings were verified by distance-to-water (DTW) measurements taken from a reference mark and checked against visual observations of nearby staff gages. The WL-15® recorders surveyed to North American Vertical Datum of 1988 (NAVD 88) from benchmarks established by SFWMD contractors.

Salinity, Conductivity, and Water Temperature

MicroCAT SBE37-SI® meters (Sea-Bird Electronics, 2005) integrated with Argonaut-ADV® units collected data for salinity, conductivity, and water temperature at culverts 77 and 89. A self-logging YSI 600 OMS® meter measured and recorded salinity, conductivity, and water temperature at culvert 108 because of a communication failure between the Argonaut-ADV® unit and the MicroCAT® meter. The MicroCAT® and YSI® meters were deployed near the top of the litter layer next to the Argonaut-ADV® meters. The MicroCAT® meters measured data that were stored in the data set recorded by the Argonaut-ADV units, which represented an instantaneous measurement at the start of each 30-minute sampling interval. The YSI 600 OMS® meter measured and stored data in its internal data recorder at 30-minute intervals. A portable YSI® conductivity/temperature probe measured salinity, conductivity, and water temperature during site visits; this technique provided independent data verification.

Flow Data Collected during Three Intensive Field Efforts

Continuous flow data collected during three intensive field efforts at seven culverts provided a better understanding of regional surface-water flow distributions along SR 9336. Data collection occurred at all culverts between culvert 23 near Royal Palm access road and culvert 155 near West Lake (fig. 1) on November 17, 2004, August 10, 2005, and September 27, 2005, Compilation and summation of four geographic segments of SR 9336 were achieved through computation of the culvert flow discharges for each intensive field effort (fig. 6). The four segment summations are: (1) culvert 22 near Royal Palm Road to culvert 42 near the access road for Pa-hay-okee Overlook; (2) culvert 43 near the access road for Pa-hay-okee Overlook to culvert 63 near the access road for Mahogany Hammock; (3) culvert 64 near the access road for Mahogany Hammock to culvert 110 near Nine Mile Pond; and (4) culvert 111 near Nine Mile Pond to culvert 155 near West Lake. A fifth geographic segment represented the area from the ENP entrance to culvert 22. Similar road segment delineations and culvert groupings are described in a previous USGS study of culvert flows measured in 1997 and 1998 (Tillis, 2001). Personnel from the ENP Research Center computed and provided flow discharge between the ENP entrance and culvert 22 near Royal Palm Road. Flows through culverts south of Nine Mile Pond near culvert 111 were not measured in the previous USGS study (Tillis, 2001), and flows through culverts south of West Lake (south of culvert 155) were not measured in this study. Significant flow exchange beneath SR 9336 south of culvert 155 was not observed during the three intensive field efforts conducted for this study.

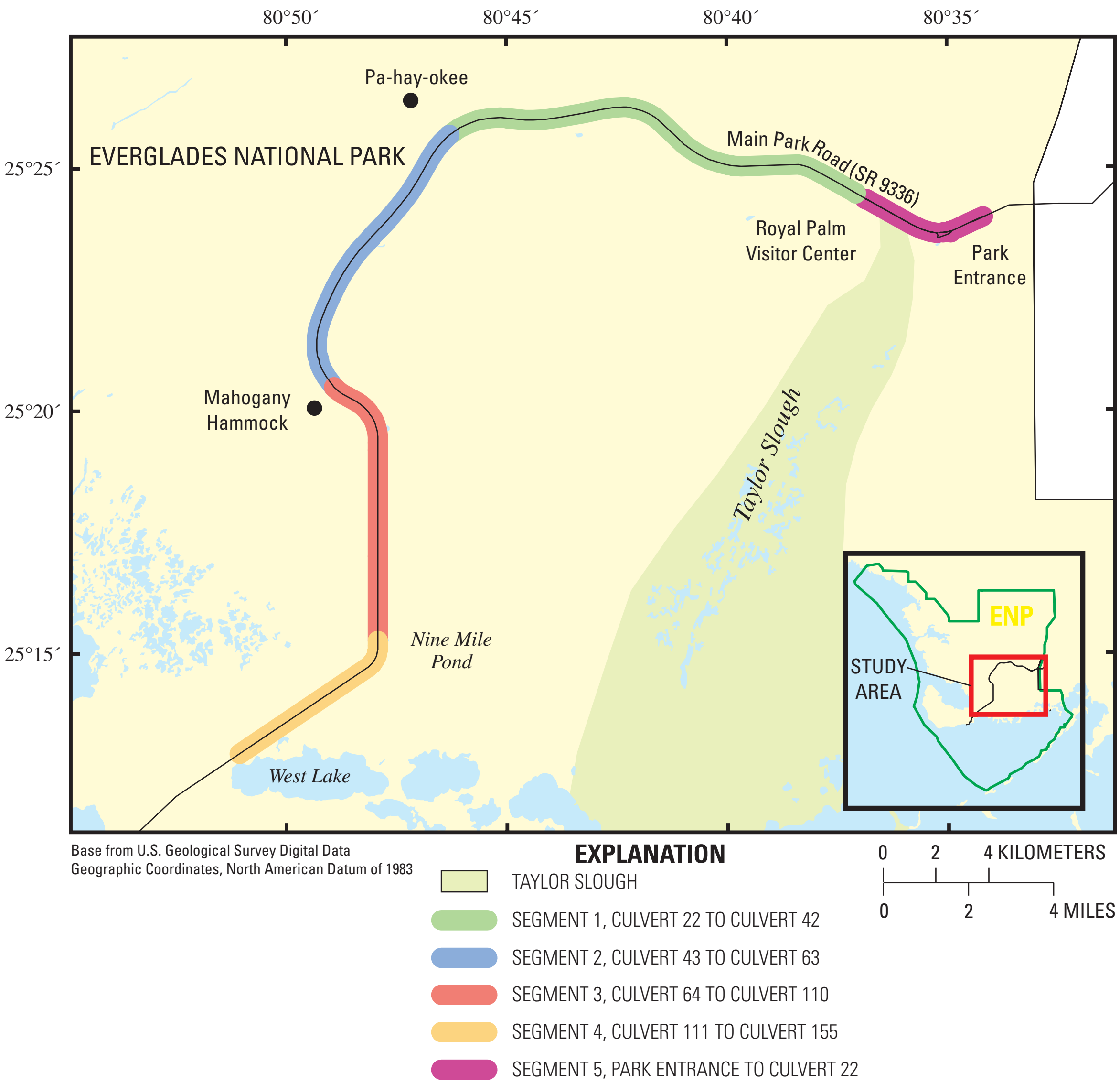

Figure 6. Geographic segments for culverts between the Everglades National Park entrance to 155 beneath State Road 9336 (SR 9336). Culvert sections correspond with segment descriptions in table 2.

