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King's Bay/Cumberland Sound, Georgia
Part I: Experiment Report
June-July 1985

by

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Technical Report

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KING'S BAY/CUMBERLAND SOUND, GEORGIA

PART I: EXPERIMENT REPORT

JUNE-JULY 1985

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ABSTRACT

A month-long field experiment was conducted during June and July, 1985 at King's Bay/Cumberland Sound, Georgia, under the combined auspices of the Naval Civil Engineering Laboratory and the Woods Hole Oceanographic Institution. Nine estuarine stations were occupied over the duration of the experiment measuring velocity, sea surface elevation, and water quality (salinity, temperature and transmissivity) as well as wind waves. The data document the amplification of the tide from St Mary's Inlet north into King's Bay (an increase in the dominant M_2 tidal range from 0.90 m offshore of St. Mary's Inlet to a high of 0.99 m at King's Bay). The M_2 tide dominates records of velocity, sea surface, temperature, and salinity throughout the estuary. Half way through the experiment, the bay became warmer and less saline, reflecting increased freshwater flow into the estuary through the Crooked River, St. Mary's River, and other smaller rivers. All velocity gauges measured a net down-estuary mean flow over the duration of the experiment. Net volume discharge of water from the inlet averaged 300-350 m^3 /second over the month of measurement. Net discharge of fine sediment is at least 2600 tonnes per day, and perhaps as high as 26,000 tonnes per day. Data from this field experiment provide the only useful basis for verification and evaluation of various numerical models applied to King's Bay/Cumberland Sound.

INTRODUCTION

A joint research effort carried out by the Naval Civil Engineering Laboratory (NCEL) under the guidance of Dr. James Bailard and the Woods Hole Oceanographic Institution (WHOI) under the guidance of Dr. David Aubrey addressed the circulation and sedimentation in King's Bay/Cumberland Sound (KBCS), Georgia. The investigation had two major focuses: first, a month-long field experiment was conducted in June and July, 1985, in the region of KBCS, for the purpose of collecting data suitable for verification of models of tidal circulation within the estuary. This data collection effort provided the first long-term measurements of sea surface and velocity throughout KBCS. Second, the program was designed to investigate the feasibility of applying a finite element, movable boundary numerical model (developed by Prof. Daniel Lynch at Dartmouth College) to the KBCS region as a diagnostic tool for examining circulation and sediment transport within KBCS. The first of these two focuses is the subject of this report. The second focus, numerical modeling, is the subject of a companion report.

This project is complementary to past and ongoing efforts in this area. The U.S. Army Waterways Experiment Station had a limited field program and a major numerical modeling effort focused on King's Bay. The Savannah and Jacksonville Districts of the Army Corps of Engineers have had bottom sampling programs and bathymetric measurements in this area over the years past, continuing approximately on a bi-yearly basis. The present program extends

the data base available for these various efforts by increasing the duration and coverage of the sampling stations. The numerical modeling is also complementary. Whereas the WES modeling is predictive, the present program emphasizes diagnostic modeling, examining the system response of the estuary in its present state, and how major modifications would alter that response. In other words, the diagnostic modeling would address the effects of altering general channel configuration, major boundary changes (such as diking), and alteration of extent of tidal flats. The WES model on the other hand is best suited for detailed examination of spatial and temporal variability of tidal flows for specific geometries. The cost of the diagnostic modeling is less than that for the WES modeling in theory, but results in poorer spatial resolution. The diagnostic modeling is geared towards examining the response of the system as a whole, and only secondarily towards examination of detailed spatial variability. No effort is made here to summarize results of previous work (e.g., McLemore et al., 1981; Redtke, 1985).

As a joint research effort carried out by NCEL and WHOI, all field tasks were divided between the two groups. Instrumentation was provided by both participants, whereas data processing took place almost entirely at WHOI. This report describes the field experiment, instrument deployments, data analysis, and interpretations derived from this work. In summary, the experiment was successful, obtaining for the first time high-quality data sets of sea surface elevation, temperature, salinity, and velocity at a number of points within the KBCS system. These results are useful for numerical modeling efforts of circulation and sedimentation, and in considerations of ship-handling and dredging operations in these waterways.

FIELD EXPERIMENT

The field experiment was conducted from 17 June 1985 through 23 July 1985 at King's Bay/Cumberland Sound, Georgia (figure 1). Eight current meters were deployed along with nine pressure gauges of various sorts. Two of these pressure gauges collected spectral wave data as well as tidal data (one located just east of St. Mary's Inlet, the second within St. Mary's inlet--figure 2).

The various instruments used are described briefly below. Deployment periods are outlined in Table 1. The major types of equipment used were:

A. Current meters: Several different types of current meters were deployed for this experiment since not enough meters of any single type were available for our needs. Although this is an undesirable arrangement considering the multitude of different problems arising from each different type of meter, it was preferable to not having enough meters. The following types of current meters were used in this work:

1. AGA current meter system: Deployed in the southeast channel leading to King's Bay (figure 2), this WHOI-owned system is composed of an array of electromagnetic current meters deployed on a "seahorse." The current meters are Marsh McBirney 10.8 cm diameter probes, connected by cable through penetrators to an instrument casing holding sampling electronics constructed by Sea Data Corporation, in Newton, MA. The instrument was originally designed as a bottom boundary layer frame, but has been used most recently to examine vertical shear in the boundary layer without estimating log-layer profiles. The electromagnetic current meters are too imprecise to obtain accurate log-layer profiles (Aubrey and Trowbridge, 1985). This device was calibrated at WHOI prior to the experiment to provide up-to-date calibration factors.

Fig. 1. General location map for King's Bay/Cumberland Sound region.

KINGS BAY/CUMBERLAND SOUND MEAN LOW WATER

Fig. 2. Specific instrument locations for King's Bay/Cumberland Sound experiment.

TABLE 1: Summary of instrument deployment at King's Bay/
Cumberland Sound, Georgia and Florida

Instrument	Location	Date Deployed	Date Retrieved	Data Quality	Remarks
Sea Data 635-12	Buoy 22	18 June 1985	24 July 1985	Excellent	Wave/Tide Gauge
Sea Data 635-9	Buoy 10	18 June 1985	22 July 1985	Excellent	Wave Gauge
TDR S/N 136	Buoy 27	19 June 1985	25 July 1985	Excellent	Pressure/Temperature
TDR S/N 392	St. Mary's River	19 June 1985	25 July 1985	Excellent	Pressure/Temperature
TDR S/N 162	Buoy 10	18 June 1985	22 July 1985	Excellent	Pressure/Temperature
TDR S/N 390	Buoy 34	19 June 1985	24 July 1985	No Data	Pressure/Temperature
TDR S/N 163	Buoy 38	19 June 1985	22 July 1985	Excellent	Pressure/Temperature
TDR S/N 101	Marker 48	19 June 1985	23 July 1985	15 Days of Good Data	Pressure/Temperature
TDR S/N 391	Buoy 72	18 June 1985	23 July 1985	Excellent	Pressure/Temperature

TABLE 1 (continued)

Instrument	Location	Date Deployed	Date Retrieved	Data Quality	Remarks
AGA	Marker 48	19 June 1985	23 July 1985	Excellent	Current Meter Array
ACM-2 S/N 66	Buoy 38	19 June 1985	22 July 1985	No Data	Acoustic Current Meter
ACM-2 NCEL	Buoy 34	19 June 1985	24 July 1985	Excellent	Acoustic Current Meter
Aanderaa S/N 4944	Buoy 27	19 June 1985	25 July 1985	Poor	Current Meter, Temperature
Aanderaa S/N 815	St. Mary's River	19 June 1985	25 July 1985	Poor	Current Meter, Temperature
Aanderaa S/N 4957	Buoy 72	18 June 1985	23 July 1985	Good	Current Meter, Temperature, Transmissometer S/N 171
Aanderaa S/N 4958	NW King's Bay	18 June 1985	Lost	Lost	Current Meter, Temperature Transmissometer S/N 192 TDR S/N 340

2. Aanderaa current meters: Four Aanderaa recording current meter models 4 and 5 (RCM 4/5; see Aanderaa Instruments manual, July, 1983) were provided by NCEL for the experiment. These were deployed on simple, light-weight quadripod frames with weights attached to the feet of the quadripod. The current meter consists of a rotor and vane; the vane measures the direction of the flow, while the rotor measures the speed of the current. Although known to be subject to considerable error in velocity in the presence of waves, they operate reasonably well in high current regimes where waves are not a factor. The major drawback of these instruments in King's Bay is their susceptibility to fouling.

