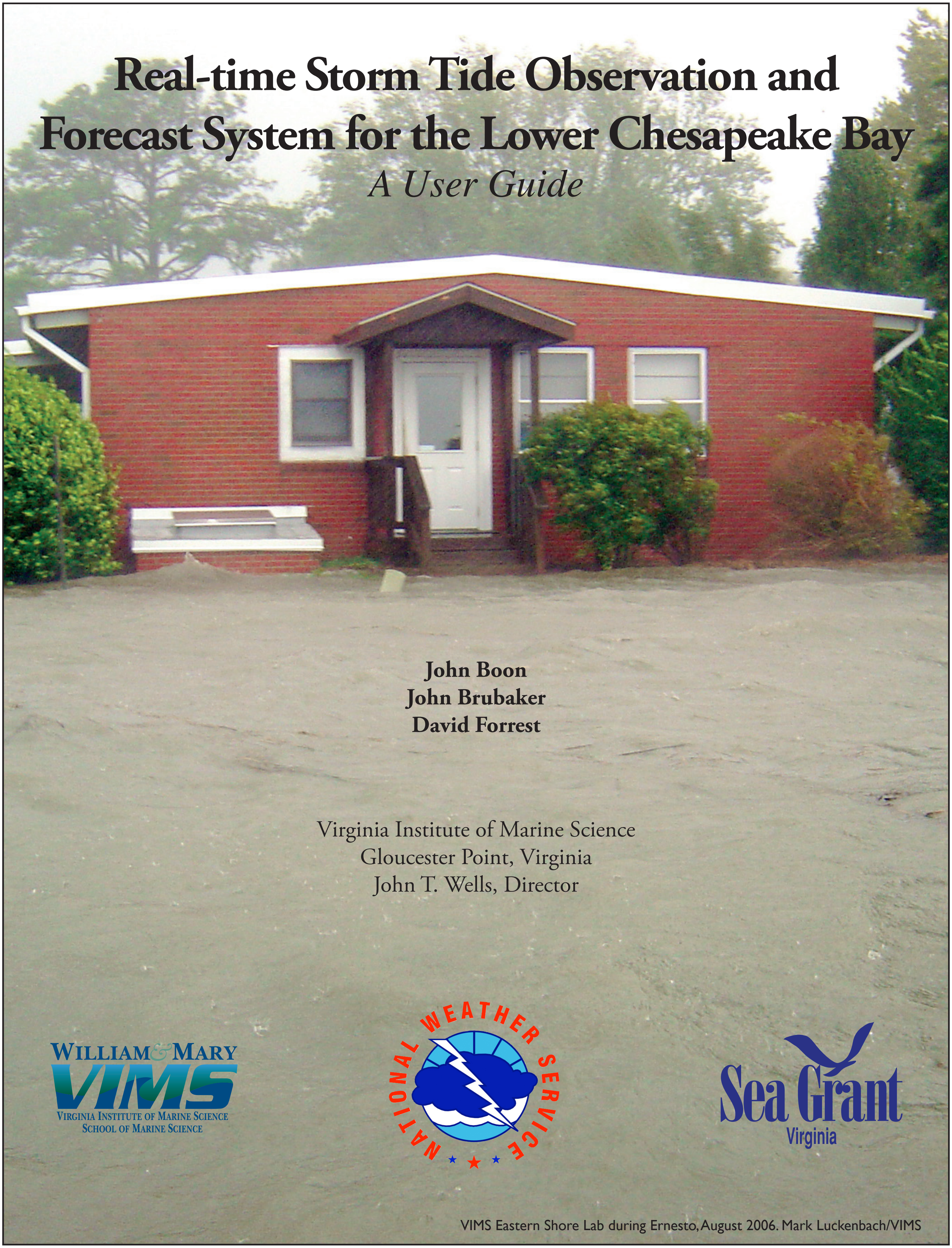
Real-time Storm Tide Observation and Forecast System for the Lower Chesapeake Bay