Data Analysis

Instrument accuracies, environmental conditions, and major weather events were factors considered during the data analysis of flow velocity, water level, salinity, and temperature. Editing techniques and criteria were used to process, quality assure, and verify data discussed in the subsequent sections.

Flow Velocity

Assessment of the Argonaut SW® data was performed using the following criteria: (1) inspection of the data set identified periods when the flow depth inside the culvert was below the detection limit of the meter, the meter was disturbed during site visits, or the meter was not functioning properly; (2) inspection of values using data plots of depth and velocity plots detected obvious errors or extreme magnitude "spikes"; (3) analysis of the x- and y-velocity components determined whether data with a dominant velocity component were collected (because the Argonaut-SW® meters were inside the culvert with the x-axis aligned parallel to the culvert wall, the y-velocity component could be relatively small); and (4) comparison of velocity data from depth cells 1 and 2 served as a diagnostic tool for verification of the depth-averaged flow velocity within the culvert. Examination of the control file recorded with the data and graphs of the ancillary data (standard deviation, signal amplitude, hydrologic, meteorological, and so forth) helped to detect velocity data errors. Additionally, evaluation of the data was based on inspection and analysis of the hydraulic trend. Suspect data were deleted or edited.

The techniques used to evaluate the Argonaut-ADV® data included: (1) application of time-varying sound-speed corrections based on the ambient water temperature and salinity; (2) inspection of the data set to identify periods when the acoustic probe was out of the water, the sample volume was disturbed during site visits, or, the meter was otherwise not functioning properly; (3) automated filtering based on recorded SNR and standard deviation values; and (4) qualitative inspection and comparison with other hydrologic and meteorological data.

The primary quantitative filter parameter used to analyze the Argonaut-ADV® data was the SNR. Bihourly measurements recorded average SNR values for each acoustic receiver. A minimum SNR value of 7 dB (decibels) was determined to indicate good acoustic signal quality (SonTek, 2000). However, this threshold value caused the removal of too many samples; subsequent inspection confirmed that sample quality was acceptable for analysis. Consequently, a filter based on a minimum three-beam average SNR of 3 dB was more acceptable for the Argonaut-ADV data. The three-beam average SNR filter was more reliable because the flow had a dominant velocity component.

All Argonaut-ADV® meters deployed with a velocity range setting of ±15 cm/s. Velocity range settings were used to extend battery life and increase measurement accuracy. The lowest velocity range that fully encompassed the expected flow velocity magnitude yielded the greatest data accuracy. However, flow velocities at culverts 77, 89, and 108 exceeded ±35 cm/s, which is the maximum horizontal velocity the Argonaut-ADV® meter is capable measuring accurately using a ±15 cm/s velocity range setting. For example, actual flow velocities exceeded 140 cm/s during field measurements at culvert 77 on September 22, 2005. Measurement aliasing occurred and flow velocities recorded by the Argonaut-ADV® meter became slower and more random than actual flow conditions. When flow velocities exceeded the velocity range setting of the Argonaut-ADV® meter, velocity standard error values were large and had a limiting value of 25.5 cm/s. Consequently, a 25.5 cm/s velocity standard error filter used in conjunction with the 3-dB SNR filter removed invalid velocity data from the data set.

The qualitative inspection included analysis and comparison of flow speeds and directions measured by the Argonaut-ADV® meter, with velocities measured by a portable FlowTracker® during intermittent site visits. Similar inspections of SNR, velocity standard deviation, water level, meteorological, and other hydrologic data verified that the measurements were accurate. Inspection and verification of any suspected data occurred when the automated standard error filter might not have fully removed erroneous data.

Water Level

Comparison of sensor readings to field observations resulted in some correction of water-level data. The DTW measurements, made from surveyed reference marks during site visits at each sensor location, yielded adjustment of recorded water-level readings to the North American Vertical Datum of 1988 (NAVD 88). The DTW measurements provided corrections for electronic sensor drift or adjustment to the vertical datum, or both.

Salinity, Conductivity, and Water Temperature

Measurements made with a portable YSI 600 OMS® meter (reference probe) during site visits verified whether the MicroCAT® readings were within a valid range. Biological growth on the sensor and electronic drift caused invalid or out-of-range readings. Correction of the MicroCAT® data accounted for biological fouling or sensor drift. Consistency of conductivity and temperature data collected by deployed MicroCAT® meters ensured data accuracy and validity. Methods documented in Riscassi and Schaffranek (2002) described how conductivity data are converted to specific conductance values for reporting purposes.

Quantity and Quality of Hydrologic Data

Data collection and analysis for flow velocity, water-level, salinity, conductivity, and water temperature resulted in a relatively complete set of data for the June 2004 to December 2005 study period. The subsequent sections present these hydrologic characteristics by data type. Suspect data that did not pass the editing criteria were not presented in this report.

Flow Velocity

Data collected by Argonaut-SW® meters at culverts 30, 34, 43, and 59 (fig. 1) generally were complete for the majority of the study (fig. 7). Quantitative or qualitative data filtering, instrumentation failure, or transducer obstruction due to vegetation or wildlife interference caused some brief periods of missing data.

Data collected by the Argonaut-ADV® meters at culverts 77, 89, and 108 (fig. 1) were more limited in quantity and of lesser quality than those collected by the Argonaut-SW® meters (fig. 7). Vegetation becoming entangled on the probe or flow-velocity magnitudes greater than the pre-set instrument range setting caused periods of missing data (fig. 8). Thus, periods of high-flow velocity greater than the pre-set range setting, especially during the second year, invalidated large parts of data during post-analysis (fig. 9).

Water Level

Continuous data collected for water levels near culverts 43 and 77 (fig. 1) for each study year are shown in figure 10. Periods of missing data were attributed to sensor malfunction. The water-level sensors deployed in June 2004 recorded water levels when surface water was present for the study period.

Salinity, Conductivity, and Water Temperature

Data collected for salinity, conductivity, and water temperature at culverts 77, 89, and 108 (fig. 1) for the study period are shown in figure 11. Data collection did not begin at culvert 77 until September 2004 and at culvert 108 until July 2005. Sensor malfunction caused periods of missing data. Suspect data that did not pass the editing criteria are not presented in this report.

Surface-Water Flow Exchange through Culverts

Data collected during this study provided a better understanding of the magnitude, direction, and nature of flow exchanges through culverts beneath SR 9336 within ENP. Prevalent hydraulic trends, predominant flow directions, and significant flow reversals defined the temporal nature of these flow exchanges.