3. Neil Brown Acoustic Current Meters, ACM-2. Two ACM-2's were deployed during this field experiment, one each owned by NCEL and WHOI. Although large, unwieldy, and known to be subject to errors in wave-dominated areas, these instruments were expected to work well in King's Bay/Cumberland Sound where wave activity is minimal. The ACM-2 uses an acoustic travel-time sensor having two horizontal axes. The differential travel time between acoustic beams traveling in opposite directions along an acoustic pathway is related to the fluid velocity within the measuring volume. Assuming little flow disturbance due to the instrument, these ACM-2's provide reliable estimates of fluid velocity.

Two of these instruments were deployed within the primary dredged channel in Cumberland Sound connecting St. Mary's Inlet with King's Bay. Surface gravity waves in this portion of the Sound are sufficiently small compared to the depth of deployment that the ACM-2's are expected to perform well.

B. Pressure Sensors: All pressure sensors used to monitor tide and storm surge behavior in the King's Bay/Cumberland Sound region were Sea Data Corporation Temperature-depth recorders (TDR), model 1-A. NCEL provided two of these instruments, while WHOI provided six of these devices. All are

internally recording devices (using a 50' continuous loop tape) using a thermistor for temperature and a strain-gauge for pressure. Temperature accuracy is 0.1°C. Depth accuracy is approximately 1 cm sea water. All sensors were calibrated at WHOI following the experiment to provide up-to-date calibrations.

These instruments are contained in small PVC cylinders, approximately 15 cm in diameter and 30 cm long. They were attached on the same frames as the current meters to provide tidal data at the same time the current measurements were being made. All performed well during the experiment except two, one of which was destroyed along with an Aanderaa current meter when the Navy dropped several tons of chain on it during a hurricane exercise. The second unit (newly rebuilt at Sea Data) failed to return data.

All TDR's sampled at 5 minute intervals, and were set in the tide mode. The tide mode allows for internal averaging to minimize aliasing due to waves resulting from the coarse sampling interval.

◦ C. Profiling Current Meter: A profiling current meter was used for a 24-hour period within St. Mary's Inlet at the conclusion of the experiment, to evaluate the depth-varying tidal flows. These data are useful for estimating momentum balances and net transport from single point current meter measurements. Limited ship time precluded more extensive use of this profiling current meter system, which was provided by NCEL.

D. Transmissometers: Two Sea-Tech 5-cm path length transmissometers were deployed to estimate flux of suspended load past two northerly current metering sites. The Sea-Tech instruments use a modulated Light Emitting Diode (LED) and a synchronous detector to measure light transmission at 660 nm. The instrument is not sensitive to ambient light. It is temperature compensated and has good long term stability, according to the specifications. These

transmissometers were expected to foul during the experiment due to biological activity, but complex logistics precluded any regular inspection dives to clear the optics. These units are described in Bartz et al. (1978) and Zaneveld et al. (1980).

E. Wave Gauges: Two WHOI wave gauges were used in the experiment. The first, a Sea Data 635-9, was deployed on the seaward margin of the ebb tidal delta. Its current meter was not operational so only one-dimensional spectra were obtained during the experiment.

The second instrument was a Sea Data 635-12 wave gauge, measuring both waves and mean flows. This gauge was deployed in the middle of St. Mary's Inlet to measure possible wave effects and to document the tidal flows in this region. The data were logged on twin Sea Data cassette drives, providing ample space for recording over a month's worth of wave and tide data. These gauges are described in the literature by Aubrey (1981) and Aubrey and Hill (1984).

Both wave gauges use a Paroscientific quartz oscillator pressure gauge having an accuracy of millimeters of water equivalent. Directional properties of waves are derived from a two-axis Marsh-McBirney electromagnetic current meter (its properties are described in detail in Aubrey, Spencer and Trowbridge, 1984; Aubrey and Trowbridge, 1985). Each was calibrated before and after deployment to assure the best accuracy in estimated velocities.

F. Thermistors: Each of the two wave gauges and the TDR's contained a thermistor for measuring water temperature. Nominal accuracy for each of these thermistors is 0.1° Centigrade, although those on the wave gauges were more accurate. Given the large temperature signals in the shallow King's Bay/Cumberland Sound region, this accuracy is sufficient for most purposes.

G. Conductivity meters: Each Aanderaa current meter had an inductive cell conductivity instrument mounted with it. Range of these instruments was 0 to 77 mmho/cm, having a resolution of 0.1% of range and a calibration accuracy of ± 0.025 mmho/cm.

METHODS

Data analysis was similar for all instruments, although the initial processing varied depending on the type of instrument used. Data from each instrument were first read from the internal recording mechanism. These data were scaled and calibrations applied to yield physical units (pressure, velocity, temperature) from the digital data. These data were then plotted for bad point editing and assessment of data quality. This editing and assessment was done for all instruments.

Following plotting and assessment, data were averaged and subsampled to provide hourly estimates. These hourly estimates were used in a harmonic analysis program (Boon and Kiley, 1979; Aubrey and Speer, 1985) to evaluate the tidal response of the different sampling points. Since data records in general exceeded 29 days, the semidiurnal tidal constituents (N_2 , M_2 , S_2) could be resolved. For those data sets lasting less than 29 days for various reasons (data record ran out, signal quality degraded, transmissometer fouled, etc.), harmonic analyses were run on data sets of reduced length.

Output from the harmonic analysis for 29-day record lengths includes estimates of amplitude and phase of 25 tidal constituents. The amplitudes for these constituents are provided in meters, while the phases are relative local phases (not Greenwich phases). The local phases are all directly comparable because the same start time was used for all the analyses. Thus phase lags and amplitude decay can be evaluated throughout the estuary directly from these data.

Two diagnostic quantities used in this analysis include the amplitude ratio and the relative phase, both of which are indicative of nonlinear transfers through the nonlinear terms in the equations of motion (see Aubrey and Speer, 1985, for more discussion). The amplitude ratio:

$$A_{M_4} / A_{M_2}$$

is an indication of the degree of nonlinearity in the estuary. A high ratio of amplitude of forced to parent tide indicates strong nonlinear energy transfer. Note that this amplitude ratio can be for either sea surface or velocity, with velocity in general being more nonlinear than sea surface.

The second diagnostic is the relative phase between the parent tide(s) and the overtides or compound tides. These overtides and compound tides are one description of the types of distortion a tide undergoes through hydrodynamic interactions. Although not the sole possible representation of these hydrodynamic effects, they are convenient from a modeling standpoint. Just as the amplitude ratio depicts the degree of interaction, the relative phase is a diagnostic indicating which of the nonlinear terms in the equations is the most important. The relative phase for the M_2 tide and its first overtide, the M_4 tide, is:

$$\varphi_{M_4} = 2\varphi_{M_2} - \varphi_{M_4}$$

Similar equations can be deduced for the compound tides (see Aubrey and Speer, 1985; Aubrey, 1986).

Wave data were reduced differently than the normal time series data. Wave data were acquired in a burst mode, deriving a specific number of samples in a burst at specified intervals between bursts. These shorter, more dense time series were subjected to directional wave analysis using techniques described in Aubrey (1981) and Grosskopf et al. (1984). Output from these analyses include full directional wave spectra, separating the time scales and directional properties of the waves.

RESULTS

Results from the experiment will be described station-by-station, beginning with the offshore region and continuing into the far reaches of the estuary. A synthesis is provided in a later section.

Buoy 10: The first sampling station was buoy 10, located on the ebb tide delta approximately 2.1 nautical miles to the east of the eastern ends of the two jetties, in a water depth of approximately 12.8 m. A Sea Data 635-9 wave gauge and a Sea Data TDR-1A were deployed on a spider tripod at this location. Table 1 provides deployment and retrieval information for these gauges.

Pressure data were converted to sea surface elevation and analyzed. The TDR-1A provided information on tides and on temperature. Tidal data are available from harmonic analysis (figures 3 and 4; tables 2 and 3). The tidal signature is clean, showing clear spring/neap tidal cycles. Tidal range in this area is close to 1.85 m on the average. The dominant tide is the M_2 tide, the lunar semidiurnal constituent. It has a height of 0.90 meters, whereas the second largest tide (N_2) has a height of only 0.19 m. The M_2 tide accounts for 88.2% of the variance of the sea surface, whereas the N_2 accounts for only 3.9%. The forced tides are relatively small. The M_4/M_2 ratio is 2.1%, whereas the M_6/M_2 ratio is 0.7%. The relative M_4-M_2 phase is 1.1° . The forced fortnightly tide (MSf) has a height of about 3 cm and a relative phase of 153° . No other tidal constituents were particularly remarkable at this location.