A User Guide



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VIMS Eastern Shore Lab during Ernesto, August 2006. Mark Luckenbach/VIMS

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FORWARD AND DISCLAIMER

The Real-time Storm Tide Observation and Forecast System (***Rstofs***) is an online service developed at the Virginia Institute of Marine Science (VIMS) to provide water level observations and forecasts at nine active tide stations in lower Chesapeake Bay. Its purpose is to provide continuously updated observations and forecast information to members of the U.S. National Weather Service (NWS), the U.S. National Oceanic and Atmospheric Administration, National Ocean Service (NOAA/NOS), state and local managers and emergency personnel in counties and communities at risk from flooding during tropical and extratropical storms.

Rstofs is a new system classified as *experimental* while continuing to undergo testing and evaluation. Until it becomes fully operational, access to this system is restricted to users who serve in an official capacity and whose duties and responsibilities include flood hazard response and mitigation. A public website providing water level observations without forecast information can be found at www.vims.edu/tidewatch.

Rstofs content includes unverified water level observations provided in near-real time by the NOS Center for Operational Oceanographic Products and Services (CO-OPS) in addition to unverified water level observations from tide stations maintained by VIMS. VIMS also generates a 36-hour water level forecast updated every half hour using extratropical storm surge (ETSS) forecasts provided online by the NWS Meteorological Development Laboratory in Silver Spring, MD.

<u>DISCLAIMER</u>: VIMS WATER LEVEL FORECASTS (RSTOFS), INCLUDING THE TIME AND HEIGHT OF FORECAST HIGH AND LOW WATER, ARE OFFERRED AS COMPUTER-GENERATED GUIDANCE. USERS OF THIS INFORMATION MUST ASSUME ALL RISK.

TABLE OF CONTENTS

	page
I. Rising Sea Level and Storm Tide Risk ……………………………………….	4
II. Understanding the Tide and Tidal Datums in Hampton Roads ………………...	5
III. VIMS Tidewatch (www.vims.edu/tidewatch) …………………………………	11
IV. VIMS Real-time Storm Tide Observation and Forecast System ………………	13
V. Tools for Providing Guidance ………….………………………………………	16
VI. Acknowledgements …………………………………………………………….	22
VII. References ………………………………………………………………………..	22

I. Rising Sea Levels and Storm Tide Risk

The lower Chesapeake Bay region is presently experiencing the highest rate of sea level rise relative to the land to be found on the U.S. East Coast. Relative sea level (RSL) has been accurately measured at active tide stations with long record lengths within the NOAA/NOS National Water Level Observation Network (NWLON) as shown in Fig. 1. RSL change measured relative to the land has two sources:

- *Subsidence* or *emergence* of the land relative to the center of the earth (or to the center of a reference ellipsoid representing the earth).

- *Absolute sea level* (ASL) trend - the worldwide change in sea level relative to the center of the earth (or to the center of a reference ellipsoid).

In the Chesapeake Bay region, subsidence accounts for slightly more than half of the average RSL rise rate (Boon et al., 2010). While there is still debate about how much ASL may change in the future, subsidence in lower Chesapeake Bay is almost certain to continue at a high rate for many years to come.

