TIDES, AND TIDAL AND RESIDUAL CURRENTS IN SUISUN AND SAN PABLO BAYS, CALIFORNIA,

RESULTS OF MEASUREMENTS, 1986

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 88-4027

Prepared in cooperation with the
CALIFORNIA STATE WATER RESOURCES CONTROL BOARD
and the
CALIFORNIA DEPARTMENT OF WATER RESOURCES
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By Jeffrey W. Gartner and Brian T. Yost

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Menlo Park, California
1988
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Conversion factors for terms used in this report are listed below:

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>centimeter (cm)</td>
<td>0.3937</td>
<td>inch (in)</td>
</tr>
<tr>
<td>centimeter per second (cm/s)</td>
<td>0.3937</td>
<td>inch per second (in/s)</td>
</tr>
<tr>
<td>kilometer (km)</td>
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<td>mile (mi)</td>
</tr>
<tr>
<td>meter (m)</td>
<td>3.281</td>
<td>foot (ft)</td>
</tr>
<tr>
<td>cubic meters per second (m³/s)</td>
<td>35.31</td>
<td>cubic feet per second (f³/s)</td>
</tr>
<tr>
<td>square kilometers (km²)</td>
<td>0.3861</td>
<td>square miles (mi²)</td>
</tr>
<tr>
<td>cubic kilometers per year (km³/yr)</td>
<td>0.2399</td>
<td>cubic miles per year (mi³/yr)</td>
</tr>
</tbody>
</table>

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

\[ °F = 1.8 \times °C + 32 \]
ABSTRACT

Current-meter data collected at 11 stations and water-level data collected at one station in Suisun and San Pablo Bays, California in 1986 are compiled in this report. Current-meter measurements include current speed and direction, and water temperature and salinity (computed from temperature and conductivity). For each of the 19 current-meter records, data are presented in two forms. These are: (1) results of harmonic analysis; and (2) plots of tidal current speed and direction versus time and plots of temperature and salinity versus time. Spatial distribution of the properties of tidal currents are given in graphic form. In addition, Eulerian residual currents have been compiled by using a vector-averaging technique. Water-level data are presented in the form of a time-series plot and the results of harmonic analysis.

Results of harmonic analysis indicate that other than at shoal stations, the tidal currents generally are bi-directional and the principal direction depends on basin bathymetry. Current speed indicates a spring/neap variation of about a factor of three and the calculated form number indicates that the tidal current is mixed but closer to semidiurnal than to diurnal. At those stations where multiple meters were deployed in the verti-
cal, the root mean square (RMS) velocity values decrease from top to bottom as expected. In general, tidal currents in shoal regions of Grizzly Bay are not bi-directional. During a period of high river inflow, several velocity records indicate flows with riverine characteristics. Eulerian residual flows at deep water stations indicate down-estuary flows during periods of high inflows, and multiple-meter stations display evidence of gravitational circulation. The magnitude of residual flows at shoal stations generally are low and values calculated from measurements at these stations probably are not meaningful.

Analysis of water-level data indicates a phase shift of about 80 to 100 degrees when compared with current data (currents lead tide) indicative of the standing-wave characteristic of tidal propagation in Grizzly Bay. Tidal-form number in Grizzly Bay is typical of values throughout Suisun Bay and indicates a mixed, mainly semidiurnal tide.
INTRODUCTION

The San Francisco Bay estuary and Delta has been the focus of extensive interdisciplinary studies undertaken to better understand the physical, chemical, and biological processes that affect this complex estuarine system (fig. 1). Broad goals of these studies are to understand the processes by which water, solutes, sediments, and organisms interact; to quantify effects of river inflow, winds, and tides; and to develop and verify various conceptual and numerical models of these relations (Cheng and Conomos, 1980). As an aid to accomplishing these goals, it is recognized that the description of hydrodynamic processes is important to the understanding of transport processes, circulation, and mixing, and as an aid to implementing hydrodynamic models.

A study to examine tides and tidal currents of San Francisco Bay was undertaken by the U.S. Geological Survey in cooperation with the California Department of Water Resources and the State Water Resources Control Board. This study was part of ongoing research being conducted by the Interagency Ecological Studies Group whose other members include California Department of Fish and Game, U.S. Bureau of Reclamation, and the U.S. Fish and Wildlife Service.

In-situ recording current-meter and tide (water-level) stations have been established throughout the bay system. The current meters record current speed and direction, and water temperature and conductivity at 2-minute intervals for deployment.
Figure 1. San Francisco Bay estuarine system.
periods of as much as 30 to 40 days. Previous reports document current-meter and water-level data collected from 1978 through 1985 (Gartner and Cheng, 1982; Cheng and Gartner, 1984; Gartner and Walters, 1986; and Gartner, 1986).

**Purpose and Scope**

The purpose of this report is to present in a useful form, all current-meter and water-level data collected in 1986. Data are displayed graphically in the form of time-series plots and the spatial distribution of major properties of tidal currents are shown. Tidal elevation and velocity data have been harmonically analyzed to determine the amplitude and phase of the primary tidal constituents (harmonic constants). The harmonic constants are used to qualitatively define the tide and may be used for tide and tidal current predictions. Eulerian residual currents have been determined by vector averaging the velocity-time series. All data collected during this period were in Suisun and San Pablo Bays. A brief summary of the data-collection program and data processing procedures is given below. More complete descriptions of equipment and deployment, recovery, maintenance, and data processing procedures are given by Cheng and Gartner (1980, 1984).

**Acknowledgments**

The authors gratefully acknowledge the assistance of the Tiburon Center for Environmental Studies who provided some of the field data documented in this report.
DATA-COLLECTION PROGRAM

Suisun and San Pablo Bays

All current-meter and water-level data collected in 1986 were from stations in Suisun and San Pablo Bays (fig. 1). Suisun Bay has a surface area of approximately 94 km$^2$ and a mean depth of 4.3 m. [All depths are referenced to mean lower low water (MLLW).] The embayment is characterized by deep channels (9-14 m) surrounding numerous shoal regions and islands. There are two subembayments (Grizzly and Honker Bays) with mean depths less than 2 m. (fig. 2). San Pablo Bay has a surface area of 271 km$^2$ and a mean depth of 2.7 m. There is a deep shipping channel to the southeast part of the embayment and a shoal region in the northwest. Fifty-seven percent of San Pablo Bay is less than 2 m deep.

Water properties vary seasonally and are controlled in part by freshwater inflows into Suisun Bay from the Sacramento and San Joaquin Rivers. Inflow values during summer months are typically 300 to 400 m$^3$/s, whereas winter flows may reach 8,000 to 12,000 m$^3$/s. Increased winter flows may cause Suisun Bay to become riverine with seaward river inflows dominating over tidal oscillations. Typical salinity values for Suisun Bay are 1 to 3 $\text{o}/\text{oo}$ near the confluence of the Sacramento and San Joaquin Rivers, and 10 to 20 $\text{o}/\text{oo}$ at the west end near Carquinez Strait. Typical salinity values for San Pablo Bay are 20 to 28 $\text{o}/\text{oo}$ and during wet winters vertical stratification may exceed 10 $\text{o}/\text{oo}$. 
Figure 2. Suisun and San Pablo Bay region and the location of current-meter moorings and water-level recorder.
Meteorological conditions for Suisun Bay are characterized by prevailing westerly or southwesterly winds in the late spring, summer, and early fall and by more intermittent northerly winds in winter. Winds in San Pablo Bay are generally southwesterly in the spring, summer, and fall, and more north or northeasterly in the winter (Gartner and Cheng, 1983). Winter winds are more variable, whereas summer winds, driven by heating of inland air masses, generally are stronger.