Temperature time series (figure 4) reveals a gradual warming, then cooling of the near-bottom waters at Buoy 10. Superimposed on this gradual trend is a tidal signature, with higher temperatures associated with ebbing currents and water discharge from the warmer bay. Mean temperatures were near 26.5°C . Harmonic analysis of the temperature data indicates that the semidiurnal tide has the strongest impact of all other tidal harmonics, but still accounts for only 3% of the variance of the temperature data (accounting for a mean range of 0.2°C). Most of the temperature signal is lower frequency, not reflecting tidal processes.

KING'S BAY

June 19 - July 21, 1985

LEGEND
TDR s/n 162, BUOY#10

Fig. 3. Sea surface elevation at Buoy 10

TABLE 2: Sea surface harmonic analysis for Buoy 10.

LOCATION	Buoy 10	INSTRUMENT	TDR 162	Sea Surface
Start Date:	6/19	13.6 hrs		
Constituent		Range		Phase
M ₂		0.903		246.22
N ₂		0.190		118.77
M ₄		0.019		131.33
M ₆		0.006		175.27
MN ₄		0.009		213.09
MS ₄		0.010		207.64
MSf		0.030		195.52

Mean Value: 11.88

M₄/M₂ = 0.021

M₆/M₂ = 0.007

M₂-M₄ Phase = 1.1

97.8% of variance explained

KING'S BAY, BUOY #10 JUNE 19 - JULY 19, 1985

Fig. 4. Temperature at Buoy 10

TABLE 3: Temperature harmonic analysis for Buoy 10.

LOCATION Buoy 10 INSTRUMENT TDR 162 Temperature

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.157	70.18
N ₂	0.016	83.27
M ₄	0.037	150.11
M ₆	0.007	276.54
MN ₄	0.005	299.73
MS ₄	0.011	283.60
MSf	0.151	208.71

Mean Value: 26.47

M₄/M₂ = 0.238

M₆/M₂ = 0.044

M₂-M₄ Phase = 350.2

6.7% of variance explained

Fig. 4. Temperature at Buoy 10

The wave gauge provided information on frequency spectra on a two-hourly burst interval, sampling at 1 second intervals for 512 seconds during each burst. The surface wave activity was low in general during this experiment, rarely exceeding significant wave heights of 0.5 m. The time series of total energy, significant wave height, and modal period (figures 5 through 7) indicate just a few short periods of significant wave activity over the interval of measurement. The maximum significant wave height reached approximately 0.75 m around 25 June, 28 June, and 5 July. General background wave height here was about 0.4 m.

Peak (modal) wave period fluctuated significantly over the experiment. The cutoff period of 4 seconds limited reporting of wave periods smaller than this; the cutoff period results from the water depth at which the instrument was installed (waves attenuate with depth, with shorter period waves attenuating faster than longer period waves). Maximum peak period occurred at approximately 0.1 hz (10 seconds), indicating a more distant source for the waves. Intervals having the largest waves had peak periods between 4 and 7 seconds, indicating local wave generation.

Buoy 22: This sampling site was in the throat of St. Marys Inlet, directly north of the state park and Fort Clinch. A Sea Data 635-12 was deployed in this location operating in both a wave and a tide mode. In the tide mode, data are written every 7.5 minutes, representing integrated samples over the measurement interval. Data written in this continuous mode include pressure, temperature, velocity (two-axes), and time. In the wave mode burst data are acquired. Burst interval for this deployment was 4 hours, with 1024 seconds (17.1 min) of data acquired every burst at a sample rate of 1 hz.

Time series of sea surface elevation and along- and cross-channel velocities (figures 8 through 20) reveal a tidally-dominated environment, as one would expect. Neap and spring cycles are clear in the sea surface and

KING'S BAY 635-9 DATA JUNE/JULY, 1985

Fig. 5. Peak energy at Buoy 10, measured by Sea Data 635-9 wave gauge.

KING'S BAY 635-9 DATA JUNE/JULY, 1985

Fig. 6. Significant wave height at Buoy 10, measured by Sea Data 635-9 wave gauge.

KING'S BAY 635-9 DATA JUNE/JULY, 1985

Fig. 7. Modal wave period at Buoy 10, measured by Sea Data 635-9 wave gauge.

KING'S BAY, BUOY #22
JUNE-JULY, 1985*

Fig. 8. Sea surface elevation at Buoy 22.

KING'S BAY, BUOY #22
JUNE-JULY, 1985, U-VEL

Fig. 9. U-velocity (along-channel) at Buoy 22.

KING'S BAY, BUOY #22 JUNE-JULY, 1985, V-VEL

Fig. 10. V-velocity (cross-channel) at Buoy 22.

KING'S BAY, BUOY #22 JUNE-JULY, 1985

Fig. 11. Temperature at Buoy 22.

Fig. 12. U-velocity (along-channel) at Buoy 34.

Fig. 13. V-velocity (cross-channel) at Buoy 38.

KING'S BAY, BUOY #38

June 19, July 18

Fig. 14. Sea surface elevation at Buoy 38.

KING'S BAY, BUOY #38 JUNE 19 - JULY 18, 1985

Fig. 15. Temperature at Buoy 38.

KING'S BAY

June 19 - July 21, 1985

LEGEND
TDR s/n 101, BUOY #48

Fig. 16. Sea surface elevation at Buoy 48.

Fig. 17. Temperature at Buoy 48.

KING'S BAY

June 19 - July 21, 1985

LEGEND

TDR s/n 391, BUOY #72

Fig. 18. Sea surface elevation at Buoy 72.

KING'S BAY, BUOY #72, TDR JUNE 19 - JULY 18, 1985

Fig. 19. Temperature (TDR) at Buoy 72.

KING'S BAY, JUNE 19, 1985
AANDERAA #4957 BUOY #72

Fig. 20. Temperature (Aanderaa) at Buoy 72.

velocity plots. In the temperature signal (figure 11) the fortnightly cycle is also present, the water temperatures being warmer on the average during neap tides and lower during spring tides (when more cool ocean water is exchanged).

Harmonic analysis of sea surface elevation (table 4) reveals several interesting results. The sensor (deployed 1.86 m off the bottom in a water depth of 15.1 m) showed dominance of the M_2 tide, accounting for 91% of the variance in the sea surface (0.88 m). The next largest tide was the N_2 tide, accounting for only 3.6% of the variance of the sea surface. Forced tides are larger than outside the inlet, although not excessively so. M_4 is 4% the size of M_2 , while M_6 is 1.2% the size of M_2 . The relative M_2 - M_4 phase is 318° . MN_4 and MS_4 are relatively small.

Harmonic analysis of velocities (tables 5 and 6) reveals greater non-linearity, as expected. The down-channel velocity has a residual velocity of 3 cm/sec out of the estuary, providing an estimate of freshwater outflow or tidal residual flow. The M_2 tide is the major constituent, accounting for 87% of the variability of the flow, a magnitude of 98.2 cm/sec. As in sea surface, N_2 is the second dominant constituent, accounting for 5% of the variability of the flow. Non-linear terms are greater in velocity than sea surface, with M_4/M_2 ratio of 0.17 and M_6/M_2 ratio of 0.05. Relative M_4 - M_2 phase is 47° . MN_4 , the second largest nonlinear term expected from scaling arguments, has a magnitude of 4.9 cm/sec.

The cross-axis velocity has little information (table 6). The mean cross-channel flow velocity is 2 cm/sec towards the middle of the channel. Variance in the signal is low. The 25 tidal constituents account for only 33 % of the variability of the flow, demonstrating the disorganized nature of this low-variability flow.

TABLE 4: Sea surface harmonic analysis for Buoy 22.

LOCATION Buoy 22 INSTRUMENT 635-12 Sea Surface

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.880	258.45
N ₂	0.175	133.10
M ₄	0.035	199.30
M ₆	0.011	140.95
MN ₄	0.011	95.69
MS ₄	0.008	253.36
MSf	0.033	192.61

Mean Value: 13.24

M₄/M₂ = 0.040

M₆/M₂ = 0.012

M₂-M₄ Phase = 317.6

99.6% of variance explained

TABLE 5: U-velocity (along-channel) harmonic analysis for Buoy 22.