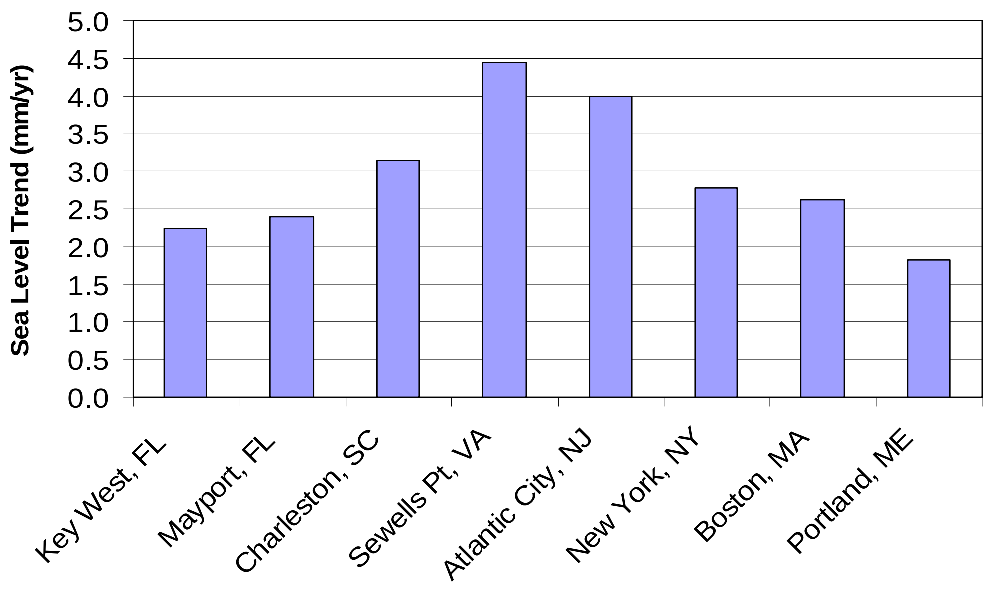


Figure 1. Linear RSL trends at eight NWLON stations along the U.S. East Coast based on total record length available at each station. Record lengths vary between 1928-2006 at Mayport, FL and 1856-2006 at New York, NY. Data from Zervas (2009).

<u>RSL trend</u> - From the perspective of increased flood risk, the RSL trend measured locally by a tide gauge is of central importance. Whether it is subsidence or ASL change that produces the almost 4.5 mm/year (1.5 feet per century) rate of rise at Sewells Point in Hampton Roads, VA (Fig. 1), RSL rise will directly impact the flood risk experienced by Hampton Roads communities as time goes on. Winter storms that caused only minor flooding in these communities in the past are likely to become an increasingly greater threat in the future.

Storm tide – A storm tide is the high water extreme produced by the combination of *storm surge* and the normal (*astronomic*) tide that occurs during a storm, in addition to other variations in water level that occur over longer periods of time. Storm surge results from the action of surface wind stress and low atmospheric pressure accompanying the storm. For a given amount of storm surge, a storm tide will reach a greater height if the peak of the surge happens to coincide with astronomic high tide, or an even higher level if this happens during a spring tide of greater range between high and low water. Other variations in water level include the *seasonal cycle*, an average cycle over the 12 months of the year. In Hampton Roads, the seasonal cycle reaches its highest levels in September and October on average and its lowest levels in January and February on average. At the long end of the time scale, an upward RSL trend continually adds to the ultimate height of the storm tide.

II. Understanding the Tide in Hampton Roads

Rationale - "Tides will be x feet above normal". Fill in the x and we have all heard this alert by the local media whenever a coastal storm is imminent. All the information given and all the information wanted in many cases. But what if the "tide" isn't normal? In July 2009 the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) issued an alert stating that

> "Observed tides have risen above predicted elevations along the entire U.S. East Coast from Maine to Florida since June. From June 19 thru June 24, water levels were between 0.6 to 2.0 feet above normal depending on location."

A full description of the event and likely reasons for its occurrence are given in NOAA Technical Report CO-OPS 051 by Sweet, Zervas and Gill, 2009, whose report is available at (http://www.tidesandcurrents.noaa.gov/pub.html). Storm surge was not among the reasons given in the report because there were no storms on the U.S. East Coast during June 2009. Water level variations of this kind are called *sea level anomalies*. Unlike the tide, these deviations from "normal" are not predictable. But because they are a type of change that occurs very slowly, a running average of observed water levels can be used to alert localities when water levels are elevated due to an anomaly. In the Chesapeake Bay region, sea level anomalies are most common in the months of September and October, a period when the risk of a tropical storm or hurricane is usually greatest.