Measurements of Tides and Tidal Currents

Tides and tidal currents in San Francisco Bay consist of the sum of numerous partial tidal constituents. Of these, half a dozen semidiurnal and diurnal partial tides and one overtide are the most important. Because the frequencies of partial tides are different, resulting tides (and tidal currents) in San Francisco Bay vary constantly as the partial tides move in phase (reinforcing each other) and out of phase (canceling each other) in a fortnightly cycle. The net effect of these phase differences gives rise to spring and neap variations of tides and tidal currents. One of the principal objectives of the present data-collection program is to measure the tides and tidal currents and define the partial tides from these data. Clearly, the longer the time-series of field data, the better each frequency can be separated and the more accurately each partial tide can be computed. Therefore, only self-contained recording current meters and tide recorders that are capable of recording data for a minimum of 15 days were used.
Equipment

Current meters used in the study are Endeco-174 digital recording current meters. The Endeco-174 is an axial-flow, ducted-impeller current meter that stores data on a magnetic tape cartridge or in CMOS memory (Cheng and Wang, 1985). As much as 40 days of data can be stored when the data-recording interval is selected to be 2 minutes. Accuracy specifications for Endeco-174 current meters provided by the manufacturer (Endeco Inc., Marion, Mass.) (Endeco 1978) are: speed, \(\pm 3.0\) percent of full scale (223 cm/s) above the threshold (2.6 cm/s); direction, \(\pm 7.2^\circ\); temperature, \(\pm 0.2^\circ C\); and conductivity, \(\pm 0.55\) mS/cm (millisiemens per centimeter).

Current speed is determined by measuring the displacement of an encoder-disc driven by an impeller through a magnetic coupler and a 500:1 reduction gear. Current direction (current meter heading) is determined from the output of a damped magnetic compass. Temperature is determined by a thermistor and conductivity by an induction type electrodeless-conductivity probe. Current speed is the average speed over the sampling interval while current direction and water temperature and conductivity are instantaneous values at the time of sampling.

\(^1\)Use of trade name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.
Water-level data were recorded by using an Endeco-1032 tide recorder. The recorder uses a semiconductor strain-gage pressure sensor and a 60-second digital integration of pressure to determine an average of pressure for each sample. This method filters out pressure variations caused by wave motion. Data are recorded on eight-track tape or stored in CMOS memory in a manner similar to that used in the Endeco-174 current meter. Pressure variations caused by daily atmospheric pressure changes were accounted for during data translation.

**Water-Level and Current-Meter Stations**

Six current-meter stations were established in Suisun Bay and two in San Pablo Bay by the Geological Survey during two time periods in 1986. Three additional stations were established in Suisun Bay during the second period by Ocean Surveys Inc. for Tiburon Center for Environmental Studies. A water-level recorder was used at one station during each time period. A total of 18 current-meter records and 1 water-level record are presented in this report; equipment were redeployed at the same location and multiple current meters were deployed at the Ocean Surveys Inc. stations. The minimum length current-meter deployment was 26 days (meter hit, dragged, and removed early); the maximum deployment was 55 days (equipment not recovered on first attempt). Useable data generally were limited to about 42 days for data collected by the Geological Survey and about 30 days for data collected by Ocean Surveys Inc. Figure 2 shows the approximate location of the current-meter and water-level stations. The
latitude and longitude and the water depth for each station are compiled in table 1. The positions of current-meter stations were determined by Loran C fixes (±30 m). Also included in table 1 are the depths at which the current meters were deployed, and the deployment and recovery dates for all equipment used. All reference times have been converted to Pacific Standard Time. Figure 3 is a chronological bargraph that indicates the period of time during which current-meter data were collected during 1986. The open bars on the bargraph indicate current-meter stations where multiple current meters were used for the indicated period of time. Table 1, figure 2, and figure 3 define the complete spatial and temporal distributions of the field data.
<table>
<thead>
<tr>
<th>Station number</th>
<th>Latitude (North)</th>
<th>Longitude (West)</th>
<th>Deployment date</th>
<th>Recovery date</th>
<th>Water depth below MLLW (meters)</th>
<th>Meter Depth (meters)</th>
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<td>C23</td>
<td>38°04'35&quot;</td>
<td>122°20'47&quot;</td>
<td>3/14/86</td>
<td>4/23/86</td>
<td>2.2</td>
<td>1.0</td>
</tr>
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<td>C23</td>
<td>38°04'41&quot;</td>
<td>122°20'48&quot;</td>
<td>9/24/86</td>
<td>11/5/86</td>
<td>2.1</td>
<td>0.9</td>
</tr>
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<td>C25</td>
<td>38°02'10&quot;</td>
<td>122°7'55&quot;</td>
<td>3/14/86</td>
<td>5/2/86</td>
<td>17.0</td>
<td>9.1</td>
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<td>11/4/86</td>
<td>1.6</td>
<td>0.4</td>
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<td>GS41</td>
<td>38°06'33&quot;</td>
<td>122°2'55&quot;</td>
<td>3/13/86</td>
<td>5/2/86</td>
<td>4.0</td>
<td>1.2</td>
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<td>38°06'28&quot;</td>
<td>122°2'46&quot;</td>
<td>9/23/86</td>
<td>11/4/86</td>
<td>2.5</td>
<td>0.3</td>
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<td>122°0'45&quot;</td>
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<td>5/1/86</td>
<td>2.1</td>
<td>0.9</td>
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<td>0.9</td>
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<td>11/4/86</td>
<td>2.2</td>
<td>1.0</td>
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<td>10/29/86</td>
<td>9.2</td>
<td>4.2</td>
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<td>OSI1</td>
<td>38°05'27&quot;</td>
<td>122°0'27&quot;</td>
<td>9/28/86</td>
<td>10/29/86</td>
<td>9.2</td>
<td>7.2</td>
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<td>10/29/86</td>
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<td>122°2'33&quot;</td>
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<td>10/29/86</td>
<td>8.2</td>
<td>3.2</td>
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<td>1.5</td>
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<td>10/31/86</td>
<td>9.8</td>
<td>4.8</td>
</tr>
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<td>OSI3</td>
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<td>122°1'30&quot;</td>
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<td>10/31/86</td>
<td>9.8</td>
<td>7.8</td>
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<td>TG43</td>
<td>38°7'17&quot;</td>
<td>122°1'35&quot;</td>
<td>3/13/86</td>
<td>4/25/86</td>
<td>1.9</td>
<td>1.4</td>
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Figure 3. Bar graph of periods when current-meter arrays and tide gage were deployed in Suisun and San Pablo Bays in 1986.
DATA-PROCESSING PROCEDURES

Data Translation

Raw data from the tide gage and current meters were translated into computer-readable code by using special tape readers (Cheng and Gartner, 1979; Cheng and Wang, 1985). The 2-minute interval data were examined for possible record gaps, and individual sensor calibration constants were applied to convert the data to engineering units. Salinity was not directly measured; it was computed from water temperature and conductivity values based upon the modified Cox relation (D. Pritchard, unpublished notes, 1978). Computer programs used in the processing of these data have been described in Cheng and Gartner (1980, 1984).

Post Processing

Fifteen-minute interval current-meter data collected by Ocean Systems Inc. were supplied in engineering units. These data were reformatted to be compatible with post-processing programs in use by the Geological Survey.

Current speeds and directions were vector-averaged to produce a time series of 30-minute averaged data for time-series plots. Similar time series of 30-minute averaged temperature and salinity data were also computed and plotted. Original speed and direction data were also vector averaged to a 30-minute interval time series as part of the harmonic analysis technique.
Time-Series Plot

A time-series plot of current-meter data is one of the most useful ways for clearly displaying temporal variations in the data. Time-series plots of all data records are given in the Appendix. The tidal-current velocity is plotted in the form of speed and direction (relative to true north) versus time. In general, current speed and direction data were not edited. Portions of the data may be invalid because of marine fouling, malfunction of instrument, or for other unknown reasons. Where questionable or unreliable data are apparent on the time-series plots in the Appendix, those sections are noted. Only valid data (our own best judgement) were used in the harmonic analyses. Whereas the time-series plots cover the entire deployment, in the case of harmonic analysis the start time and the length of the record analyzed are noted on the harmonic analysis summary sheets.