Flow Trends

Flow trends from the three intensive field efforts conducted during this study were similar to those of the September and November 1997 measurements documented by Tillis (2001). Flow measurements for SR 9336 in the segment from Nine Mile Pond to West Lake (fig. 6 and table 2) from this study could not be compared with the Tillis (2001) study because culvert flows were not measured for this area in September and November 1997. Personnel at the ENP Research Center computed the inflows into Taylor Slough between the ENP entrance and culvert 22.

Net flow discharge through the culverts beneath SR 9336 was into the Taylor Slough Basin from Shark River Slough Basin in the road segment between Royal Palm Road and Pa-hay-okee Overlook access road. Shark River Slough Basin had a net flow discharge through the culverts beneath SR 9336 from Taylor Slough Basin in the segments between Pa-hay-okee Overlook and Mahogany Hammock access roads, and between Mahogany Hammock access road and Nine Mile Pond. For the three intensive flow measurements in this study and the September and November 1997 measurements in the previous USGS study (Tillis, 2001), the amount of discharge into Taylor Slough Basin from Shark River Slough Basin in the segment of SR 9336 between Royal Palm Road and Pa-hay-okee Overlook access road was always the smallest quantity of flow through the compared road segments, between Royal Palm Road and Nine Mile Pond. The largest flow discharge occurred over the segment of SR 9336 between Mahogany Hammock access road and Nine Mile Pond, except for the extreme low flow measured during November 1997. The total flow through the two road segments that discharged into Shark River Slough Basin always exceeded the flow into Taylor Slough Basin from the segment between Pa-hay-okee Overlook and Mahogany Hammock access roads. Thus, a net flow loss resulted from Taylor Slough Basin through the culverts beneath SR 9336 between Royal Palm Road and Nine Mile Pond towards Shark Slough Basin. Individual culvert flows measured during the three intensive field efforts and a summary of notes taken during the field measurements are accessible as electronic files (see appendix).

Flow Directions

A summary of continuous flow-velocity data collected at the seven culverts during this study is presented in table 3. The percentage of valid flow-velocity data collected at each of the seven culverts during the two study years and the percentage of valid velocity data at each culvert that indicated flow into Taylor Slough Basin (conversely, remaining percentage of velocity data indicated flow into Shark River Slough Basin) are identified in table 3.

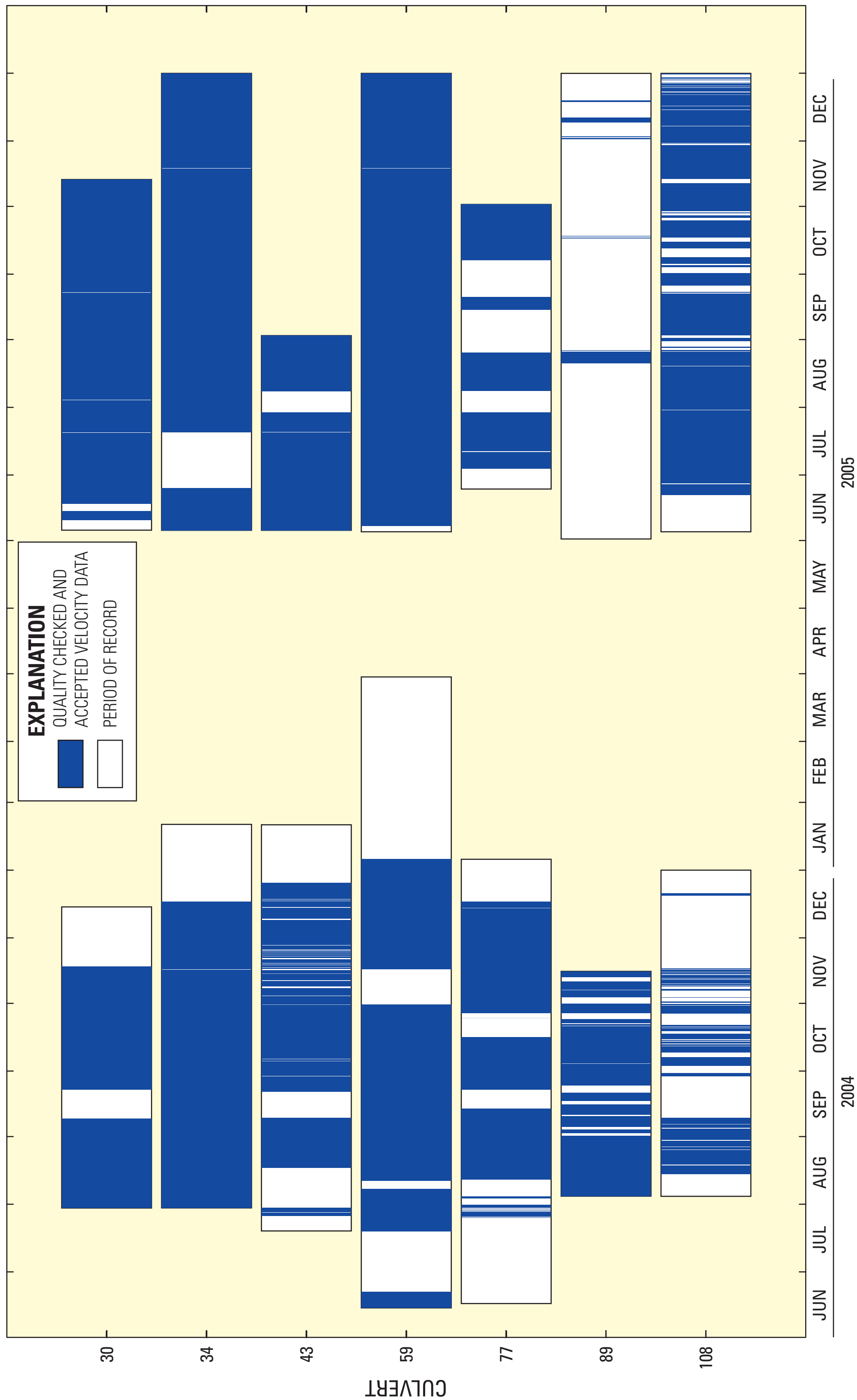

Figure 7. Periods of flow-velocity data collection at the culverts during the study.