Origin of the Tide – Whereas storm surge is caused by winds and atmospheric pressure change, astronomic tides are caused by gravity. The earth's gravity is just one force acting on the world's oceans - a very important one as it keeps them bound to the planet! The moon's gravity, though much weaker than the earth's, is still sufficient to set up horizontal (tractive) forces to which the oceans and seas respond. Weaker still is the sun's gravity but strong enough to exert its own influence. The combination of tractive forces from the earth-moon system can be thought of as a field of forces spread like a net over the globe (Fig. 2), driving the tides as the earth rotates inside the net. Although parts of it are hidden in Fig. 2, the net consists of two halves: one half facing the moon and tending to draw water toward the moon and one half on the opposite side of the earth tending to draw water away from the moon. A similar "net" is cast by the earth-sun system.

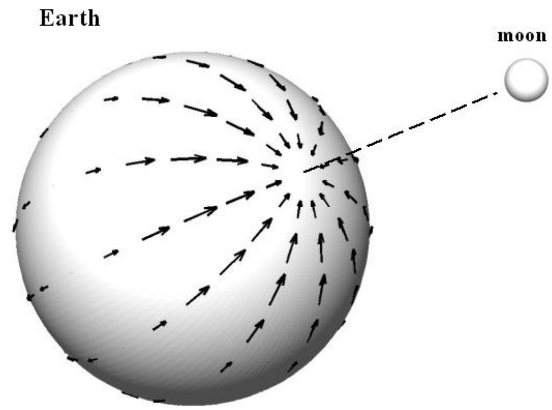


Figure 2. A "net" of lunar tractive forces cast over the surface of the earth that aligns with the moon. A similar net exists that aligns with the sun. Tides are produced as the earth turns inside both nets and the oceans respond (Boon, 2007).

According to equilibrium theory, a pair of tidal "bulges" should form at the points on the earth where the tractive forces converge: one point on the side toward the moon (Fig. 2) and the other on the side away from the moon. On an imaginary earth covered entirely by water to a certain depth, high water should occur just as the moon passes over the local meridian (and again as it passes the antimeridian on the opposite side of the earth) at a place where tides are recorded. This would happen twice in a *lunar day* or one earth rotation relative to the moon, a period of 24 hours and 50 minutes of solar time (also called a *tidal day*). However, the earth is not covered entirely by water and there is usually a lag between the time of the moon's passing the local meridian and the time of the next high water (in times past this interval was called the *establishment of the port*). Despite this drawback, the theory is still useful in visualizing how lunar and solar motions produce the tidal cycles we observe.

Lunar - Solar Cycles – Spring and Neap Tides

Borrowing from equilibrium theory, spring and neap tide can be explained as the result of conjunction or opposition between the lunar and solar tractive forces as the moon orbits the earth, a cycle of motion that takes 29½ mean solar days for recurrence of the same lunar phase; e.g., new or full moon (Fig. 3a,b). A mean solar day is the time required for one earth rotation relative to the sun averaged over the calendar year.

Figure 3a illustrates the occurrence of *spring tides* when the moon and sun are in line with the earth during either full or new moon. During this time, lunar and solar tractive forces combine to produce higher than usual high tides and lower than usual low tides; i.e., tides of greater *range*. With the aid of the tidal bulge concept (black margin surrounding the earth), it is easy to see that an observer on a rotating earth would first witness high tide at lunar noon, low tide 6 lunar hours later, another high tide 12 lunar hours later, another low 18 lunar hours later, and high tide again after one lunar day producing two highs and two lows.

Figure 3b shows the moon in quadrature positioned at a right angle to the earth-sun line. During this part of the lunar orbit, the lunar and solar tractive forces oppose one another and produce lower highs and higher lows – *neap tides* of lesser range. During a lunar month, spring tides and neap tides will each occur twice.