A time-series plot of water temperature and salinity versus time is also given for each data file. Accuracy of conductivity (from which salinity is calculated) data may be affected by several factors including marine growth on the external sensor and battery voltage (a function of the deployment duration and water temperature). Bottle samples for salinity analysis were collected during equipment recovery or deployment cruises for later comparison to recorded values. Spurious temperature and conductivity readings in the records were corrected or deleted when identified.
Harmonic Analysis

The method of harmonic analysis for tide and tidal current data is well documented by Schureman (1940) and Cheng and Gartner (1984). In all cases the data sets are truncated to an even number of $M_2$ cycles. The $M_2$ cycle (12.42 hours) is used for this purpose because it is by far the most dominant tidal constituent (partial tide) in San Francisco Bay. The method of referring to partial tidal constituents is to use a letter which stands for the origin of the constituent, and a lower case number which refers to the number of cycles per day. The origins, cycles per day, and angular frequencies of the tidal constituents included in the analysis are given in table 2.

In the case of water-level data, major harmonic constituents ($O_1$, $K_1$, $N_2$, $M_2$, $S_2$, $M_K$, and $M_4$) were solved by least-squares technique and secondary constituents ($O_1$, $P_1$, $J_1$, $^\nu_2$, $L_2$, $K_2$, $^\mu_2$, $M_1$, and $T_2$) were computed by inference based on equilibrium theory. In the case of the current (velocity) data, six harmonic constituents ($O_1$, $K_1$, $N_2$, $M_2$, $S_2$, $M_4$) were computed for east-west and north-south tidal velocity components. Harmonic constants derived from the two velocity component series were then combined to define a tidal current ellipse for the partial tide. Results of harmonic analysis are included in the Appendix and may be used for prediction of tides and tidal currents at the same location (Cheng and Gartner, 1984). Included with the results of harmonic analysis of velocity data are some general properties of tidal currents computed by the harmonic analysis program such as the RMS current speed, spring current maxima, neap tidal current
Table 2.--Principal astronomical partial tidal constituents

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Period (solar hours)</th>
<th>Angular frequency (degrees per hour)</th>
<th>Origin and name</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₁</td>
<td>23.93</td>
<td>15.0411</td>
<td>Luni-solar</td>
</tr>
<tr>
<td>O₁</td>
<td>25.82</td>
<td>13.9430</td>
<td>Principal lunar</td>
</tr>
<tr>
<td>P₁</td>
<td>24.07</td>
<td>14.9589</td>
<td>Principal solar</td>
</tr>
<tr>
<td>Q₁</td>
<td>26.87</td>
<td>13.3987</td>
<td>Larger lunar elliptic</td>
</tr>
<tr>
<td>J₁</td>
<td>23.10</td>
<td>15.5854</td>
<td>Small lunar elliptic</td>
</tr>
<tr>
<td>M₁</td>
<td>24.83</td>
<td>14.4967</td>
<td>Smaller lunar elliptic</td>
</tr>
</tbody>
</table>

**DIURNAL SPECIES**

**SEMIDIURNAL SPECIES**

**TERDIURNAL SPECIES**

**QUARTER DIURNAL SPECIES**
minima, principal tidal current direction, tidal current form number, and Eulerian residual current (time averaged velocity) (Cheng and Gartner, 1984). Depending upon the usable length of the record, the time average velocities are computed for every 12 $M_2$ tidal cycles, and an even number less than 12 $M_2$ cycles for the remaining available data in the record. The time average for the entire record length (maximum even $M_2$ cycles) is also given.

TIDE IN SUISUN BAY

Only one of the two water-level records collected in Suisun Bay during 1986 contained usable data. That record was at station GS43 in Grizzly Bay. Results of harmonic analysis and the time-series plot of that record are shown in the appendix. A tidal form number, $F$ has been defined as the ratio of the sum of the amplitudes of the diurnal tidal constituents over the sum of the amplitudes of the semidiurnal tidal constituents. The ratio $F=(O_1+K_1)/(M_2+S_2)$ may be used to define the tide type. Form numbers less than 0.25 indicate a semidiurnal tide while form numbers greater than 3.0 indicate a diurnal tide. Form numbers between 0.25 and 3.0 indicate a mixed tide. Analyses of results shows that the tide is mixed, mainly semidiurnal ($F=0.77$) and is typical of the tide in Suisun Bay. The $M_2$ constituent amplitude is damped relative to the tide at the Golden Gate whereas the other constituents are somewhat amplified. That is atypical of the tidal characteristics in Suisun Bay and may be a function of the analysis of a rather short record (42 days) during a period of unusually high Delta inflow. Constituent phase angles are
typical and reflect the 2- to 3-hour delay in arrival of the tide at that location relative to the Golden Gate.

Comparison of the phase angles of the tide relative to the tidal currents is an indication of the characteristics of tidal propagation. A phase difference of 0° between tides and currents is indicative of tidal propagation as a progressive wave whereas a difference of 90° (tidal currents leading tidal elevation) is indicative of tidal propagation as a standing wave. The difference between the tide and tidal current phase for the M₂ (primary) constituent is about 70° and the average of the K₁, O₁, N₂, and S₂ constituents is about 80°. The tide propagates like a standing wave in the area of station GS43.
Velocity records from the deep stations (C32, C25, OSI1, OSI2, and OSI3) in Suisun Bay indicate that, in general, the tidal currents are strongly bi-directional and that the current directions parallel the channel at those stations. The tidal ellipses for the partial tides are highly eccentric; ratios of major to minor axes exceed 30:1 in most cases. Tidal ellipses computed from analysis of data from the top and middle meters at stations OSI2 and OSI3 were somewhat less eccentric. Multiple meter stations have typical velocity profiles with RMS speed values decreasing with depth, and there is little variation in principal direction among records at the same station. There is more than a 3:1 factor in the variation in current speed between maximum spring and minimum neap tides. Records from station C32 and station C25 (spring deployment) include periods of highly riverine characteristics during a period of high river inflow (greater than 5,900 m³/s based on a 10-day average of Delta outflow provided by the California Department of Water Resources). Delta outflow is an estimate of inflow to Suisun Bay. Specifically, from the beginning of the deployment through Julian day 80 to 81, river inflow dominated over tidal flow and flood tides were minimal or nonexistent.

Those records from stations in shallow regions of Grizzly Bay show quite different characteristics. Records from both the spring and fall deployments are clearly less bi-directional than are records from channel stations. The partial tidal ellipses
are less eccentric; ratios of the major axes to minor axes are generally less than 5:1 and in many cases 1:1 ratios indicate nearly circular tidal ellipses. As expected, speeds are lower in the shallow regions than in the channels. The calculated principal directions are east-northeast and result from the propagation of the flood tide into Grizzly Bay from the northeasterly trending channel on the west side of Suisun Bay. The record from the spring deployment at station GS41, the deepest-water deployment of the four stations in Grizzly Bay, also shows the period of riverine-like flow seen at the deep-water stations. No direction information is available at station GS44 because of an electronic failure in the current meter.