LOCATION	Buoy 22	INSTRUMENT	635-12	U-Velocity
Start Date:	6/19	13.6 hrs		
Constituent	Range	Phase		
M ₂	0.982	11.09		
N ₂	0.235	258.85		
M ₄	0.165	334.96		
M ₆	0.045	275.09		
MN ₄	0.049	231.54		
MS ₄	0.022	2.84		
MSf	0.016	334.14		

Mean Value: 0.03

M₄/M₂ = 0.168

M₆/M₂ = 0.046

M₂-M₄ Phase = 47.2

98.5% of variance explained

TABLE 6: V-velocity (cross-channel) harmonic analysis for Buoy 22.

LOCATION Buoy 22 INSTRUMENT 635-12 V-Velocity

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.014	12.96
N ₂	0.008	131.74
M ₄	0.014	286.93
M ₆	0.009	325.08
MN ₄	0.015	180.92
MS ₄	0.004	318.58
MSf	0.008	124.28

Mean Value: -0.02

M₄/M₂ = 0.985

M₆/M₂ = 0.660

M₂-M₄ Phase = 99.0

33.1% of variance explained

Near bottom temperature (table 7) shows results contrasting with data from buoy 10. Average temperature in St. Mary's Inlet was 21.4° centigrade, as opposed to the 26.5° temperature in the offshore waters. This result is unexpected since one would expect the temperature near the estuary to be higher due to greater warming. The primary warming has periods of 2 weeks (fortnightly, accounting for 32% of the variability in the data) and semi-diurnal (M_2 , accounting for 16% of the data variability). The M_2 signature has a value of 0.2 degrees in temperature, whereas the MSF has a 0.3 degree range. No other time scales appear important in this analysis. Once again, warmest temperatures occur during neap tides, lowest during spring tides.

Buoy 34: Proceeding up the channel through Cumberland Sound towards Kings Bay the next deployment is at Buoy 34, consisting of a Neil Brown Acoustic Current Meter (ACM-2) and a TDR (serial number 390). The TDR did not work correctly due to a tape-drive malfunction (even though it was a newly rebuilt unit), so only the ACM-2 data were analyzed.

Current direction at buoy 34 was bimodal, with little cross-channel activity. The signal was primarily tidal (figures 12 and 13), with small residuals. There was a net down-channel residual flow of 3.5 cm/sec averaged over the duration of the experiment, and a residual of 5.8 cm/sec towards the west (reflecting the outflow from the eastern branch of Cumberland Sound). The along channel currents were tidally dominated (tables 8 and 9), having 83% of the variance taken up in the M_2 tide (44. cm/sec amplitude, average); 6.5% of the variance was accounted for by the N_2 tide (12.2 cm/sec, average). The overtides were significant, with the M_4 tide reaching 9.2% of the M_2 tide (0.7% of the total variability), and the M_6 tide reaching 7.7% of the total tide. The M_4 - M_2 relative phase was 353°, while the MN_4 relative phase was 339°.

TABLE 7: Temperature harmonic analysis for Buoy 22.

LOCATION	Buoy 22	INSTRUMENT	635-12	Temperature
Start Date:	6/19	13.6 hrs		
Constituent		Range		Phase
M ₂		0.217		112.56
N ₂		0.060		155.23
M ₄		0.024		227.85
M ₆		0.015		165.45
MN ₄		0.012		166.05
MS ₄		0.004		244.98
MSf		0.312		182.35

Mean Value: 21.40

M₄/M₂ = 0.112

M₆/M₂ = 0.069

M₂-M₄ Phase = 357.3

53.0% of variance explained

TABLE 8: U-velocity (along-channel) harmonic analysis for Buoy 34.

LOCATION Buoy 34 INSTRUMENT NBIS ACM-2 U-Velocity

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	44.047	12.75
N ₂	12.220	250.91
M ₄	4.033	32.90
M ₆	3.484	240.46
MN ₄	0.940	284.82
MS ₄	0.555	6.96
MSf	3.739	315.93

Mean Value: 3.48

M₄/M₂ = 0.092

M₆/M₂ = 0.077

M₂-M₄ Phase = 352.6

94.3% of variance explained

TABLE 9: V-velocity (cross-channel) harmonic analysis for Buoy 34.

LOCATION	Buoy 34	INSTRUMENT	NBIS ACM-2	V-Velocity
Start Date:	6/19	13.6 hrs		
Constituent	Range	Phase		
M ₂	1.821	266.90		
N ₂	0.578	188.70		
M ₄	3.267	20.24		
M ₆	0.714	55.50		
MN ₄	0.861	288.92		
MS ₄	1.192	82.44		
MSf	1.101	27.18		

Mean Value: 5.75
M₄/M₂ = 1.794
M₆/M₂ = 0.392
M₂-M₄ Phase = 153.6

13.2% of variance explained

In the cross channel axis, M_4 dominated the tidal signal, accounting for 4.6% of the total variance (3.3 cm/sec). These signals are clearly less energetic than the along-channel flows. Cross-channel data showed some spikes in readings, which may be related to various types of passing boat traffic. The cross-channel variability is linked to non-tidal forcing in large part, as the 25 primary tidal constituents account for only 13% of the cross-channel variability.

Buoy 38: Two instruments were deployed at Buoy 38: another Neil Brown ACM-2 and a TDR (S/N 163). The Neil Brown failed shortly after deployment, so no usable data were retrieved from this instrument. The TDR operated well, deployed 1 meter off the bottom in a water depth of 12 meters.

The sea surface record is tidally dominated (figure 14; table 10), with the M_2 tide the largest constituent, accounting for 90% of the variability in sea surface (0.97 m tidal height). The second major constituent is the N_2 tide, having a height of 0.19 m, or 3.4 % of the variability in sea surface. The overtides are small, the M_4/M_2 ratio being 2.8 % and the M_6/M_2 ratio being 0.9%. The relative phase of M_4-M_2 is 252° . Since the instrument was deployed only one meter from the bottom, these represent near bottom conditions which are most critical for resuspension and sediment transport considerations.

Temperature measured by this TDR exhibits interesting relationships (figure 15; table 11). The mean temperature over the period of measurement was 27.9°C , increasing slightly over the period of study. The largest variation in temperature was on a fortnightly cycle, exhibiting a temperature range of 0.6°C on that time period (44% of the variability in temperature over this month). The M_2 constituent exhibited a 0.5°C range, or 26% of the total variability. The diurnal warming/cooling trend is less significant than M_2

TABLE 10: Sea surface harmonic analysis for Buoy 38.

LOCATION	Buoy 38	INSTRUMENT	TDR 390	Sea Surface
Start Date:	6/19	13.6 hrs		
Constituent		Range		Phase
M ₂		0.966		265.21
N ₂		0.187		141.43
M ₄		0.027		278.45
M ₆		0.009		107.71
MN ₄		0.018		212.82
MS ₄		0.013		303.14
MSf		0.028		222.24

Mean Value: 10.95

M₄/M₂ = 0.028

M₆/M₂ = 0.009

M₂-M₄ Phase = 252.0

99.1% ov variance explained

TABLE 11: Temperature harmonic analysis for Buoy 38.

LOCATION	Buoy 38	INSTRUMENT	TDR 390	Temperature
Start Date:	6/19	13.6 hrs		
Constituent		Range		Phase
M ₂		0.497		104.67
N ₂		0.132		126.54
M ₄		0.045		103.87
M ₆		0.020		81.15
MN ₄		0.019		213.09
MS ₄		0.014		347.32
MSf		0.645		184.11

Mean Value: 27.87

M₄/M₂ = 0.091

M₆/M₂ = 0.041

M₂-M₄ Phase = 105.5

74.7% of variance explained

tidal exchange, since all diurnal constituents are small. No other single constituent accounted for more than 2% of the temperature variability at this location.

Marker #48: The next deployment was north along Cumberland Sound, in the southeast corner of King's Bay. Here the AGA current meters were deployed along with a TDR (S/N 101) in a water depth of approximately 7 m. The AGA data show a strong tidal signal, complicated by the burst sampling used in the deployment. The AGA had limited sampling duration due to its numerous probes, so data were acquired at 3 hour burst intervals, for a duration of 2050 seconds (34.2 minutes). Since these data are not directly related to the tidal phasing problem, they are not discussed in detail here.