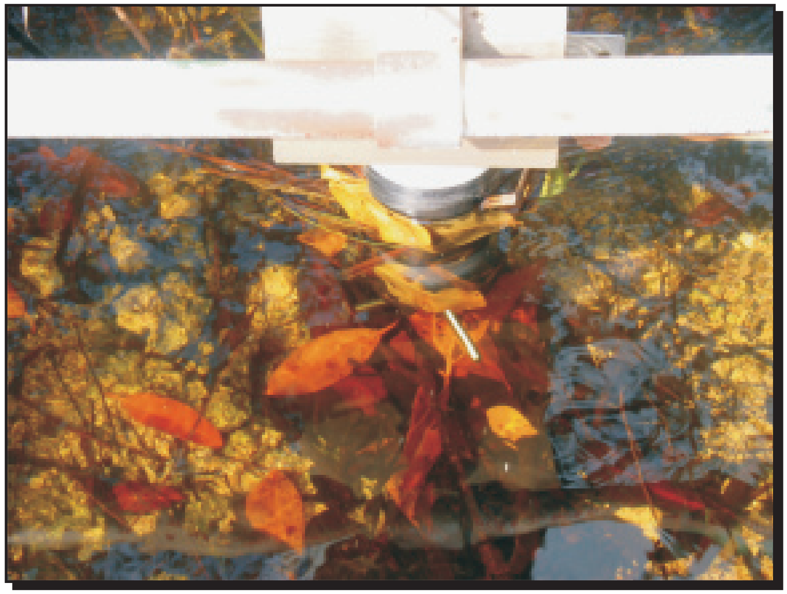

Figure 8. Leaves covering the Argonaut-ADV® transducer. Periods of missing data sometimes resulted from accumulations of vegetation, biological fouling, and wildlife interference of the instruments. The transducers (silver with a leaf on it) were just below the water surface.

Figure 9. High-flow velocity that exceeded the Argonaut-ADV® program setting, causing suspect data spikes. Suspect data were deleted from this study.

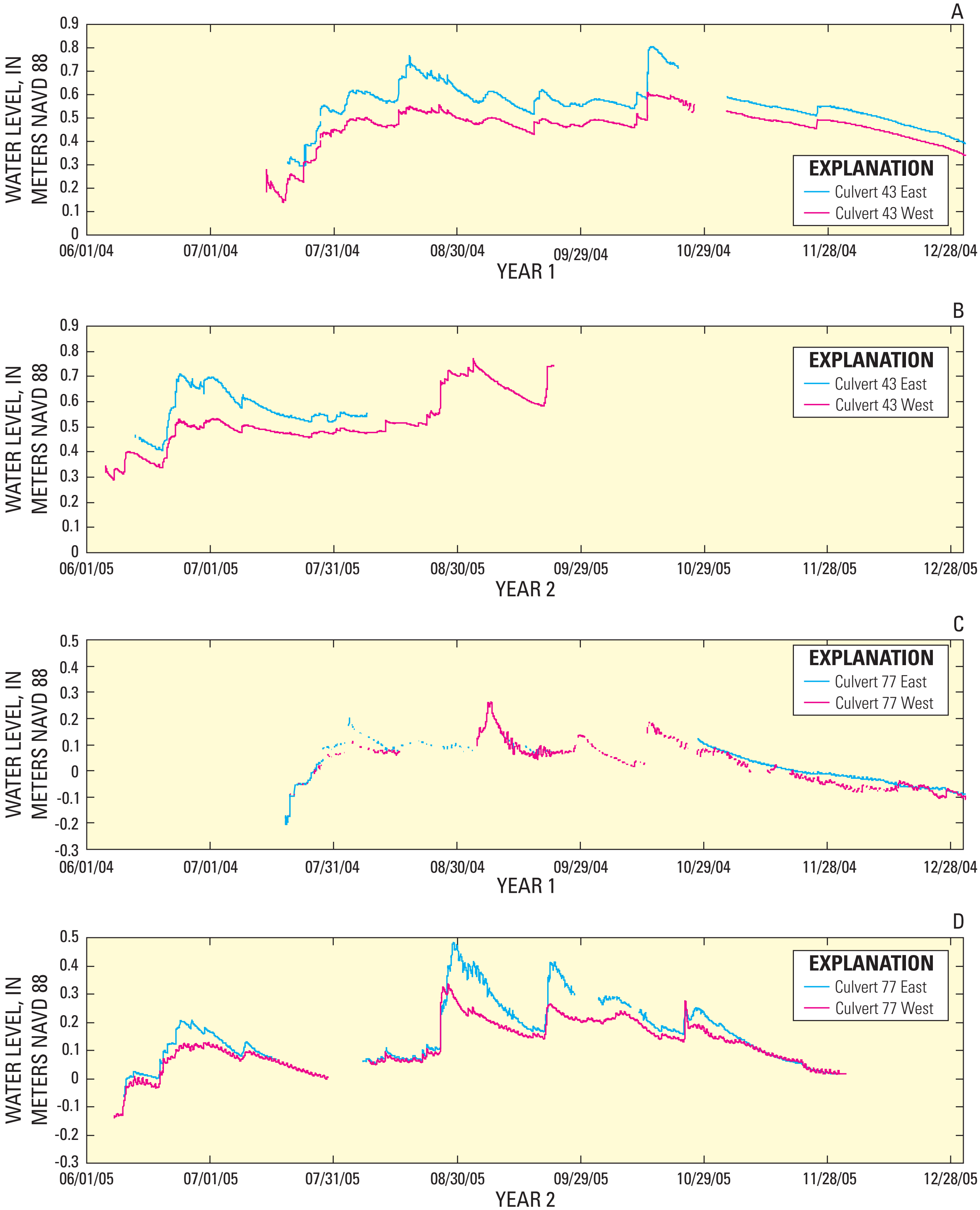

Figure 10. Water levels at culverts 43 and 77 during study years 1 and 2.