Records from both the spring and fall deployments at station GS40 in San Pablo Bay indicate that wind affected the velocity record. Neither record appears usable for harmonic analysis, and even a qualitative evaluation of current speed or direction is impossible from data at this very shallow station. It appears likely that, in addition to being affected by wind waves, the current meter was above the water surface during numerous periods of the deployment. Under these circumstances the temperature and salinity records are also suspect. Results of harmonic analysis (both deployments) and time-series plots from the spring deployment are not presented. The speed and direction plots from the fall deployment are included in the appendix only for reference. An expanded plot of one week of data from station GS40 is shown in figure 4 and the unusual character of the velocity record is clearly apparent. Full speed scale for the current meter is 223 cm/s; impeller revolutions caused by higher speeds will be
Figure 4. Expanded time-series plot of current velocity showing sections of incorrect readings.
incorrectly interpreted to mean lower speeds. This would occur if a current meter (on fixed platform and exposed above the water surface) were exposed to wind of greater speed than the maximum for the speed scale in use (223 cm/s). This appear to have occurred at station GS40. On the other hand, station C23 was deployed nearby in deeper water and shows the typical spring/neap variation in speed and current direction parallel to bathymetry lines. Water temperature at stations GS41 and GS44 appears unusually low during the early part of the fall deployment (prior to Julian day 282). No explanation is presented and temperature data from these records should be used with caution.

The spatial distribution of descriptive tidal current properties is plotted in figure 5 in which the \( M_2 \), RMS, and the estimated spring and neap tidal current vectors are plotted in the principal tidal current direction at each station.

A tidal current form number, \( F' \) is defined as the ratio of the sum of the semimajor axes of diurnal tidal species to the sum of the semimajor axes of semidiurnal species. As in the case of the tidal form number, the ratio \( F' = (O_1 + K_1) / (M_2 + S_2) \) may be used to define the tidal current type. The range of form numbers for all velocity records is 0.23 to 0.46; the tidal currents in Suisun and San Pablo Bays are mixed semidiurnal and diurnal types; for the most part, the tidal current type is closer to semidiurnal than diurnal.
Figure 5. Spatial distribution of tidal current properties in Suisun and San Pablo Bays.
Figure 5. Continued.
EULERIAN RESIDUAL CURRENTS IN SUISUN AND SAN PABLO BAYS

The Eulerian residual current is defined here to be the vectorial average of the current-meter data made over several (an even number of) $M_2$ tidal cycles. This serves to average out the tidal signal; what remains is an estimate of the Eulerian residual. The Eulerian residual current is generally a factor of ten smaller than the tidal current. As the speed accuracy of the current meter is stated to be about $\pm 7$ cm/s and the current-meter record represents speed only at a single point in the water column (and the water depth varies over a tidal cycle), one must be careful in drawing conclusions from the Eulerian residual currents calculated in this way. The computed Eulerian residual currents are given in the summary for each current-meter data file in the format of north/south (north $-$ +) and east/west (east $-$ +) components. Figure 6 shows the vectors representing the calculated Eulerian residual currents at each available station. At multiple meter stations only the middle record is displayed. The factors that affect the Eulerian residual currents are rather complex. Basin bathymetry, Delta outflow, spatial distribution of tidal currents (tidal current shear), long term temporal variations of tidal currents (spring and neap variations), and wind forcing at the water surface are all important factors which may have effects on the magnitude and spatial distribution of the Eulerian residual currents (see Walters, 1982; Walters and Gartner, 1985; and Cheng and Gartner, 1985). Since the Delta outflow is one of the variables which affect the Eulerian resi-
Figure 6. Eulerian residual currents in Suisun and San Pablo Bays.
Figure 6. Continued.
dual current, the averaged values of the Delta outflow (preliminary) during the current-meter deployments have been computed and are given in the summary sheets.

Those Eulerian residual current vectors that were calculated at deep stations (including GS41) during the spring deployment (figure 6) clearly indicate the down estuary residual flow driven by the high Delta inflows. Data are not available from these stations for the fall deployment but examination of records from these stations from other years (Cheng and Gartner, 1984) does not show significant down estuary residual flows during sustained periods of low Delta inflow (less than about 200$m^3$/s). Where more than one record is available in the vertical, Eulerian residuals indicate the presence of gravitational circulation evidenced by a general shift from down estuary to up estuary residual flow as one moves from top to bottom in the water column. This is clearly shown at all three Ocean Surveys stations in spite of the generally low values of the residual flows. Residual values at the shoal stations (both spring and fall deployments) are generally less than 1-2 cm/s and are probably not of sufficient magnitude to be meaningful.
SUMMARY

Analyses of hydrodynamic field data collected in Suisun and San Pablo Bays demonstrate the presence of a mixed, mainly-semidiurnal tide. Comparison of the results of harmonic analyses of water-level and velocity data indicates that the tide propagates mainly like a standing wave in Grizzly Bay. Velocity data indicate that the tidal currents are generally bi-directional except at shoal stations where the tidal ellipses have a more circular character. Current principal directions are aligned with basin bathymetry, and where multiple meters were used in the vertical, the RMS speed values decrease from top to bottom. Current magnitudes vary over a spring-neap cycle by about a factor of three.

Records from several current meters include periods when flows were riverine in character. High river inflows overwhelmed the normal flood and ebb current directions and residual flows generally were down estuary at deep-water stations. Otherwise, multiple meter stations exhibit evidence of gravitational circulation. Residual currents in the shallows generally were small enough that calculated values are probably insignificant.
REFERENCES


-----1985, Harmonic analysis of tides and tidal currents in South San Francisco Bay, California: Estuarine Coastal and Shelf Science, 21, p. 57-74.


APPENDIX

The current-meter data are presented chronologically and station-by-station in Appendix A. For each file, the measured data and the results of analyses are presented in two forms: (1) results from the harmonic analyses; and (2) time series plots of tidal-current velocity (speed and direction) versus time, and salinity and temperature versus time. These results are given in the order of station numbers as listed in table 1.

The following abbreviations are used in the appendix:

MLLW Mean lower low water (a tidal reference datum).
PST Pacific standard time.
CM/S Centimeters per second
DEG T Degrees true (angular measurement from true north).
RMS Root mean square.
CMS Cubic meters per second; $m^3/s$ is used in the text.
**STATION NUMBER** = TG43A1
**TIME IN THE ORIGINAL DATA IS PST**
**START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 3 DAY=14 HOUR= 0**
**TIME MERIDIAN= 120 W**
**STATION POSITION= 38- 7-17N 122- 1-35W**
**APPROXIMATE RECORD LENGTH IS 43 DAYS**
**THERE ARE 1044 DATA POINTS**

**TIME SERIES MEAN** = 228.243

**RESULTS OF LEAST SQUARES AFTER TIDAL INFEREN**

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RECORD LENGTH IS 76 M2 CYCLES: 1886 DATA POINTS

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NEAP TIDAL CURRENT MAXIMUM (CM/S) = 13.81
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ALL 76 1.0 -0.4
CURRENT-METER OBSERVATIONS (30 MINUTE AVERAGES)
USGS STATION C23  38-4 35N 122-20-47W
METER  1.0 METERS BELOW MLLW. WATER DEPTH  2.2 METERS
Portions of conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30 MINUTE AVERAGES)
USGS STATION C23  38° 4'-35N 122°20'-47W
METER 1.0 METERS BELOW MLLW. WATER DEPTH 2.2 METERS
STATION NUMBER - C25

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TIME MERIDIAN = 120 W

STATION POSITION = 38-2-ION 122-7-55W

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<td>37.4</td>
<td>79.5</td>
<td>COUNTER-CLOCKWISE</td>
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ROOT-MEAN-SQUARES SPEED, (CM/S) = 62.49

STANDARD DEVIATION, U SERIES (CM/S) = 17.36

STANDARD DEVIATION, V SERIES (CM/S) = 11.39

TIDAL-FORM NUMBER = 0.41

SPRING TIDAL CURRENT MAXIMUM (CM/S) = 137.10

NEAP TIDAL CURRENT MAXIMUM (CM/S) = 37.96

PRINCIPAL CURRENT DIRECTION (DEG. T.) = 60.61

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
<th>EAST-WEST (CM/S)</th>
<th>NORTH-SOUTH (CM/S)</th>
<th>OUTFLOW CHIPPS IS. (CMS)</th>
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ALL 94  -7.5  -1.8
Portions of conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION C25 38° 2'10"N 122° 7'55"W
METER 9.1 METERS BELOW MLLW. WATER DEPTH 17.1 Meters
STATION NUMBER- C32
START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 3 DAY=13 HOUR=1105
TIME MERIDIAN= 120 W
STATION POSITION= 38- 2-55N 121-55-25W
METER DEPTH= 5.2M BELOW MLLW WATER DEPTH= 11.3M
RECORD LENGTH IS 46 M2 CYCLES: 1142 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES</th>
<th>MEAN</th>
<th>LOCAL</th>
<th>MODIFIED</th>
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<tbody>
<tr>
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<td>PER DAY</td>
<td>AMPLITUDE</td>
<td>EPOCH</td>
<td>EPOCH</td>
</tr>
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**RESULTS FOR V (+NORTH) SERIES**