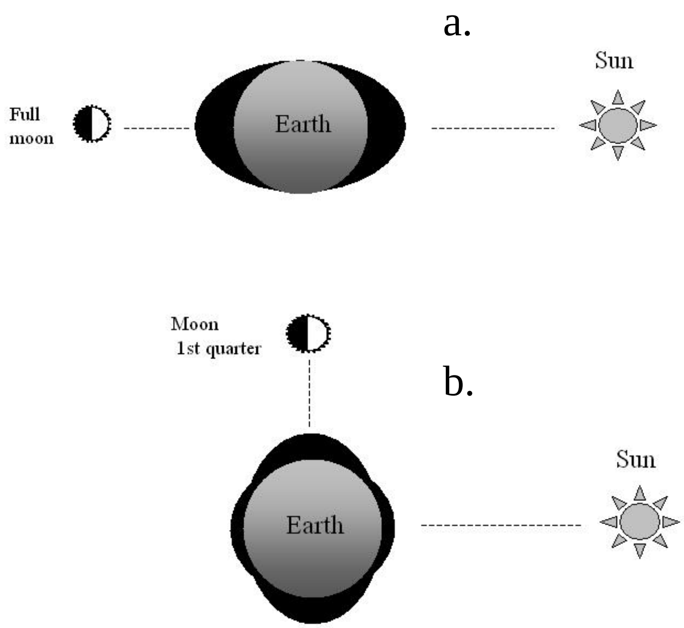


Figure 3. Spring tides of greater range occur as the moon in its orbit around the earth aligns with the earth and sun during full or new moon (a). During lunar quadrature, lunar and solar tractive forces oppose one another, producing neap tides of lesser range (b).

Lunar Cycles – Perigean and Apogean Tides

The moon's orbit around the earth is not a perfect circle but an ellipse. When the moon is farthest from the earth in its elliptical orbit (lunar apogee), its tractive forces are less because the gravitational force acting between two bodies such as the moon and the earth vary inversely as the square of the distance between them (for the tractive forces it's actually as the inverse cube of the distance). As in the case of neap tides, *apogean tides* have minimum range. Likewise, when the moon is closest to the earth in its orbit (lunar perigee) lunar tractive forces reach a maximum producing *perigean tides* of greater range. One cycle in lunar distance requires 27½ solar days to complete.

All of these cycles take place at once and the resulting change in water level as recorded by a tide gauge can appear rather complex. In making tidal predictions, both cycles are represented by a combination of three simple cosine waves, each having a fixed period of oscillation. These are given the symbols M2 for the main lunar semidiurnal wave, S2 for the main solar semidiurnal wave and N2 for the lunar distance wave (the waves are called *tidal constituents*, the basic components or "building blocks" of the tide). Because these three waves each have a different period that is not a multiple of either of the other waves, they continually pass in and out of phase. For example, when M2 and S2 are in phase, spring tides occur (Fig. 3a) and later when out of phase, neap tides occur (Fig. 3b). A few times a year when all three waves are in phase *perigean-spring tides* of maximum range occur. A month-long tide curve for the combined spring-neap, perigean-apogean cycles might look like the one presented below in Fig. 4.