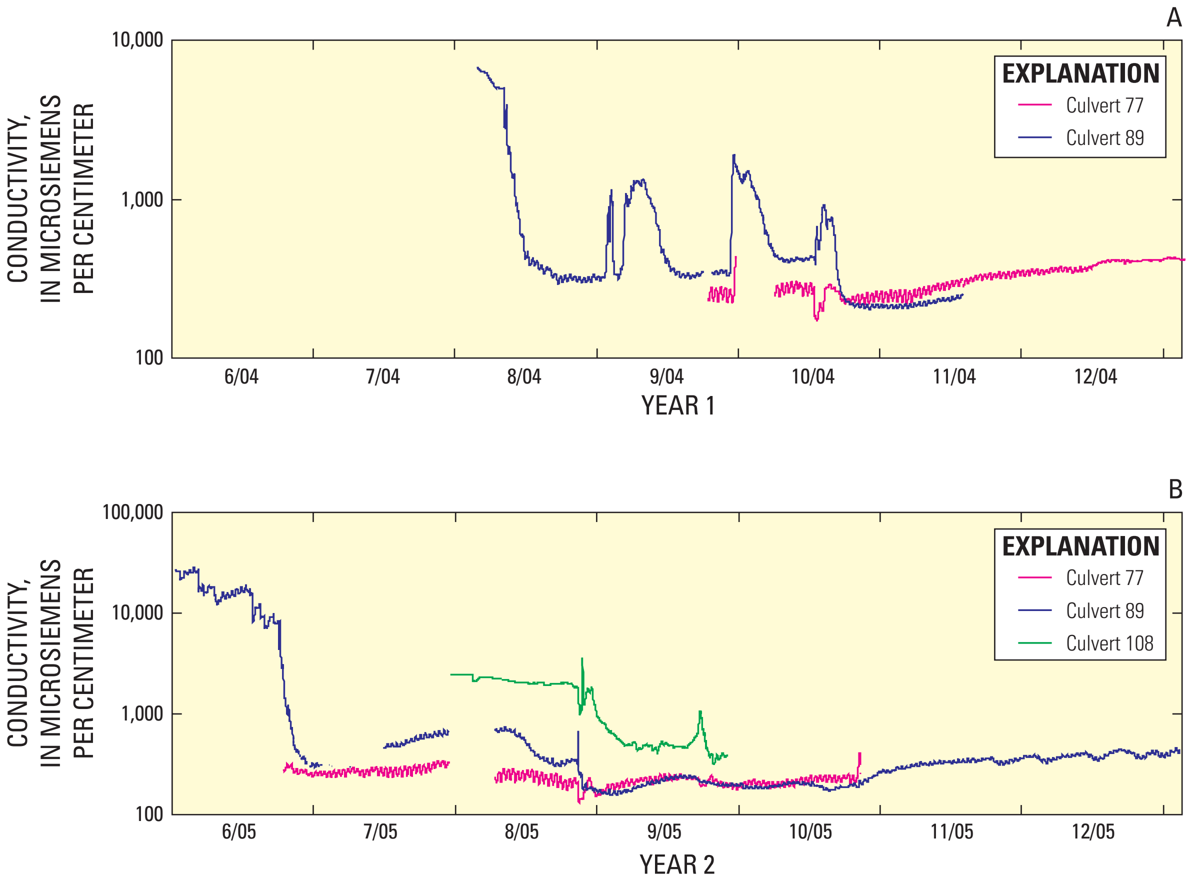

Figure 11. Conductivities at culverts 77, 89, and 108 during study years 1 and 2.

Table 2. Net flows measured through culvert sections beneath State Road 9336 within Everglades National Park (ENP) during 2004-05.

[Geographic road segments are shown in figure 6. Net flows are either positive for inflow to the Taylor Slough basin or negative for outflow toward Shark Slough basin. Net flows for section 5 were determined by the ENP Research Center]

Road segment number	Culvert section description	Net flow (cubic meters per second)		
		11/17/2004	8/10/2005	9/27/2005
1	Culverts 22-42	0.34	0.58	3.31
2	Culverts 43-63	-.44	-1.04	-4.08
3	Culverts 64-110	-.51	-1.54	-10.68
4	Culverts 111-155	-.16	-.61	-4.48
5	ENP entrance to east of culvert 22	2.54	3.79	10.47

Table 3. Summary of valid data for the collection period and valid data with flow into Taylor Slough at monitoring culverts beneath State Road 9336 within Everglades National Park during 2004-05.

Culvert number	Study year	Percentage of valid data for collection period	Percentage of valid data with flow into Taylor Slough
30	1	71.7	87.0
	2	94.4	88.6
34	1	84.5	95.7
	2	87.6	92.3
43	1	61.6	.7
	2	88.7	1.9
59	1	58.5	2.3
	2	98.1	.7
77	1	57.2	5.0
	2	87.9	.5
89	1	84.1	22.6
	2	4.4	12.3
108	1	32.4	29.9
	2	76.3	5.5

Discharges collected by Argonaut-SW® meters at culverts 30, 34, 43, and 59 (fig. 1) during the study period are shown in figure 12. Positive discharges identified flow into Taylor Slough Basin and negative discharges identified flow into Shark River Slough Basin. Flow depths recorded by the Argonaut-SW® meters indicated that sustained culvert flows occurred during the second year of the study (fig. 13B). Culverts 30 and 34 discharged to the southeast into the Taylor Slough basin (fig. 12). As identified in table 3, 87 to 89 percent and 92 to 96 percent of the flow from culverts 30 and 34, respectively, discharged into Taylor Slough Basin during the two wet seasons. Culverts 43 and 59 typically discharged to the northwest into Shark River Slough (fig. 12). Only 1 to 2 percent of the flow from culverts 43 and 59 during the two wet seasons was discharged into Taylor Slough (table 3). The majority (98 to 99 percent) of the flow from culverts 43 and 59 discharged into Shark River Slough. On August 26-27, 2005 (fig. 12B), culverts 43 and 59 recorded the highest discharges during this study.

Flow velocities collected by Argonaut-ADV® meters at culverts 77, 89, and 108 (fig. 1) during the study period are shown in figure 14. Flows from culverts 77, 89, and 108 were primarily to the west into Shark River Slough Basin with brief periods of eastward flow into Taylor Slough Basin (fig. 14). Large gaps existed in the Argonaut-ADV® data recorded at these three culverts, particularly during the second year of the study (fig. 14B); analysis of available data (remaining ADV data, water-level data, field observations, and so forth) indicated that the dominant flow direction was toward the west. Discharge from culvert 77 was west into Shark River Slough Basin (95 to 99 percent) during the monitoring period (table 3). Discharge was less often directed into Shark River Slough at culverts 89 (77-88 percent) and 108 (70-95 percent) during the monitoring period (table 3). Brief periods of discharge to the east, less than 2 days in duration, were simultaneously recorded at culverts 77, 89, and 108 during September and October 2004 (fig. 14A) and August 2005 (fig. 14B). Culverts 77 and 108 also had brief periods of negative flow during October and November 2005, a period in which data from culvert 89 were not available.

Flow Reversals

Flow reversals occurred when water in a culvert discharged in a direction opposite the predominant flow direction for the culvert (table 3). Discharge toward the northwest (into Shark River Slough Basin) defined a flow reversal at culverts 30 and 34, whereas discharge toward the southeast (into Taylor Slough Basin) defined a flow reversal at culverts 43 and 59, and eastward, discharge (into Taylor Slough Basin) defined a flow reversal at culverts 77, 89, and 108. No sustained flow reversals occurred at culvert 34 or 43, although minor short-term reversals in flow direction occasionally existed, typically during periods of slow velocity flows associated with low culvert discharges (fig. 12).

Flow reversals typically occurred either at the start of the wet season or shortly after substantial rainfall or significant storm events. Culvert 89 recorded a period of eastward flow in August 2004 at the start of the first wet season (fig. 14A). Culvert 108 recorded a period of eastward flow in June 2005 at the start of the second wet season (fig. 14B).