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<th>MEAN</th>
<th>LOCAL</th>
<th>MODIFIED</th>
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</thead>
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<td>AMPLITUDE</td>
<td>EPOCH</td>
<td>EPOCH</td>
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<td>254.11</td>
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</table>

NAME | MAJOR | MINOR | DIR | PHASE | E | ROTATION
CM/S | CM/S | DEG.T. | DEG. | DEG. |
O1    | 10.95 | 0.03  | 102.4 | 93.8 | 25.6 | CLOCKWISE
K1    | 20.21 | 0.24  | 102.3 | 110.1 | 243.1 | COUNTER-CLOCKWISE
N2    | 18.61 | 0.62  | 101.2 | 28.0 | 126.6 | COUNTER-CLOCKWISE
M2    | 65.85 | 0.47  | 102.2 | 44.7 | 267.3 | COUNTER-CLOCKWISE
S2    | 24.26 | 0.42  | 101.8 | 42.5 | 331.5 | COUNTER-CLOCKWISE
M4    | 6.42  | 0.29  | 103.9 | 84.3 | 174.6 | COUNTER-CLOCKWISE

ROOT-MEAN-SQUARES SPEED, (CM/S)= 65.45
STANDARD DEVIATION, U SERIES (CM/S)= 19.23
STANDARD DEVIATION, V SERIES (CM/S)= 4.52
TIDAL-FORM NUMBER= 0.35
SPRING TIDAL CURRENT MAXIMUM (CM/S)= 121.27
NEAP TIDAL CURRENT MAXIMUM (CM/S)= 32.33
PRINCIPAL CURRENT DIRECTION (DEG. T.)= 102.19

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<thead>
<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
<th>EAST-WEST (CM/S)</th>
<th>NORTH-SOUTH (CM/S)</th>
<th>OUTFLOW CHIPPS IS. (CMS)</th>
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<tbody>
<tr>
<td>1</td>
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<td>12</td>
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<td>8.3</td>
<td>3937</td>
</tr>
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<td>3</td>
<td>12</td>
<td>-21.9</td>
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<td>2496</td>
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<td>4</td>
<td>10</td>
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<td>1948</td>
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ALL      | 46              | -34.9            | 7.6                |                           |
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION C32 38° 2'-55N 121° 55'-25W
METER 5.2 METERS BELOW MLLW. WATER DEPTH 11.3 METERS
TEMPERATURE, IN DEGREES CELSIUS

SALINITY, IN PARTS PER THOUSAND

Conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION C32 38-2-55N 121-55-25W
METER 5.2 METERS BELOW MLLW. WATER DEPTH 11.3 METERS
**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES PER DAY</th>
<th>AMPLITUDE EPOCH</th>
<th>LOCAL MODIFIED EPOCH</th>
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<tbody>
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<td>306.54</td>
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**RESULTS FOR V (+NORTH) SERIES**

<table>
<thead>
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<th>NAME</th>
<th>CYCLES PER DAY</th>
<th>AMPLITUDE EPOCH</th>
<th>LOCAL MODIFIED EPOCH</th>
</tr>
</thead>
<tbody>
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<tr>
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**MAJOR MINOR DIR PHASE E ROTATION**

<table>
<thead>
<tr>
<th>NAME</th>
<th>MAJOR CM/S</th>
<th>MINOR CM/S</th>
<th>DIR DEG.T.</th>
<th>PHASE DEG.</th>
<th>E ROTATION</th>
</tr>
</thead>
<tbody>
<tr>
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<td>241.2</td>
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</table>

**ROOT-MEAN-SQUARES SPEED, (CM/S) = 33.22**

**STANDARD DEVIATION, U SERIES (CM/S) = 7.77**

**STANDARD DEVIATION, V SERIES (CM/S) = 2.64**

**TIDAL-FORM NUMBER = 0.46**

**SPRING TIDAL CURRENT MAXIMUM (CM/S) = 70.84**

**NEAP TIDAL CURRENT MAXIMUM (CM/S) = 20.17**

**PRINCIPAL CURRENT DIRECTION (DEG. T.) = 81.26**

**TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW**

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
<th>EAST-WEST (CM/S)</th>
<th>NORTH-SOUTH (CM/S)</th>
<th>CHIPPS IS. (CMS)</th>
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</thead>
<tbody>
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<td>1</td>
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<td>3.0</td>
<td>6384</td>
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<tr>
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<td>12</td>
<td>-17.1</td>
<td>2.7</td>
<td>3937</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>-13.4</td>
<td>3.4</td>
<td>2496</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>-13.0</td>
<td>3.5</td>
<td>1888</td>
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<td>5</td>
<td>12</td>
<td>-11.8</td>
<td>3.2</td>
<td>1441</td>
</tr>
<tr>
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<td>12</td>
<td>-7.0</td>
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</tr>
<tr>
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<td>6</td>
<td>-5.0</td>
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<td>936</td>
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</table>

**ALL** | 78              | -13.5            | 3.1                |
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS41 38-6-33N 122-2-55W
METER 1.2 METERS BELOW MLLW, WATER DEPTH 4.0 METERS
 Portions of conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS41 38° 6-33N 122° 2-55W
METER 1.2 METERS BELOW MLLW. WATER DEPTH 4.0 METERS
STATION NUMBER- GS42
START TIME OF THE SERIES (PST): YEAR=1986 MONTH=3 DAY=13 HOUR=1475
TIME MERIDIAN- 120 W
STATION POSITION= 38-6-13N 122-0-45W
METER DEPTH= 0.9M BELOW MLLW WATER DEPTH=2.1M
RECORD LENGTH IS 78 M2 CYCLES: 1936 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES</th>
<th>PER DAY MEAN</th>
<th>LOCAL AMPLITUDE</th>
<th>EPOCH</th>
<th>MODIFIED EPOCH</th>
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**RESULTS FOR V (+NORTH) SERIES**

<table>
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<th>LOCAL AMPLITUDE</th>
<th>EPOCH</th>
<th>MODIFIED EPOCH</th>
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<tr>
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<th>MAJOR CM/S</th>
<th>MINOR CM/S</th>
<th>DIR. DEG.T.</th>
<th>PHASE DEG.</th>
<th>E ROTATION</th>
<th>ROOT-MEAN-SQUARES SPEED, (CM/S)=</th>
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<td>219.5</td>
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<td>14.5</td>
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STANDARD DEVIATION, U SERIES (CM/S)= 3.74
STANDARD DEVIATION, V SERIES (CM/S)= 5.78
TIDAL-FORM NUMBER= 0.25
SPRING TIDAL CURRENT MAXIMUM (CM/S)= 16.14
NEAP TIDAL CURRENT MAXIMUM (CM/S)= 5.17
PRINCIPAL CURRENT DIRECTION (DEG. T.)= 29.1

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
<th>EAST-WEST (CM/S)</th>
<th>NORTH-SOUTH (CM/S)</th>
<th>MIPPS IS. (CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
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<td>3.4</td>
<td>6384</td>
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<tr>
<td>ALL</td>
<td>78</td>
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<td>-0.1</td>
<td>50</td>
</tr>
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</table>
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS42 38-6-13N 122-0-45W
METER 0.9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS
TEMPERATURE, IN DEGREES CELSIUS