The TDR experienced some difficulties in the experiment as well, ceasing to work after approximately 15 days (figures 16 and 17; tables 12 and 13). Consequently the analysis of this data was restricted to the first 14.7 days of the experiment, decreasing the resolution of the tidal harmonic analysis. Analysis of the shorter (14.7-day) record indicated a dominance of the M_2 constituent, accounting for 89% of the variability, a height of 1.05 m. This represents an increase in M_2 range over the length of the estuary, a possible effect of the interaction of Cumberland Sound with the tidal waters to the north. This amplification was noted in numerical work by WES. Nonlinear transfer was again weak in this location. The M_4/M_2 and M_6/M_2 ratios are small here, with M_4 reaching only 4 cm in height. Relative M_4-M_2 phase was 155° .

Temperature data were similarly restricted to 15 days of analysis. Mean temperature over this interval was 27.5°C , increasing slightly over the period of measurement. The temperature signal was dominated by a fortnightly modulation, poorly resolved in this analysis. Highest temperatures were during neap

TABLE 12: Sea surface harmonic analysis for Buoy 48.

LOCATION Buoy 48 INSTRUMENT TDR 101 Sea Surface

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	1.050	265.00
N ₂		
M ₄	0.041	304.82
M ₆	0.016	110.97
MN ₄		
MS ₄		
MSf		

Mean Value: 6.29

M₄/M₂ = 0.039

M₆/M₂ = 0.015

M₂-M₄ Phase = 225.2

91.1% of variance explained

TABLE 13: Temperature harmonic analysis for Buoy 48.

LOCATION Buoy 48 INSTRUMENT TDR 101 Temperature

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.178	3.47
N ₂		
M ₄	0.055	49.81
M ₆	0.028	236.51
MN ₄		
MS ₄		
MSf		

Mean Value: 27.53

M₄/M₂ = 0.309

M₆/M₂ = 0.157

M₂-M₄ Phase = 317.1

2.1% of variance explained

tides, when tidal exchange was restricted. Temperature data were noisy and had to be edited during the analysis (figure 17 shows the non-corrected, noisy temperature data). The M_2 tide was the dominant tide in the analysis, accounting for a 0.2°C temperature variation.

NW King's Bay: An Aanderaa (4958) and a TDR (S/N 340) were deployed in the northwest sector of King's Bay, at a depth of 14 m. These instruments were buried during the period of deployment by heavy chain deployed by the Navy during a hurricane watch. The instruments could not be recovered intact following their destruction, so no data were obtained from this location.

Buoy 72: Located at the northern extreme of Cumberland Sound along the intercoastal waterway, this was the northerly current meter of this experiment. An Aanderaa meter (S/N 4957) was deployed with a TDR (S/N 391), at a depth of 5 m. A Sea-Tech transmissometer (S/N 171) was deployed with these two other instruments.

Sea surface varied tidally throughout the deployment (figure 18; table 14). The M_2 tide accounted for 91% of the total variability of the tide, having a height of 99 cm. The next largest tide again was the N_2 tide, having a height of 0.19 m. The 25 tidal constituents represent about 99.2% of the variability in the sea surface data.

The tide is not very nonlinear, with the M_4 and M_6 constituents very small (ratios of M_4 to M_2 are 2.4% and 1.5% respectively). Relative phases are 231° for both the M_4 and MS_4 compound tides. Relative phase for MN_4 is 188° .

Temperature data show a similar pattern to other temperatures within the experiment (figures 19-20; tables 15 and 16). The average TDR temperature was 28.4°C , higher than the other gauges. The temperature rose slightly throughout the experiment. The largest tidal constituent was the MS_f (fortnightly),

TABLE 14: Sea surface harmonic analysis for Buoy 72.

LOCATION Buoy 72 INSTRUMENT TDR 391 Sea Surface

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	0.986	270.06
N ₂	0.191	147.81
M ₄	0.024	309.05
M ₆	0.015	139.75
MN ₄	0.020	230.37
MS ₄	0.012	312.52
MSf	0.018	225.98

Mean Value: 4.35

M₄/M₂ = 0.024

M₆/M₂ = 0.015

M₂-M₄ Phase = 231.1

99.2% of variance explained

TABLE 15: Temperature (TDR) harmonic analysis for Buoy 72.

LOCATION Buoy 72 INSTRUMENT TDR 390 Temperature

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.159	86.70
N ₂	0.042	126.02
M ₄	0.045	2.58
M ₆	0.025	303.31
MN ₄	0.015	353.85
MS ₄	0.004	137.72
MSf	0.700	183.44

Mean Value: 28.37

M₄/M₂ = 0.283

M₆/M₂ = 0.156

M₂-M₄ Phase = 170.8

75.5% of variance explained

TABLE 16: Temperature (Aanderaa) harmonic analysis for Buoy 72.

LOCATION	Buoy 72	INSTRUMENT	Aanderaa 4957	Temperature
Start Date:	6-19	13.6 hrs		
Constituent	Range		Phase	
M ₂	0.156		86.98	
N ₂	0.037		127.82	
M ₄	0.047		358.92	
M ₆	0.024		305.31	
MN ₄	0.013		339.69	
MS ₄	0.005		206.03	
MSf	0.694		183.60	

Mean Value: 28.31

M₄/M₂ = 0.300

M₆/M₂ = 0.157

M₂-M₄ Phase = 175.0

74.5% of variance explained

having a range of 0.7°C, accounting for 65% of the variability. The second largest influence was the M₂ tide, accounting for 3% of the total variability and 0.16°C in range. The temperature increased notably following the 15th day of deployment. Whether this increase was related to the tidal conditions or to greater freshwater outflow cannot be determined with these limited data. Data from the Aanderaa temperature sensor (figure 20; table 16) gave results nearly identical to those of the TDR sensor.

Transmission data were reasonable for the first two weeks of deployment, following which they decayed rapidly (figure 21). This record showed approximately 70% transmission during the first week of the experiment, reducing to nearly 50% before the rapid decrease in transmission at the end of the second week. This drop off could result from biofouling or from an increase in freshwater inflow and associated suspended material. It is not possible to determine with great certainty which of these explanations is correct. Salinity and temperature data do suggest different freshwater inflow conditions during the last two weeks of the experiment, so the change in transmissometer signal may result from both biofouling and increased sediment load.

To interpret these transmissometer data, the behavior of light transmission must be understood. The transmissometer sensor registers a voltage (I) proportional to the light intensity at a distance x from the emitter (light source):

$$I = I_0 e^{-\beta x}$$

where:

I = voltage generated at the receiver

I₀ = voltage at the emitter

β = attenuation coefficient (units of inverse meters)

x = distance along the beam (units of meters)

AANDERRA #4957 KING'S BAY BUOY #72

Fig. 21. Light transmission at Buoy 72.

Note that β is made up of three different components (Moody et al., 1985), which include both absorption and scattering effects:

$$\beta = \beta_w + \beta_p + \beta_y$$

where:

β = total attenuation

β_w = attenuation from pure water

β_p = attenuation from suspended matter

β_y = attenuation from dissolved organic matter.

In many studies the amount of dissolved organic matter is assumed to be negligible; this is not the case in King's Bay. Since we don't know the concentration of dissolved organic matter, errors might be large if assumed to be zero. This problem is largely eliminated by use of a red light source (wavelength of 660 nm), at which wavelength the attenuation of yellow water (organic material) is negligible. If we assume we can measure the transmission in pure water with an equal amount of dissolved organic matter (I_{wy}), we can then calculate the light attenuation coefficient for suspended matter:

$$\beta_p = (x^{-1}) \ln(I/I_{wy})$$

The suspended particle attenuation coefficient, β_p , for a specified particle diameter, D_i , is related to the number of particles, N , per unit volume and to the cross-sectional area by (Moody et al., 1985; Spinrad et al., 1983):

$$\beta_p = NQ\pi D_i^2/4$$

where Q is an effective area coefficient for light attenuation. Assuming that particles have density ρ_s and are spherical, the suspended matter concentration can be expressed in terms of N to yield a relation between suspended matter concentration in size class i to the corresponding light attenuation coefficient, β_{p1} :

$$C_i = (2 \rho_s D_i/3Q) \beta_{p1} = B_i \beta_{p1}$$

where C_i is the suspended matter concentration for size class i .