Flow reversals occurred at culvert 30 on October 15, 2004; June 6, 2005; August 26, 2005; and October 24, 2005 (figs. 12A and 12B). These brief reversals had subsequent periods of sustained higher velocity flows to the southeast (into Taylor Slough Basin). No flow reversals occurred at culvert 34, although periods of higher velocity flows to the southeast were recorded concurrent with the flow reversals at culvert 30. Brief flow reversals occurred at culverts 43 and 59 before the high discharge events on August 26-27, 2005 (fig. 12B). A brief flow reversal occurred at culvert 59 on October 24, 2005 (fig. 12B).

The east-to-west crossing of Hurricane Katrina over southern Florida (after making landfall on the southeastern coast near North Miami Beach) during August 26-27, 2005 (fig. 12B), caused flow reversals and subsequent high velocities at the culverts. The west-to-east crossing of Hurricane Wilma over southern Florida (after making landfall on the southwestern coast near Naples) on October 24, 2005, was influenced by flow reversals from winds. The east- to-west passage of Hurricane Rita south of Florida through the Florida Straits and into the Gulf of Mexico on September 20, 2005, probably caused reduced discharges into Taylor Slough Basin through culverts 30 and 34, with increased discharges into Shark River Slough through culvert 59 (fig. 12B).

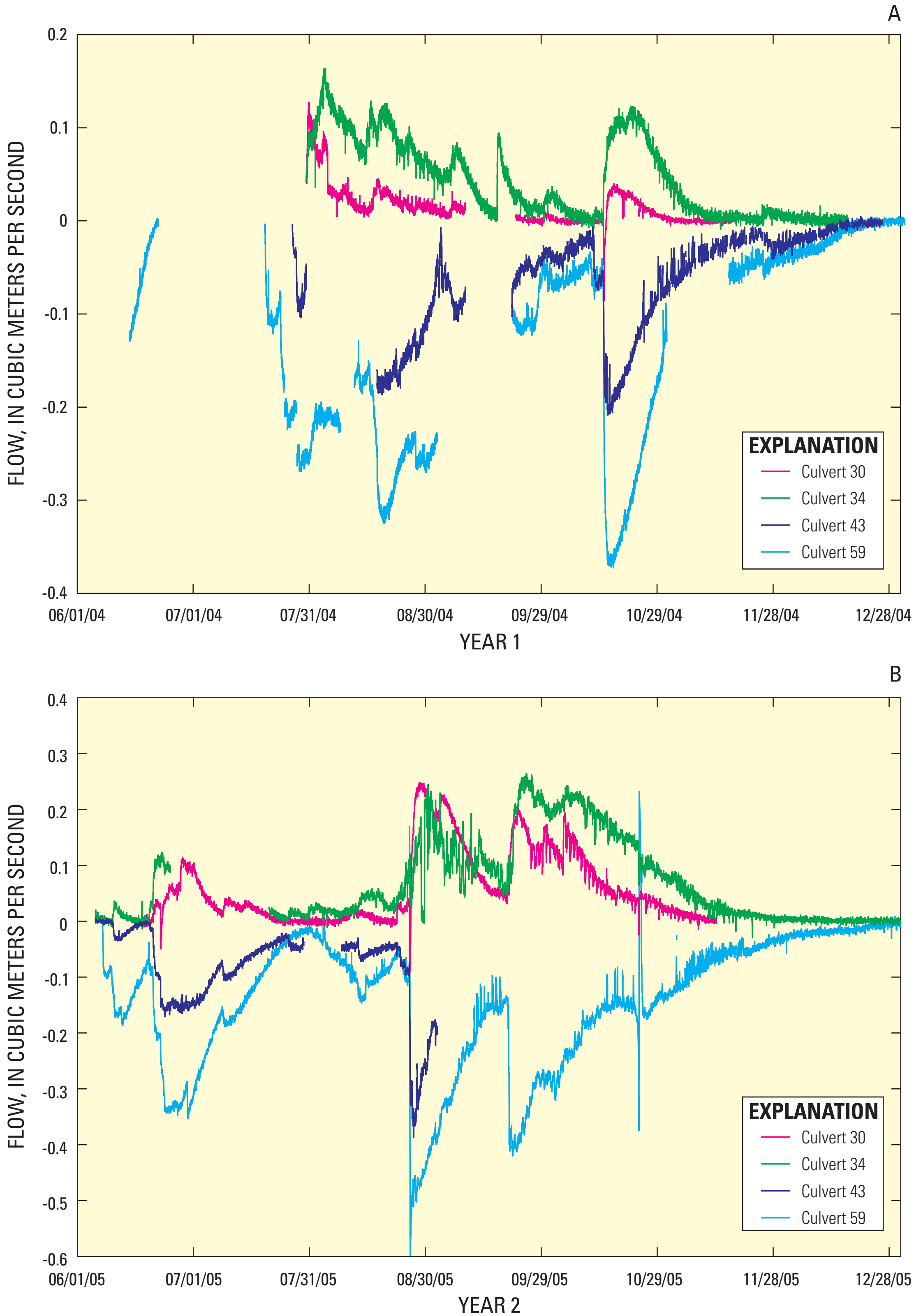

Figure 12. Computed discharge at culverts 30, 34, 43, and 59 during study years 1 and 2. Flows are positive for inflow to the Taylor Slough basin and negative for outflow toward Shark Slough basin during study years 1 and 2.