SALINITY, IN PARTS PER THOUSAND

Conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS42 38° 6'13"N 122° 0'45"W
METER .9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS
STATION NUMBER= GS43
START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 3 DAY=13 HOUR=1575
TIME MERIDIAN= 120 W
STATION POSITION= 38- 7-17N 122- 1-35W
METER DEPTH= 0.9M BELOW MLLW WATER DEPTH= 2.1M
RECORD LENGTH IS 78 M2 CYCLES: 1936 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

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**RESULTS FOR V (+NORTH) SERIES**

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ROOT-MEAN-SQUARES SPEED, (CM/S)= 6.54
STANDARD DEVIATION, U SERIES (CM/S)= 2.47
STANDARD DEVIATION, V SERIES (CM/S)= 1.87
TIDAL-FORM NUMBER= 0.33
SPRING TIDAL CURRENT MAXIMUM (CM/S)= 13.61
NEAP TIDAL CURRENT MAXIMUM (CM/S)= 4.37
PRINCIPAL CURRENT DIRECTION (DEG. T.)= 53.83

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<th>NORTH-SOUTH (CM/S)</th>
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SPEED, IN CENTIMETERS PER SECOND

DIRECTION, IN DEGREES TRUE

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS43 38-7-17N 122-1-35W
METER .9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS
Conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS43 38° 7'17"N 122° 1'35"W
METER .9 METERS BELOW MLLW, WATER DEPTH 2.1 METERS
STATION NUMBER = GS44
START TIME OF THE SERIES (PST): YEAR = 1986 MONTH = 3 DAY = 13 HOUR = 1681
TIME MERIDIAN = 120 W
STATION POSITION = 38° 7' 13" N 122° 2' 46" W
METER DEPTH = 0.9 M BELOW MLLW WATER DEPTH = 2.1 M
RECORD LENGTH IS 78 M2 CYCLES: 1936 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

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**RESULTS FOR V (+NORTH) SERIES**

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NAME | MAJOR CM/S | MINOR CM/S | DIR DEG.T. | PHASE DEG. | E ROTATION DEG. |
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ROOT-MEAN-SQUARES SPEED, (CM/S) = 14.06
STANDARD DEVIATION, U SERIES (CM/S) =
STANDARD DEVIATION, V SERIES (CM/S) =
TIDAL-FORM NUMBER =
SPRING TIDAL CURRENT MAXIMUM (CM/S) =
NEAP TIDAL CURRENT MAXIMUM (CM/S) =
PRINCIPAL CURRENT DIRECTION (DEG. T.) =

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<th>NORTH-SOUTH (CM/S)</th>
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SPEED, IN CENTIMETERS PER SECOND

DIRECTION, IN DEGREES TRUE

Direction data not usable

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS44 38-7-13N 122-2-46W
METER .9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS
Conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS44 38° 7'-13N 122° 2'-46W
METER .9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS
STATION NUMBER= C23
START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 9 DAY=24 HOUR=1210
TIME MERIDIAN= 120 W
STATION POSITION= 38- 4-41N 122-20-48W
METER DEPTH= 0.9M BELOW MLLW WATER DEPTH= 2.1M
RECORD LENGTH IS 78 M2 CYCLES: 1936 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

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<th>NAME</th>
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**RESULTS FOR V (+NORTH) SERIES**

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**NAME | MAJOR CM/S | MINOR CM/S | DIR DEC. T. | PHASE DEC. | E | ROTATION**
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ROOT-MEAN-SQUARES SPEED, (CM/S)= 18.60
STANDARD DEVIATION, U SERIES (CM/S)= 3.89
STANDARD DEVIATION, V SERIES (CM/S)= 4.09
TIDAL-FORM NUMBER= 0.37
SPRING TIDAL CURRENT MAXIMUM (CM/S)= 38.20
NEAP TIDAL CURRENT MAXIMUM (CM/S)= 13.94
PRINCIPAL CURRENT DIRECTION (DEG. T.)= 39.14

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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TEMPERATURE, IN DEGREES CELSIUS

SALINITY, IN PARTS PER THOUSAND

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION C23 38° 41'N 122° 20'W
METER .9 METERS BELOW MLLW, WATER DEPTH 2.1 METERS
STATION NUMBER: GS40
START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 9 DAY=24 HOUR=1310
TIME MERIDIAN= 120 W
STATION POSITION= 38- 5-29N 122-22-34W
METER DEPTH= 0.3M BELOW MLLW WATER DEPTH= 1.5M
RECORD LENGTH IS 78 M2 CYCLES: 1936 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES</th>
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<th>MODIFIED</th>
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**RESULTS FOR V (+NORTH) SERIES**

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<th>LOCAL</th>
<th>MODIFIED</th>
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NAME  MAJOR  MINOR  DIR.  PHASE  E  ROTATION
CM/S  CM/S  DEG.T.  DEG.  DEG.

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<thead>
<tr>
<th>NAME</th>
<th>MAJOR</th>
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<th>E</th>
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ROOT-MEAN-SQUARES SPEED, (CM/S)=
STANDARD DEVIATION, U SERIES (CM/S)=
STANDARD DEVIATION, V SERIES (CM/S)=
TIDAL-FORM NUMBER=
SPRING TIDAL CURRENT MAXIMUM (CM/S)=
NEAP TIDAL CURRENT MAXIMUM (CM/S)=
PRINCIPAL CURRENT DIRECTION (DEG. T.)=

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
<th>EAST-WEST OUTFLOW</th>
<th>NORTH-SOUTH OUTFLOW</th>
<th>CHIPPS IS. (CMS)</th>
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<tr>
<td>ALL</td>
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SPEED, IN CENTIMETERS PER SECOND

DIRECTION, IN DEGREES TRUE

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION gs40 38-5-29N 122-22-34W
METER .3 METERS BELOW MLLW. WATER DEPTH 1.5 METERS
Conductivity data not usable

Temperature data not usable

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION gs40 38-5-29N 122-22-34W
METER .3 METERS BELOW MLLW. WATER DEPTH 1.5 METERS
**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES PER DAY</th>
<th>AMPLITUDE</th>
<th>LOCAL EPOCH</th>
<th>MODIFIED EPOCH</th>
</tr>
</thead>
<tbody>
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**RESULTS FOR V (+NORTH) SERIES**

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<th>MODIFIED EPOCH</th>
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**MAJOR CM/S**

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<thead>
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<th>E ROTATION</th>
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**MINOR CM/S**

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</table>

**ROOT-MEAN-SQUARES SPEED, (CM/S)=** 10.75

**STANDARD DEVIATION, U SERIES (CM/S)=** 3.75

**STANDARD DEVIATION, V SERIES (CM/S)=** 5.78

**TIDAL-FORM NUMBER=** 0.27

**SPRING TIDAL CURRENT MAXIMUM (CM/S)=** 15.96

**NEAP TIDAL CURRENT MAXIMUM (CM/S)=** 5.14

**PRINCIPAL CURRENT DIRECTION (DEG. T.)=** 51.73

**TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW**

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<thead>
<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
<th>EAST-WEST (CM/S)</th>
<th>NORTH-SOUTH (CM/S)</th>
<th>CHIPPS IS. (CMS)</th>
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**ALL** | 78               | -1.8             | 0.9                |
CONDUCTIVITY

IN PARTS PER THOUSAND

SALINITY

JULIAN DAY

265 269 273 277 281 285 289 293 297 301 305

CONDUCTIVITY BELOW RANGE OF SENSOR

RECORD MAY CONTAIN

SECTIONs OF ERRONEOUS DATA

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)

USGS STATION GS41 38° 6' 28" N 122° 2' 46" W

METER 1.2 METERS BELOW MLLW. WATER DEPTH 2.4 METERS
**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES</th>
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<th>AMPLITUDE EPOCH</th>
<th>LOCAL EPOCH</th>
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**RESULTS FOR V (+NORTH) SERIES**