Moody et al. (1985) show the concentration regression slope B_i to be linearly related to the particle size, for a single size class of particles:

$$B_i = 1.12 D_i$$

For mixtures, this simple equation does not hold, requiring the following approximation:

$$C_t = B_{avg} \beta_t$$

where β_t is the sum of the attenuation coefficients for each size class. The concentration of each size class can be represented as the percentage, P_i of each size class in the total sample, to yield the following:

$$B_{avg} = (\sum \{P_i/B_i\})^{-1}$$

Using the results for the unimodal studies, the average calibration slope can be represented as:

$$B_{avg} = 1.12 (\sum \{P_i/D_i\})^{-1}$$

No analyses of particle size distributions of Cumberland Sound suspended sediments were available at the time of this report. If such become available in the future, the data can be reduced from transmission to suspended matter concentrations, C . Calibration on the deck before deployment indicated a reading of 4.712 volts DC in air, with an offset of 0.003 volts DC. No readings were taken in water immediately prior to deployment, but the previous calibration gave a clear water reading of 960. Figure 21 provides measurements of transmission as a ratio of the in situ reading to the calibration reading in clear water.

Salinity data were acquired during the experiment, measured by a conductivity cell and corrected to salinity. Conductivity worked well for the first 12 days of deployment (figures 22 and 23), yielding an average salinity of about 32 ppt. Following that, the salinity dropped to approximately 20 ppt in an interval of two days, decreasing to about 18 ppt by the end of the month.

KING'S BAY, BUOY #72 AANDERAA #4957

Fig. 22. Conductivity at Buoy 72.

KING'S BAY, BUOY #72 AANDERAA #4957

Fig. 23. Salinity at Buoy 72.

TABLE 17: Salinity harmonic analysis for Buoy 72.

LOCATION Buoy 72 INSTRUMENT Aanderaa 4957 Salinity

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.035	294.81
N ₂	0.145	182.39
M ₄	0.048	299.50
M ₆	0.013	194.62
MN ₄	0.014	51.70
MS ₄	0.055	242.31
MSf	2.423	250.17

Mean Value: 25.74

M₄/M₂ = 1.364

M₆/M₂ = 0.358

M₂-M₄ Phase = 290.1

61.1% of variance explained

The source of this salinity drop is likely increased freshwater inflow. The timing of this freshening corresponds to the reduction in transmission at this location. Alternately, the salinity drop may suggest instrument malfunction, although the concurrence of the transmission and salinity drop more strongly support an interpretation of increased, turbid freshwater inflow. This interpretation is supported by measurements at other locations. No time series of vertical sections were taken at any of these locations, nor were any independent measurements made, so it is not possible to rule out instrumental errors completely.

Harmonic analysis of salinity (table 17) indicates a mean value for salinity over the interval of deployment of 25.7 ppt. The tidal signature for salinity was negligible, the largest influence being the apparent fortnightly variability, accounting for 61% of the variability of the entire data set. The remainder of the variability was accounted for in the large change in salinity around the fifteenth day of record.

Velocity data (figures 24 and 25) provide some insight into currents at buoy 72. The current meter apparently worked well until the 16th or 17th day, following which current meter performance was seriously degraded. The reason for this degradation is most likely biofouling or tilt of the mounting frame. Prior to that time, the tidal signature was clear, dominating the spectrum. The north-south velocity exceeded the east-west velocity, to be expected with the geometry of this location. The east-west axis of velocity showed no tidal signature in the 15-day harmonic analysis results (tables 18 and 19), accounting for only 2% of the variability of the data. The north-south axis was dominantly tidal, with the M_2 tide accounting for 86% of the variability in the data set. Tidal velocities here reached 23 cm/sec in amplitude, easily energetic enough to transport sand and finer size material (shear velocities were in excess of critical shear velocities). Overtides were negligible at this location, having no significant energies associated with them.

AANDERAA #4957 KING'S BAY, BUOY #72

Fig. 24. U-velocity (cross-channel) at Buoy 72.

TABLE 18: U-velocity (cross-channel) harmonic analysis for Buoy 72.

LOCATION Buoy 72 INSTRUMENT Aanderaa 4957 U-Velocity

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	0.335	144.21
N ₂		
M ₄	0.331	225.12
M ₆	0.167	303.06
MN ₄		
MS ₄		
MSf		

Mean Value: -1.00

M₄/M₂ = 0.988

M₆/M₂ = 0.499

M₂-M₄ Phase = 63.3

2.0% of variance explained

AAANDERAA #4957 KING'S BAY, BUOY #72

Fig. 25. V-velocity (along-channel) at Buoy 72.

TABLE 19: V-velocity (along-channel) harmonic analysis for Buoy 72.

LOCATION	Buoy 72	INSTRUMENT	Aanderaa 4957	V-Velocity
Start Date:	6-19	13.6 hrs		
Constituent	Range	Phase		
M ₂	46.071	8.06		
N ₂				
M ₄	3.470	20.02		
M ₆	3.316	279.76		
MN ₄				
MS ₄				
MSf				
Mean Value:	2.33			
M ₄ /M ₂	= 0.075			
M ₆ /M ₂	= 0.072			
M ₂ -M ₄ Phase	= 356.1			

87.4% of variance explained

Mean monthly current velocity was directed towards the south (ebb flow), at an average rate of 2.3 cm/sec. This indicates a net freshwater flux from the Crooked River to Cumberland Sound.

St. Mary's River: The next station was the entrance to St. Mary's River, adjacent to the town of St. Mary's, Georgia (figure 2). This instrument tripod was deployed in a water depth of approximately 14.5 m, and included an Aanderaa RCM 4/5, a pressure sensor, thermistor, and a conductivity cell. These instruments were mounted on an aluminum deployment frame, subject to possible movement during periods of high velocity. This movement is not expected with currents less than 50 cm/sec.

The surface tide at St. Mary's River is distinctly semi-diurnal, having a large spring/neap cycle (figure 26). 91% of the sea surface variability is contained within the M_2 tide (a tidal range of 95 cm - table 20). Total tidal height is 1.93 meters. The second largest tide is the N_2 tide, accounting for 18 cm of tidal range. The nonlinear ratios are low, 2.7% and 0.6% for M_4 and M_6 , respectively. Relative M_2 - M_4 phase is 240° .

Near bottom temperature shows a tidal dominance as well, with some low-frequency, gradual warming superimposed (figures 27 and 28). Two sets of temperature data were available. Temperature measured on the TDR and on the Aanderaa show a remarkable similarity. Mean temperature of Aanderaa data was 27.6°C , while mean temperature for the TDR was 27.5°C (tables 21 and 22). Harmonic analyses for both data sets were virtually identical, indicating that 28% of the variability in the data is contained in the M_2 tide (0.52°C), and 34% contained in a fortnightly modulation (0.57°C). Following day 15 a gradual increase in temperature occurred, accompanied by no decrease in tidal signature. This indicates an event (or variability) which was consistent with the concept of tidal dominance.

KING'S BAY

June 19 - July 21, 1985

LEGEND
TDR s/n 392, St. Mary's Entrance

Fig. 26. Sea surface elevation at St. Mary's River.

TABLE 20: Sea surface harmonic analysis for St. Mary's River.

LOCATION St. Mary's INSTRUMENT TDR 392 Sea Surface

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.948	262.69
N ₂	0.182	137.18
M ₄	0.026	285.35
M ₆	0.006	94.19
MN ₄	0.016	210.90
MS ₄	0.012	296.81
MSf	0.025	199.87

Mean Value: 14.09

M₄/M₂ = 0.027

M₆/M₂ = 0.006

M₂-M₄ Phase = 240.0

99.5% of variance explained

KING'S BAY, ST. MARY'S JUNE 19 - JULY 18, 1985, TDR

Fig. 27. Temperature (TDR) at St. Mary's River.

TABLE 21: Temperature (TDR) harmonic analysis for St. Mary's River.

LOCATION St. Mary's INSTRUMENT TDR 392 Temperature

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	0.519	110.03
N ₂	0.108	139.26
M ₄	0.061	70.39
M ₆	0.039	193.15
MN ₄	0.023	117.58
MS ₄	0.024	207.27
MSf	0.573	181.01

Mean Value: 27.47

M₄/M₂ = 0.117

M₆/M₂ = 0.076

M₂-M₄ Phase = 149.7

68.6% of variance explained

KING'S BAY JUNE 19, 1985
 AANDERAA #815, ST. MARY'S

Fig. 28. Temperature (Aanderaa) at St. Mary's River.