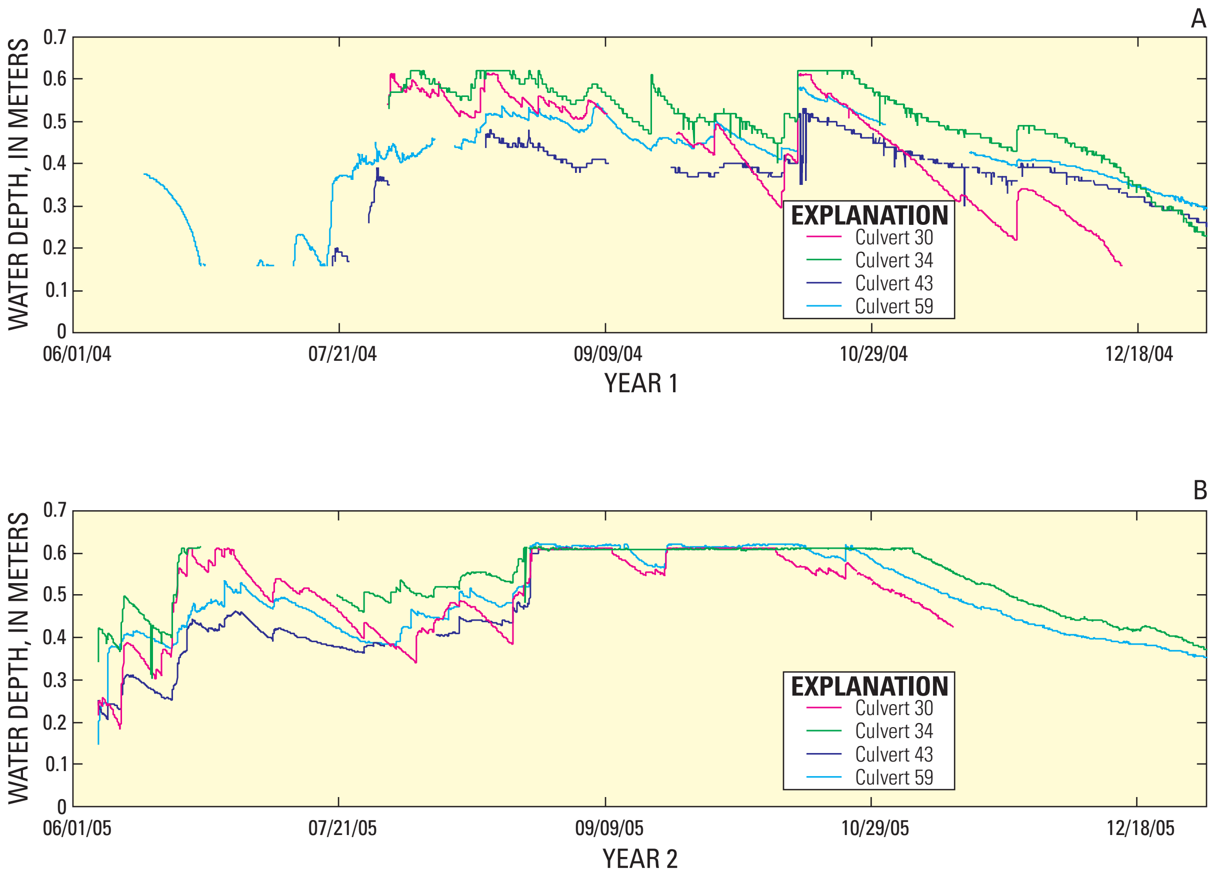

Figure 13. Recorded depth of water in culverts 30, 34, 43, and 59 during study years 1 and 2.

A flow reversal at culvert 77 started about 0900 hours on September 6, 2004, and ended about 48 hours later (fig. 15). A gradual increase in flow velocity during the first 24 hours and a gradual decrease in velocity during the final 24 hours characterized this flow. The cause of this flow reversal was a substantial amount of rainfall during a short period of time that initiated a rapid increase in water level on the west (Shark River Slough) end of the culvert. The Royal Palm meteorological station recorded more than 6 cm of rainfall on September 5, 2004. The P35, P36, and SH1 hydrologic stations in Shark River Slough recorded about 5 cm of rainfall on September 5, 2004. The Fire Cache wind station recorded a steady 8 to 16 km/hr wind from the south on September 6, 2004. Analysis of this flow reversal and others in 2004 did not identify wind as the primary influence on flow reversals in the culverts. However, wind seemed to have a greater effect on flow during weather events characterized by prolonged high-wind speeds from a consistent direction, such as those typically associated with tropical storms and hurricanes.

Suggestions for Further Study

Although data collected during the timeframe of this study have provided some further insight into the temporal behavior of flow exchanges through selected culverts along State Road 9336 within ENP, additional investigation in the following areas would help further clarify and characterize these flow exchanges.

1. Monitoring and analysis of long-term temporal and spatial salinity fluctuations along the marsh-mangrove interface would help clarify the driving forces that affect freshwater-saltwater mixing. The limited amount of valid salinity data collected in the present study near the Hells Bay and Noble Hammock canoe trailheads did not enable determination of long-term trends needed to analyze supply and forcing factors that affect mixing.

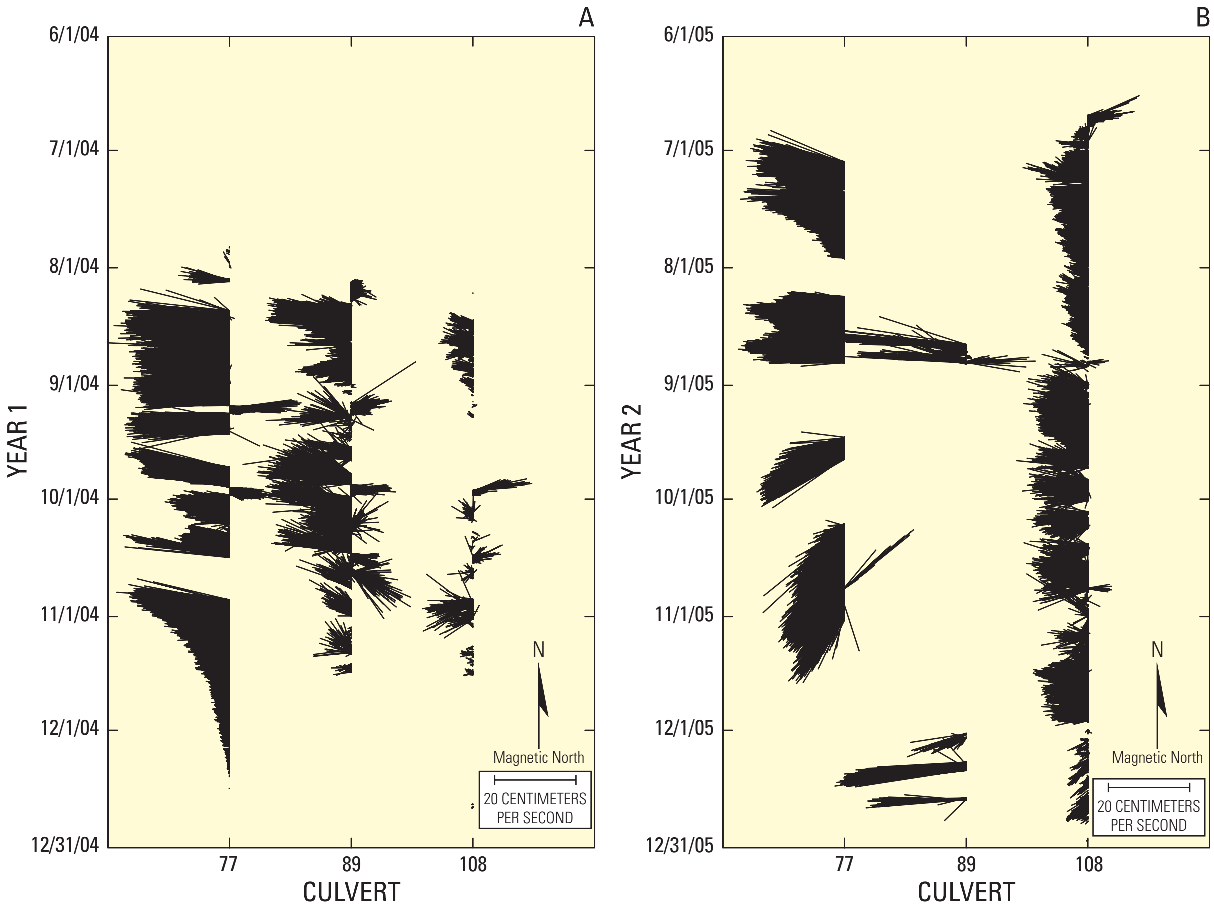

Figure 14. Flow velocities and flow directions at culverts 77, 89, and 108 during study years 1 and 2.