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<th>AMPLITUDE EPOCH</th>
<th>LOCAL EPOCH</th>
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<th>DIR</th>
<th>PHASE</th>
<th>E</th>
<th>ROTATION</th>
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<td>DEG.</td>
<td>DEG.</td>
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ROOT-MEAN-SQUARES SPEED, (CM/S) = 17.52
STANDARD DEVIATION, U SERIES (CM/S) = 4.34
STANDARD DEVIATION, V SERIES (CM/S) = 7.76
TIDAL-FORM NUMBER = 0.37
SPRING TIDAL CURRENT MAXIMUM (CM/S) = 25.88
NEAP TIDAL CURRENT MAXIMUM (CM/S) = 8.04
PRINCIPAL CURRENT DIRECTION (DEG. T.) = 90.26

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
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<th>NORTH-SOUTH (CM/S)</th>
<th>OUTFLOW CHIPPS IS. (CMS)</th>
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</table>

68
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS42 38° 6' 6N 122° 0'56W
METER .9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS
TEMPERATURE, IN DEGREES CELSIUS

SALINITY, IN PARTS PER THOUSAND

Portions of conductivity below range of sensor

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION CS42 38° 6' N 122° 0' W
METER .9 METERS BELOW MLLW, WATER DEPTH 2.1 METERS
STATION NUMBER: GS44
START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 9 DAY=23 HOUR=1403
TIME MERIDIAN= 120 W
STATION POSITION= 38- 7-13N 122- 3- 4W
METER DEPTH= 0.9M BELOW MLLW WATER DEPTH= 2.1M
RECORD LENGTH IS 78 M2 CYCLES: 1936 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES PER DAY</th>
<th>MEAN AMPLITUDE</th>
<th>LOCAL EPOCH</th>
<th>MODIFIED EPOCH</th>
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**RESULTS FOR V (+NORTH) SERIES**

<table>
<thead>
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<th>NAME</th>
<th>CYCLES PER DAY</th>
<th>MEAN AMPLITUDE</th>
<th>LOCAL EPOCH</th>
<th>MODIFIED EPOCH</th>
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NAME | MAJOR DIR. PHASE E ROTATION
CM/S | CM/S DEG. T. DEG. E DEG.
O1   | 185.9 119.1 146.7 303.6 60.9 247.3
K1   | 119.1 146.7 303.6 60.9 247.3
N2   | 146.7 303.6 60.9 247.3
M2   | 303.6 60.9 247.3
S2   | 60.9 247.3
M4   | 247.3

ROOT-MEAN-SQUARES SPEED, (CM/S)= 14.11
STANDARD DEVIATION, U SERIES (CM/S)=
STANDARD DEVIATION, V SERIES (CM/S)=
TIDAL-FORM NUMBER=
SPRING TIDAL CURRENT MAXIMUM (CM/S)=
NEAP TIDAL CURRENT MAXIMUM (CM/S)=
PRINCIPAL CURRENT DIRECTION (DEG. T.)=

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<th>NORTH-SOUTH (CM/S)</th>
<th>CHIPPS IS. (CMS)</th>
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71
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS44 38° 7'13"N 122° 3'4"W
METER .9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION GS44 38-7-13N 122-3-4W
METER .9 METERS BELOW MLLW. WATER DEPTH 2.1 METERS

Conductivity below range of sensor

Record may contain sections of erroneous data
**RESULTS FOR U (+EAST) SERIES**

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<tr>
<th>NAME</th>
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<th>MODIFIED</th>
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**RESULTS FOR V (+NORTH) SERIES**

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**NAME**

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<th>PHASE</th>
<th>E</th>
<th>ROTATION</th>
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**ROOT-MEAN-SQUARES SPEED, (CM/S)=** 44.82
**STANDARD DEVIATION, U SERIES (CM/S)=** 9.40
**STANDARD DEVIATION, V SERIES (CM/S)=** 4.97
**TIDAL-FORM NUMBER=** 0.42
**SPRING TIDAL CURRENT MAXIMUM (CM/S)=** 102.03
**NEAP TIDAL CURRENT MAXIMUM (CM/S)=** 34.93
**PRINCIPAL CURRENT DIRECTION (DEG. T.)=** 113.81

**TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW**

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<th>NO OF M2 CYCLES</th>
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<th>NORTH-SOUTH (CM/S)</th>
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**ALL** 58 -4.0 0.3
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION 0511 38° 5-27N 122° 0-27W
METER 4.2 METERS BELOW MLLW, WATER DEPTH 9.2 METERS
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION 0511 38° 5-27N 122° 0-27W
METER 4.2 METERS BELOW MLLW. WATER DEPTH 9.2 METERS
**RESULTS FOR U (+EAST) SERIES**

<table>
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<td>AMPLITUDE EPOCH EPOCH</td>
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**RESULTS FOR V (+NORTH) SERIES**

<table>
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</table>

**EQUIVALENT ANGULAR VELOCITY UNITS**

| NAME | MAJOR MINOR DIR. PHASE E ROTATION |
|------|---------|-----------------------|----------------|
|      | CM/S    | CM/S     DEG.T. DEG. DEG. |
| O1   | 11.60   | 0.31     109.9 106.0 97.0 COUNTER-CLOCKWISE |
| K1   | 15.28   | 0.37     111.0 107.1 164.9 COUNTER-CLOCKWISE |
| N2   | 10.16   | 0.19     109.5 28.4 36.8 COUNTER-CLOCKWISE |
| M2   | 49.36   | 0.69     112.0 43.9 260.6 COUNTER-CLOCKWISE |
| S2   | 14.39   | 0.09     112.0 27.2 142.5 COUNTER-CLOCKWISE |
| M4   | 2.89    | 0.60     107.8 19.5 161.2 COUNTER-CLOCKWISE |

ROOT-MEAN-SQUARES SPEED, (CM/S)= 39.95
STANDARD DEVIATION, U SERIES (CM/S)= 9.30
STANDARD DEVIATION, V SERIES (CM/S)= 4.02
TIDAL-FORM NUMBER= 0.42
SPRING TIDAL CURRENT MAXIMUM (CM/S)= 90.63
NEAP TIDAL CURRENT MAXIMUM (CM/S)= 31.29
PRINCIPAL CURRENT DIRECTION (DEG. T.)= 111.58

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
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<th>NORTH-SOUTH (CM/S)</th>
<th>OUTFLOW CHIPPS IS. (CMS)</th>
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SPEED, IN CENTIMETERS PER SECOND

DIRECTION, IN DEGREES TRUE

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OS11 38-5-27N 122-0-27W
METER 7.2 METERS BELOW MLLW. WATER DEPTH 9.2 METERS
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OS11 38° 5-27N 122° 0-27W
METER 7.2 METERS BELOW MLLW. WATER DEPTH 9.2 METERS
**RESULTS FOR U (+EAST) SERIES**

<table>
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<th>NAME</th>
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<th>MODIFIED EPOCH</th>
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**RESULTS FOR V (+NORTH) SERIES**

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**RESULTS FOR U (+EAST) SERIES**

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ROOT-MEAN-SQUARES SPEED, (CM/S)= 53.38

STANDARD DEVIATION, U SERIES (CM/S)= 20.50

STANDARD DEVIATION, V SERIES (CM/S)= 5.42

TIDAL-FORM NUMBER= 0.33

SPRING TIDAL CURRENT MAXIMUM (CM/S)= 108.50

NEAP TIDAL CURRENT MAXIMUM (CM/S)= 37.74

PRINCIPAL CURRENT DIRECTION (DEG. T.)= 93.99

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<th>NO OF M2 CYCLES</th>
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<th>NORTH-SOUTH (CM/S)</th>
<th>OUTFLOW CHIPPS IS. (CMS)</th>
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<td>404</td>
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CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OS12 38° 3'-54"N 122° 2'-33"W
METER 1.5 METERS BELOW MLLW. WATER DEPTH 8.2 METERS
Conductivity data not usable