TABLE 22: Temperature (Aanderaa) harmonic analysis for St. Mary's River.

LOCATION St. Mary's INSTRUMENT Aanderaa 815 Temperature

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	0.524	110.82
N ₂	0.108	139.24
M ₄	0.062	68.89
M ₆	0.040	197.69
MN ₄	0.019	122.19
MS ₄	0.024	217.52
MSf	0.578	181.08

Mean Value: 27.63
M₄/M₂ = 0.118
M₆/M₂ = 0.075
M₂-M₄ Phase = 152.8

68.7% of variance explained

Salinity (figures 29 and 30) shows an interesting pattern, perhaps suggesting degradation of the sensor through time or freshwater inflow. The salinity during the first 14 days is approximately 34 ppt, with a strong tidal signature. Following the 14th day, the salinity decreased to about 28 ppt, and finally down to 24 ppt on the 28th day. The gradual decline suggests possible sensor malfunction, while the undiminished tidal salinity signature indicates the instrument worked well. With this unaffected tidal response, one must believe the instrument worked well. With this assumption, the instrument indicates a gradual freshening of the estuary beginning about day 12 and continuing to the end of the deployment. Harmonic analysis (table 23) shows salinity to be tidally controlled, as 72% of the salinity variability is accounted for in the 25 dominant tidal constituents. The dominant tide is the M_2 , accounting for 1.5 ppt in salinity, or 39% of the total salinity variation. The largest constituent was the fortnightly tide, accounting for 1.3 ppt, or 28.5% of the data variability. Mean salinity over the entire period of deployment was 29.8 ppt.

Interestingly, salinity showed a strong forced tidal response, with the M_4/M_2 ratio being 11.5% and the M_6/M_2 ratio being 9.0%. This suggests that the surface tidal asymmetry may be impacting the salinity field strongly.

Currents were measured using an Aanderaa current meter (S/N 815 - figures 31 and 32). Current meter performance deteriorated after about eight days, suggesting the meter may have been displaced or fouled. During the period when the meter was operable (see figures 31 through 32), the tidal flow was approximately 20 cm/sec in amplitude. Following the eighth day, the recorded tidal amplitude decreased drastically and was not reliable. Harmonic constants and phasing are not presented here because of the poor quality of the data set. During the eight operable days, the mean velocity was to the east, in an ebb direction with a speed of about 2 cm/sec.

KING'S BAY, ST. MARY'S AANDERAA #815

Fig. 29. Salinity at St. Mary's River.

TABLE 23: Salinity harmoinc analysis for St. Mary's River.

LOCATION St. Mary's INSTRUMENT Aanderaa 815 Salinity

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	1.549	246.32
N ₂	0.224	95.75
M ₄	0.179	274.15
M ₆	0.139	239.90
MN ₄	0.073	192.64
MS ₄	0.067	276.20
MSf	1.328	206.19

Mean Value: 29.84
M₄/M₂ = 0.115
M₆/M₂ = 0.090
M₂-M₄ Phase = 218.5

72.0% of variance explained

KING'S BAY, ST. MARY'S ANDERAA #815

Fig. 30. Conductivity at St. Mary's River.

ANDERAA #815
KING'S BAY, ST. MARY'S

Fig. 31. U-velocity (cross-channel) at St. Mary's River.

Fig. 32. V-velocity (along-channel) at St. Mary's River.

Buoy 27: The final deployment was at Buoy 27, located in the Amelia River south of the entrance to Cumberland Sound. This location was the site for an Aanderaa current meter (S/N 4944), a conductivity cell, two temperature gauges (one on the Aanderaa, one on the TDR), and a pressure gauge (TDR S/N 136). Deployment depth was approximately 12 m MSL.

The surface tide (figure 33) was again distinctly semidiurnal, showing clear neap/spring tides. The dominant tide is the M_2 tide, accounting for 91% of the data variability (0.92 m in height - table 24). Total tidal range is approximately 1.9 m. The second largest constituent was the N_2 tide. Overtides were small, accounting for 2.5% and 0.7% of the M_2 tide, for M_4 and M_6 respectively. Relative M_2 - M_4 phase was 263° , again indicating ebb dominance.

Temperature was measured both with the Aanderaa and the TDR (figures 34 and 35). Mean temperature over the deployment interval for the Aanderaa was 27.5°C , and for the TDR was 27.6°C (tables 25 and 26). Details of the two records show remarkable agreement. Harmonic analysis results for the two sensors are nearly identical as well. Fortnightly temperature fluctuations account for 34% of the variability in temperature (0.56°C), with the M_2 tide following close behind with 22% of the variability (0.44°C range). The M_4 tide accounted for 26% of the M_2 temperature signal, suggesting considerable nonlinearity in temperature.

Salinity shows strong tidal control superimposed over a gradually decreasing mean salinity (figures 36 and 37). Mean salinity is near 34 ppt for the first 8 days of deployment, followed by a gradual decline to nearly 18 ppt by the end of the deployment. The tidal signature does not decline over the course of the experiment, indicating that the salinity decline is real. Furthermore, the salinity decline occurs at the same time as declines at the other instrument locations. This can indicate either of two things: the

KING'S BAY, BUOY #27 June 19 - July 18

Fig. 33. Sea surface elevation at Buoy 27.

TABLE 24: Sea surface harmonic analysis for Buoy 27.

LOCATION Buoy 27 INSTRUMENT TDR 136 Sea Surface

Start Date: 6/19 13.6 hrs

Constituent	Range	Phase
M ₂	0.915	260.25
N ₂	0.180	134.20
M ₄	0.023	257.14
M ₆	0.007	101.86
MN ₄	0.013	193.06
MS ₄	0.012	281.01
MSf	0.013	274.65

Mean Value: 11.74

M₄/M₂ = 0.025

M₆/M₂ = 0.007

M₂-M₄ Phase = 263.4

99.6% of variance explained

KING'S BAY, BUOY #27 JUNE 19 - JULY 18, 1985, TDR

Fig. 34. Temperature (TDR) at Buoy 27.

TABLE 25: Temperature (TDR) harmonic analysis for Buoy 27.

LOCATION Buoy 27 INSTRUMENT TDR 136 Temperature

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	0.440	85.92
N ₂	0.125	136.76
M ₄	0.113	37.63
M ₆	0.028	173.37
MN ₄	0.049	97.90
MS ₄	0.012	264.51
MSf	0.562	179.03

Mean Value: 27.56

M₄/M₂ = 0.257

M₆/M₂ = 0.064

M₂-M₄ Phase = 134.2

64.8% of variance explained

KING'S BAY, JUNE 19, 1985 AANDERAA #4944, BUOY #27

Fig. 35. Temperature (Aanderaa) at Buoy 27.

TABLE 26: Temperature (Aanderaa) harmonic analysis for Buoy 27.

LOCATION Buoy 27 INSTRUMENT Aanderaa 4944 Temperature

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	0.444	85.48
N ₂	0.121	138.50
M ₄	0.116	39.70
M ₆	0.031	175.64
MN ₄	0.048	99.38
MS ₄	0.016	267.40
MSf	0.557	178.65

Mean Value: 27.51

M₄/M₂ = 0.261

M₆/M₂ = 0.069

M₂-M₄ Phase = 131.3

63.7% of variance explained

KING'S BAY, BUOY #27 AANDERAA #4944

Fig. 36. Salinity at Buoy 27.

TABLE 27: Salinity harmonic analysis for Buoy 27.

LOCATION Buoy 27 INSTRUMENT Aanderaa 4944 Salinity

Start Date: 6-19 13.6 hrs

Constituent	Range	Phase
M ₂	0.787	231.52
N ₂	0.087	128.27
M ₄	0.164	125.61
M ₆	0.113	215.10
MN ₄	0.030	226.54
MS ₄	0.044	207.04
MSf	0.795	285.33

Mean Value: 27.43

M₄/M₂ = 0.208

M₆/M₂ = 0.143

M₂-M₄ Phase = 337.4

29.2% of variance explained

KING'S BAY, BUOY #27 AANDERAA #4944

Fig. 37. Conductivity at Buoy 27.

instruments all fouled at approximately the same time, or the entire estuary became fresher at approximately the same time. All samples of salinity are near-bottom measurements, indicating that the entire water column also became fresher, assuming stable density stratification. Harmonic analysis (table 27) of salinity data indicates that little of the variability is due to tidal action. The largest tidal dominance is in the fortnightly tide, accounting for 0.80 ppt or 14% of the data variability. The M_2 tide accounts for 13% of the data variability, or 0.79 ppt in salinity. Mean salinity over the 29-day deployment interval was 27.4 ppt.