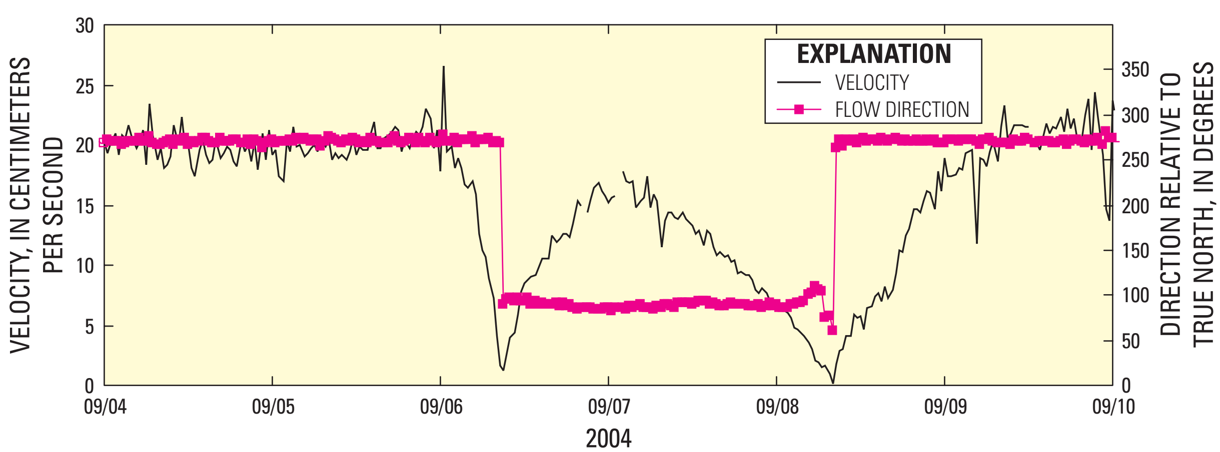

Figure 15. Flow-reversal event at culvert 77 during September 4-10, 2004.

2. Long-term monitoring of flow velocities in the wetlands that border State Road 9336 within ENP would provide data needed to determine temporal and spatial flow patterns between culverts along the road. Although monitoring of flow patterns within the wetlands was planned for the present study, permitting issues precluded instrument deployment.

3. Some additional insight into areal flow patterns along State Road 9336 within ENP could be obtained by establishing culvert ratings to provide more spatial coverage of inter-basin flow exchanges. Much of the data collected during the present study could be utilized to help establish these culvert ratings.

4. Numerical model simulations can be used to investigate regional flow patterns in and around the Main Park Road to analyze the effect of alternative Everglades restoration scenarios on inter-basin flow exchanges. The data collected in this study should be of use in developing and refining numerical models, designing numerical simulations, and evaluating model results for quantifying flows from various restoration designs and operational control scenarios.

Summary and Conclusions

Data were collected for flow velocity, water level, salinity, conductivity, and water-temperature between June 2004 and December 2005 to investigate the temporal and spatial nature of flow exchanges through culverts beneath SR 9336 within Everglades National Park. Flow data collected during this study revealed the predominant direction of culvert discharges, typical magnitude and duration of flow reversals within the culverts, and spatial distribution of flow exchanges along segments of SR 9336.

Continuous flow data recorded at seven culverts during two wet seasons indicated that between the ENP entrance and Pa-hay-okee Overlook access road, the predominant direction of discharges through SR 9336 culverts was into Taylor Slough Basin. Between Pa-hay-okee Overlook access road and West Lake, the predominant direction of SR 9336 culvert discharges was into Shark River Slough Basin. Discharges through two SR 9336 culverts east of Pa-hay-okee Overlook access road flowed into Taylor Slough Basin from 87 to 96 percent of the time, whereas discharges through five SR 9336 culverts between Pa-hay-okee Overlook access road and Nine Mile Pond flowed into Shark River Slough Basin from 70 to 99 percent of the time. Flow reversals in the culverts were brief and mainly occurred at the onset of the wet season, after substantial rainfall events, or were driven by significant weather events typically associated with tropical storms or hurricanes. The predominant westward discharge of flow continuously monitored through five SR 9336 culverts south of Pa-hay-okee Overlook access road indicated that SR 9336 did not adversely affect the flow of freshwater into Florida Bay. Continuous flow data collected for this study support previous assertions and observations that sections of SR 9336 within Everglades National Park help retain flow in Taylor Slough Basin and provide a beneficial water supply to Florida Bay.

Discharges measured synoptically at all culverts during three intensive field efforts revealed flow trends similar to those measured through three road segments in 1997 and documented in a previous study. There was a net flow discharge into Taylor Slough Basin from Shark River Slough Basin in the segment of SR 9336 between Royal Palm and Pa-hay-okee Overlook access roads. Conversely, there was net flow discharge into Shark River Slough Basin from Taylor Slough Basin in the segments between Pa-hay-okee Overlook and Mahogany Hammock access roads, and between Mahogany Hammock access road and Nine Mile Pond.

The data provided within this report will assist scientists and managers to gain a better understanding and to make informed decisions about issues regarding the movement of water within the southern Everglades ecosystem that borders northern Florida Bay. The additional insight provided by these data can be useful in designing and evaluating restoration scenarios for the Everglades.

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Appendix: Data Files

(Link accessible from web)

Data files for this study are categorized by station and study year. All data are reported in Eastern Standard Time (EST).

Year 1 of the study (June - December, 2004) included data collected from the initial instrumentation deployment through the last period of satisfactory data before the water level at the sensor was lower than the minimum depth required for sampling, or, an equipment malfunction.

Year 2 included data from June 2005 through the last period of satisfactory data before the water level at the sensor was lower then the minimum depth required for sampling, equipment malfunction, or December 31, 2005. Data recorded after December 31, 2005, were removed due to the lack of field visits to assure data accuracy.