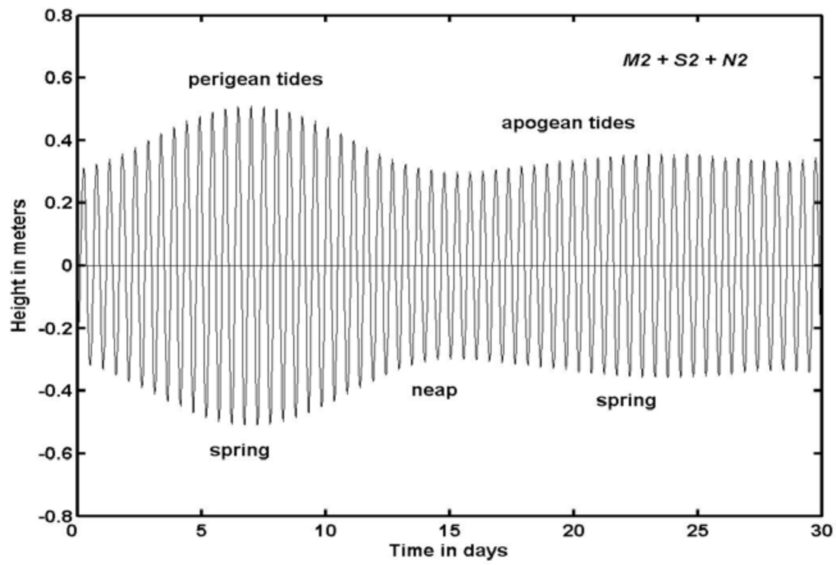


Figure 4. A 30-day tide curve produced by the M_2, S_2, and N_2 tidal constituents.

Lunar Cycles – Tropic and Equatorial Tides

The plane of the moon's orbit around the earth is inclined to the plane of the earth's equator. This results in another cycle called the lunar declinational cycle in which the moon in its orbit travels above and below the equatorial plane. As the moon is passing through the plane and thus lying on the equator, an observer (call him Joe) on the rotating earth will encounter equal highs and equal lows each tidal day (Fig. 5a). These are called *equatorial tides*. But later, as the moon reaches maximum declination north or south of the equator, the same observer may witness successive highs and/or lows that are unequal in height (Fig. 5b). This condition is referred to as a *diurnal inequality*. In the Chesapeake Bay region, diurnal inequalities appear mainly in the high waters observed during *tropic tides*. The lunar declinational cycle takes about 27 ¼ solar days to complete and is represented primarily by two tidal constituents with the symbols O1 and K1. Adding these to the M2, S2 and N2 constituents results in a monthly tide curve looking like the one shown in Fig. 6.

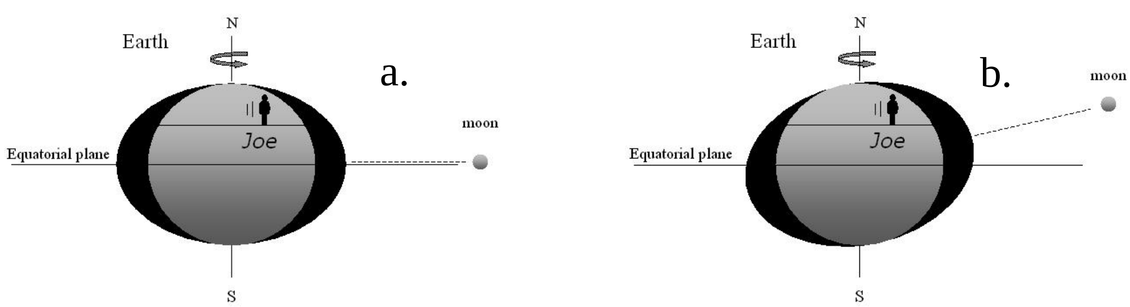


Figure 5. Equatorial tides of zero declination (a) and tropic tides of maximum north declination (b).