The Aanderaa current meter deployed at this location did not perform well during the deployment. The tidal currents were not adequately resolved, exhibiting noise and data that are not consistent with the salinity and temperature data. Although difficult to resolve, the most credible interpretation is that the current meter did not work correctly.

INTERPRETATION AND CONCLUSIONS

Several features of the tidal response of King's Bay/Cumberland Sound stand out. The tide is not as nonlinear as many other estuaries studied along the U.S. east coast (e.g., Aubrey and Speer, 1985; Speer and Aubrey, 1985; Aubrey, 1986; Aubrey, Friedrichs and Speer, 1986). The tidal nonlinearity in sea surface is generally lower than four percent, averaging only three percent through the estuary. Relative tidal phase for M_2 - M_4 sea surface is generally between 240-260°, which is slightly ebb-dominated. The major implication of this slight ebb dominance is that the estuary tends to be more self-flushing due to higher velocities on the ebb tide. This is discussed in greater detail in Part II: Numerical modeling.

M_2 amplitude decreases slightly from the offshore into the tidal inlet proper (from 0.90 m down to 0.86 m; figure 38). Once inside the estuary, however, tidal amplitude increases (figure 38). This amplification of the M_2

KINGS BAY, GEORGIA JUNE-JULY, 1985

Fig. 38. Tidal properties and behavior along channel at King's Bay/Cumberland Sound.

tide is consistent with Dronkers (1964), where this occurs in the absence of strong friction and/or other dissipation terms. This amplification reaches approximately 10% of the offshore tidal amplitude at the far northern reaches of Cumberland Sound. The amplitude increase also is linked to interaction between Cumberland Sound and Crooked River to the north.

Mean temperature increases with distance into the estuary (figure 38). The mean ocean temperature was about 26.5°C, while temperatures within the estuary were generally between 27.5° and 28.5°C. This warming reflects the shallow nature of the estuary compared to the offshore waters. The anomalous reading within the inlet proper (21.5°C) is likely due to an offset in the instrument reading, and not environmental.

Mean salinity decreases to the north, from a value of 32.5 ppt in the southern reaches of Cumberland Sound down to a value of 32 ppt near the connection to Crooked River along the intracoastal waterway. This decrease in salinity is consistent with increased freshwater exchange from the rivers to the north. The possibility of a large freshwater inflow during the experiment causing the large drop in salinity midway through the experiment cannot be discounted. Alternatively the drop in salinity could be due to malfunction of the conductivity cells (simultaneous with the temperature, transmission, and current). The continued presence of tidal oscillations in the salinity records suggests that the freshwater inflow was real, and that the instruments functioned normally. Temperature, transmission and current records show simultaneous evidence for increased freshwater inflow.

Velocity information collected was of limited use because of limited spatial coverage and failure of some Aanderaas due to fouling. The instruments which did work measured a mean current in the ebb direction of approximately 4 cm/sec, showing the influence of the freshwater outflow on the system. On top of tidal asymmetry, then, is the influence of freshwater outflow that helps flush the freshwater-borne sediments from the system.

Data collected during the field experiment at King's Bay will help in the design and evaluation of the King's Bay/Cumberland Sound channel. For the first time tidal velocities and sea surface behavior have been defined for a large portion of the bay. Tidal constituents for velocity, sea surface, temperature and salinity shed light on the dynamics of this system. Sedimentation is significant due to large source terms, but much will be flushed by strong ebb-dominated currents and resultant large near-bed shear stresses. In every location near-bed shear stress is sufficient to transport sediment and maintain it in suspension. The net seaward velocity combined with these strong near-bed shear stresses helps minimize sedimentation in most shallow areas. The deeper channels and embayments, however, will continue to experience some sedimentation. The magnitude and rate of sedimentation are not possible to project with these limited field observations.

A rough indication of the asymmetry in near-bed transport resulting from the tidal asymmetry in St. Mary's Inlet can be obtained from Aubrey (1986). Velocity data for St. Mary's Inlet (Buoy 22) indicates a velocity asymmetry of 0.17 in M_4/M_2 ratio, having a relative M_2-M_4 phase of 227° (table 5). Aubrey (1986) indicates this results in an ebb asymmetry, with flood lasting nearly 7 hours and ebb lasting less than 6 hours. Near-bed transport asymmetry is approximately 1.5 to 1, so ebb transports approximately 50% more sediment than flood. This maintains the inlet channel clear of sand-sized material as this coarse sediment is swept out towards the ebb tide delta. Observation shows the channel floor is covered with a coarse cobble lag deposit. Near-bed shear stresses and internal levels of turbulence are high enough to maintain sediment in suspension during its transit through the inlet, leaving the inlet bottom clear of suspended fine sediment. Once the channel flow expands past the east end of the jetties, sediment can fall from suspension during intervals of low wave activity. Thus the ebb tide delta is a mixture of the

coarse bedload material flushed from the inlet proper and fine sediment falling from suspension as the ebb flow expands and internal shear stresses decrease. Field observations support this conclusion.

The volume discharge of fine sediment emanating from Cumberland Sound onto the offshore region is difficult to estimate, due to lack of sufficient measurements of sediment concentration. We can estimate the average water discharge from the inlet, assuming mean flow from the inlet averaged 3 cm/sec out of the estuary. With an inlet cross-sectional area of approximately 10^4 m² across the inlet channel near the location of the current meter, and applying a boundary layer model for a laterally homogeneous flow (limiting assumptions, but good for order of magnitude estimates), net volume flux of water averages about 300–350 m³/sec. If average volume concentration of suspended material is one gm/liter, the resultant transport of fine sediment from the estuary would be 300–350 kg/sec, or 26,000 tonnes per day. For a volume concentration of 0.1 g/liter, the net seaward transport would be 2,600 tonnes per day. These figures are order of magnitude estimates, and should be refined with improved measurements through the inlet mouth.

Previous investigators have made observations to support the above calculations. Parchure (1982) found a cross-sectional area of 16,440 m² for the inlet channel section where the 635-12 was deployed. He also estimates a freshwater discharge of 250 m³/sec. McConnell et al. (1983) estimated river discharge at St. Mary's River (41 m³/sec), Crooked River (2.2 m³/sec) and Amelia Rivers (<2.2 m³/sec). The sum of these is less than our estimate based on a single current meter record from a month-long period. McConnell et al. (1983) also report seasonal range of suspended sediment concentrations of 50–80 mg/litre for King's Bay and 58 to 94 mg/L for Cumberland Sound.

A major use of the data set collected during this experiment is for model verification. Numerical and physical models designed to evaluate sedimentation in the estuary need realistic input. The present data set provides this input. Some numerical experiments addressing the circulation and sedimentation problems will be described in Part II of this report.

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16. Abstract (Limit: 200 words) A month-long field experiment was conducted during June and July, 1985 at King's Bay/Cumberland Sound, Georgia, under the combined auspices of the Naval Civil Engineering Laboratory and the Woods Hole Oceanographic Institution. Nine estuarine stations were occupied over the duration of the experiment measuring velocity, sea surface elevation, and water quality (salinity, temperature and transmissivity) as well as wind waves. The data document the amplification of the tide from St Mary's Inlet north into King's Bay (an increase in the dominant M ₂ tidal range from 0.90 m offshore of St. Mary's Inlet to a high of 0.99 m at King's Bay). The M ₂ tide dominates records of velocity, sea surface, temperature, and salinity throughout the estuary. Half way through the experiment, the bay became warmer and less saline, reflecting increased freshwater flow into the estuary through the Crooked River, St. Mary's River, and other smaller rivers. All velocity gauges measured a net down-estuary mean flow over the duration of the experiment. Net volume discharge of water from the inlet averaged 300-350 m ³ /second over the month of measurement. Net discharge of fine sediment is at least 2600 tonnes per day, and perhaps as high as 26,000 tonnes per day. Data from this field experiment provide the only useful basis for verification and evaluation of various numerical models applied to King's Bay/Cumberland Sound.				
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