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OS12 38° 3-54N 122° 2-33W
METER 1.5 METERS BELOW MLLW. WATER DEPTH 8.2 METERS
**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES PER DAY</th>
<th>MEAN AMPLITUDE</th>
<th>LOCAL EPOCH</th>
<th>MODIFIED EPOCH</th>
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**RESULTS FOR V (+NORTH) SERIES**

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**MAJOR CM/S**

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<th>DIR. DEG.</th>
<th>PHASE DEG.</th>
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ROUTES MEAN SQUARES SPEED, (CM/S) = 43.35

STANDARD DEVIATION, U SERIES (CM/S) = 13.13

STANDARD DEVIATION, V SERIES (CM/S) = 9.94

TIDAL FORM NUMBER = 0.38

SPRING TIDAL CURRENT MAXIMUM (CM/S) = 91.31

NEAP TIDAL CURRENT MAXIMUM (CM/S) = 31.09

PRINCIPAL CURRENT DIRECTION (DEG. T.) = 93.72

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
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<th>NORTH-SOUTH (CM/S)</th>
<th>CHIPPS IS. (CMS)</th>
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83
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OS12 38° 3-54N 122° 2-33W
METER 3.2 METERS BELOW MLLW. WATER DEPTH 8.2 METERS
Conductivity data not usable

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OSI2 38-3-54N 122-2-33W
METER 3.2 METERS BELOW MLLW. WATER DEPTH 8.2 METERS
STATION NUMBER- OSI3
START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 9 DAY=28 HOUR=1646
TIME MERIDIAN= 120 W
STATION POSITION= 38- 4-28N 122-1-30W
METER DEPTH= 1.5M BELOW MLLW WATER DEPTH= 9.8M
RECORD LENGTH IS 60 M2 CYCLES: 1491 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
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<th>LOCAL</th>
<th>MODIFIED</th>
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**RESULTS FOR V (+NORTH) SERIES**

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<th>PHASE</th>
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ROOT-MEAN-SQUARES SPEED, (CM/S)= 51.01
STANDARD DEVIATION, U SERIES (CM/S)= 10.90
STANDARD DEVIATION, V SERIES (CM/S)= 5.85
TIDAL-FORM NUMBER= 0.40
SPRING TIDAL CURRENT MAXIMUM (CM/S)= 114.26
NEAP TIDAL CURRENT MAXIMUM (CM/S)= 41.12
PRINCIPAL CURRENT DIRECTION (DEG. T.)= 106.30

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

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<th>NORTH-SOUTH (CM/S)</th>
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CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION 0513 38-4-28N 122-1-30W
METER 1.5 Meters below MLLW. WATER DEPTH 9.8 METERS
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OS13 38- 4-28N 122- 1-30W
METER 1.5 METERS BELOW MLLW. WATER DEPTH 9.8 METERS
**Results for U (+East) Series**

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**Results for V (+North) Series**

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**Root-Mean-Squares Speed, (cm/s)= 45.51**

**Standard Deviation, U Series (cm/s)= 9.84**

**Standard Deviation, V Series (cm/s)= 5.20**

**Tidal-Form Number= 0.39**

**Spring Tidal Current Maximum (cm/s)= 101.92**

**Neap Tidal Current Maximum (cm/s)= 37.29**

**Principal Current Direction (deg. t.)= 108.10**

**Time-Averaged Velocity and Mean Delta Outflow**

<table>
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<th>Interval</th>
<th>No of M2 Cycles</th>
<th>East-West (cm/s)</th>
<th>North-South (cm/s)</th>
<th>Outflow (cm/s)</th>
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<td>404</td>
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<td>4</td>
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<td>ALL</td>
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89
SPEED, IN CENTIMETERS PER SECOND

DIRECTION, IN DEGREES TRUE

JULIAN DAY

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OS13 38-42N 122-1-30W
METER 4.8 METERS BELOW MLLW. WATER DEPTH 9.8 METERS
CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION 0513 38- 4-28N-122- 1-30W
METER 4.8 METERS BELOW MLLW. WATER DEPTH 9.8 METERS
STATION NUMBER= OSI3
START TIME OF THE SERIES (PST): YEAR=1986 MONTH= 9 DAY=28 HOUR=1513
TIME MERIDIAN= 120 W
STATION POSITION= 38- 4-28N 122- 1-30W
METER DEPTH= 7.8M BELOW MLLW WATER DEPTH= 9.8M
RECORD LENGTH IS 60 M2 CYCLES: 1491 DATA POINTS

**RESULTS FOR U (+EAST) SERIES**

<table>
<thead>
<tr>
<th>NAME</th>
<th>CYCLES</th>
<th>MEAN</th>
<th>LOCAL</th>
<th>MODIFIED</th>
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<td>PER DAY AMPLITUDE EPOCH</td>
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**RESULTS FOR V (+NORTH) SERIES**

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<th>DIR. PHASE E ROTATION</th>
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<td></td>
<td>CM/S</td>
<td>CM/S</td>
<td>DEG.T. DEG. DEG.</td>
</tr>
<tr>
<td>O1</td>
<td>11.30</td>
<td>0.14</td>
<td>112.6 83.5 74.4</td>
</tr>
<tr>
<td>K1</td>
<td>16.54</td>
<td>0.06</td>
<td>110.6 94.5 140.6</td>
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<tr>
<td>N2</td>
<td>7.38</td>
<td>0.12</td>
<td>110.2 24.2 350.7</td>
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<tr>
<td>M2</td>
<td>54.26</td>
<td>0.58</td>
<td>110.7 29.7 213.6</td>
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<tr>
<td>S2</td>
<td>14.61</td>
<td>0.06</td>
<td>110.6 18.4 93.9</td>
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<tr>
<td>M4</td>
<td>2.17</td>
<td>1.13</td>
<td>151.5 285.6 67.2</td>
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ROOT-MEAN-SQUARES SPEED, (CM/S)= 43.18
STANDARD DEVIATION, U SERIES (CM/S)= 9.05
STANDARD DEVIATION, V SERIES (CM/S)= 4.39
TIDAL-FORM NUMBER= 0.40
SPRING TIDAL CURRENT MAXIMUM (CM/S)= 96.71
NEAP TIDAL CURRENT MAXIMUM (CM/S)= 34.40
PRINCIPAL CURRENT DIRECTION (DEG. T.)= 110.87

TIME-AVERAGED VELOCITY AND MEAN DELTA OUTFLOW

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>NO OF M2 CYCLES</th>
<th>EAST-WEST (CM/S)</th>
<th>NORTH-SOUTH (CM/S)</th>
<th>OUTFLOW CHIPPS IS. (CMS)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>5.2</td>
<td>0.3</td>
<td>442</td>
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<tr>
<td>2</td>
<td>12</td>
<td>6.5</td>
<td>-0.7</td>
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<tr>
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<td>12</td>
<td>5.6</td>
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<tr>
<td>4</td>
<td>12</td>
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<td>283</td>
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<tr>
<td>5</td>
<td>12</td>
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<tr>
<td>ALL</td>
<td>60</td>
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<td>-0.3</td>
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</tbody>
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CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OSI3 38-4-28N 122-1-30W
METER 7.8 METERS BELOW MLLW. WATER DEPTH 9.8 METERS
TEMPERATURE, IN DEGREES CELSIUS

SALINITY, IN PARTS PER THOUSAND

CURRENT-METER OBSERVATIONS (30-MINUTE AVERAGES)
USGS STATION OSI3 30° 4-28N 122° 1-30W
METER 7.8 METERS BELOW MLLW. WATER DEPTH 9.8 METERS