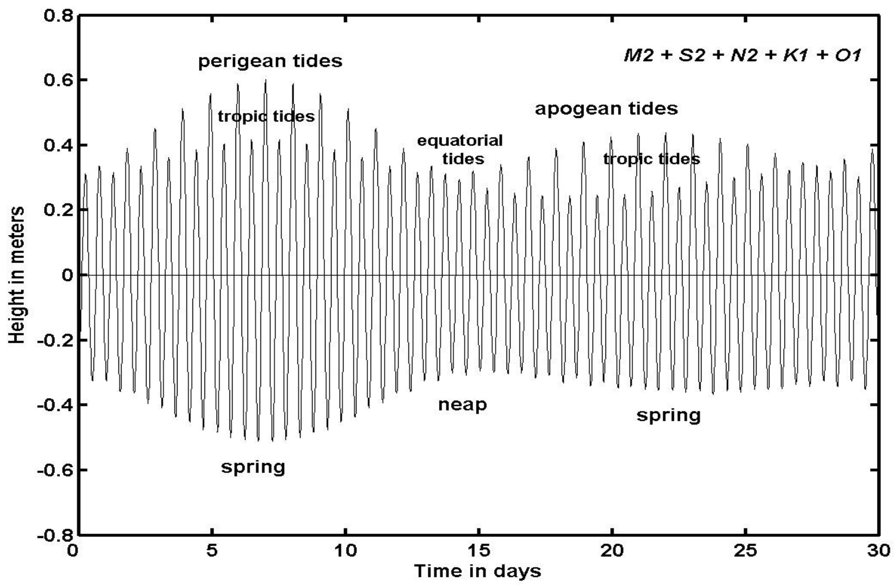


Figure 6. A 30-day tide curve produced by the M_2, S_2, N_2, K_1 and O_1 tidal constituents.

Why is this important?

It's important to recall that a storm tide consists of a storm surge combined with an astronomic tide. Whether or not a storm tide causes flooding of a neighborhood might depend on whether the peak surge happens to coincide with a high tide – and whether the high is likely to occur during a time of minimal tidal range (apogean-neap) or maximum range (perigean-spring). In this sense, there is no 'normal' tide and we should ask: Are mid-range tides about to become spring tides at the moment a decision is needed? Are equatorial tides giving way to tropic tides where one high water may be succeeded by another of still greater height? A glance at a graphic like the one in Fig. 6 as a storm approaches can offer valuable clues. To get the most recent 30-day water level history in lower Chesapeake Bay, go to our public web site at www.vims.edu/tidewatch. This site is described in section III.

Tidal Datums – Both the everyday tide as well as storm tides need a vertical reference. In the U.S., all tidal predictions are referenced to a *tidal datum* such as mean lower low water (MLLW), the chart datum used on nautical charts. MLLW is defined as the average of the lower of the two low waters that occur each tidal day over a 19-year period called the National Tidal Datum Epoch (NTDE). The current NTDE includes the years 1983-2001, a 19-year period that is updated by NOAA as need arises or roughly every 20 years in the Chesapeake Bay region. Anyone who doubts that relative sea level has been rising in our region should consider the fact that the NTDE has been revised upward three times since the first NTDE spanning 1924-1942! Other tidal datums such as mean higher high water (MHHW) are similarly defined, including mean sea level (MSL) defined as the average of the hourly tide heights recorded at a tide station over the current NTDE.

We use all three of the above tidal datums on our Tidewatch graphs. Although the "zero" for our water levels is MLLW, we also show MSL and MHHW on these graphs as horizontal lines. The difference in elevation between MHHW and MLLW defines the diurnal range of tide at a particular location. The reason for including MSL is explained below.

<u>What is extratidal water level?</u>

In addition to the U.S. tidal datums, we include two other tidal datums on our graphs that are used in other countries: Highest astronomic tide (HAT) defined as the *highest predicted tide* and lowest astronomic tide (LAT) defined as the *lowest predicted tide* at a location over the current NTDE. The tidal datum to which predictions refer is MSL. If this seems confusing, take another look at Fig. 4 and note that the predicted tide in that figure oscillates evenly about the zero line. This line becomes MSL when the predictions are referenced to a tidal datum; if we then choose to refer tides to another datum such as MLLW (to avoid a lot of negative numbers like those in Figs. 4-6) we simply add an *offset* equal to the MSL-MLLW difference.

While MSL remains fixed during the current NTDE, HAT and LAT mark the limits of the *intertidal zone*, a zone that boats and other vessels underway need to be concerned with - but not property owners as a rule. Waterfront houses, businesses and other land-based infrastructure need to be concerned only when the water level rises enough to produce an *extratidal high water* measured in feet above HAT. Vessels navigating shallow channels need to take special precautions when water level falls below LAT and produces an *extratidal low water* measured in feet below LAT.

<u>How do water levels become extratidal?</u>

Four possible ways:

- A storm surge adds to the astronomic tide raising water levels above HAT.
- Sea level rise raises mean sea level above MSL datum for the current NTDE.
- A sea level anomaly occurs such as the one described on page 5.
- There is a 'sub-tidal' variation in water level.

Sub-tidal variation in water level is a common feature in the Chesapeake Bay region. It is sometimes called the "weather tide" because it is forced by recurring weather systems rather than by lunar and solar gravity. Whereas storm surge typically has a limited duration measured in hours, sub-tidal oscillations have periods measured in days with amplitudes sometimes as large as the astronomic tide itself inside Chesapeake Bay. It can be argued that storm surge is, in fact, part of the sub-tidal change and simply emerges from it as a peak that exceeds the norm. Note that storm surge and sub-tidal variations can also be negative producing extreme extratidal lows.

In the following section we will show how to track each of the above parameters using the information available at the VIMS Tidewatch site.

III. VIMS Tidewatch (www.vims.edu/tidewatch)

Our public website displays water level series for the past 30-days, updated at half-hour intervals at nine tide stations in lower Chesapeake Bay. These include seven NOAA/NOS stations and two VIMS stations identified by the following 4-letter codes arranged alphabetically (see Fig. 11 for station locations):

Tidewatch – List of Active Stations

- BISH - Bishops Head, MD
- BRDH - Back River Dandy Haven, VA
- CBBT - Chesapeake Bay Bridge Tunnel, VA
- JMTN - Jamestown, VA
- KIPT - Kiptopeke, VA
- MNPT - Money Point, VA
- SWPT - Sewells Point, VA
- WMPT - Windmill Point, VA
- YRCG - Yorktown Coast Guard Training Center

An example of a Tidewatch 30-day graph is shown in Fig. 7 for CBBT during August and September, 2010. Water levels are given in feet above MLLW on the left side of the graph with the five tidal datums shown on the right with elevations in feet above MLLW. Tidal datums are fixed in elevation and will not change until NOAA/NOS issues an updated NTDE which will adjust (upward very likely) all five datums by roughly the same amount. Again, the main 19-year datum is MSL and the others are offsets from this datum. The red horizontal line marked m30 is not a tidal datum but a running mean of water levels over the past 30 days. Fig. 7 shows that mean water level locally (m30) was elevated by 2.10–1.42 = 0.68 feet relative to MSL, not unusual for this time of year. The difference m30-MSL is the *sea level anomaly*. It indicates the sea level that a coming tide and surge will build upon.

The difference between observed (red) and astronomic (blue) water level is the *residual* water level shown in green in Fig. 7. Unlike NOAA/NOS predictions, our astronomic water levels are computed every half-hour relative to m30 rather than MSL. This is done so that the residual curve will have a mean of zero over the past 30 days, allowing the sea level anomaly to be separated from the sub-tidal change and storm surge, if present. Incidentally, there are three sub-tidal peaks in the green curve in Fig. 7. Can you tell (without looking at the dates on the bottom axis) which one is due to Hurricane Earl?

Figure 8 illustrates a three-day plot. This one shows the last three days of a 30-day run ending August 24, 2010, 9:54 am local daylight time. Starting on August 21 at 10:00 am, the observed water level (red curve) and the astronomic tide (blue curve) were nearly identical with the residual (green curve) near zero. By the next day, however, the residual had begun to rise causing the observed water level to become extratidal by August 24 aided by a sea level anomaly of 0.43 feet (m30-MSL=1.85-1.42). Note that when water levels exceed HAT, three-day plots add a scale on the right showing feet above HAT and mark the time and height of extratidal high water (XHW) as of the latest update.

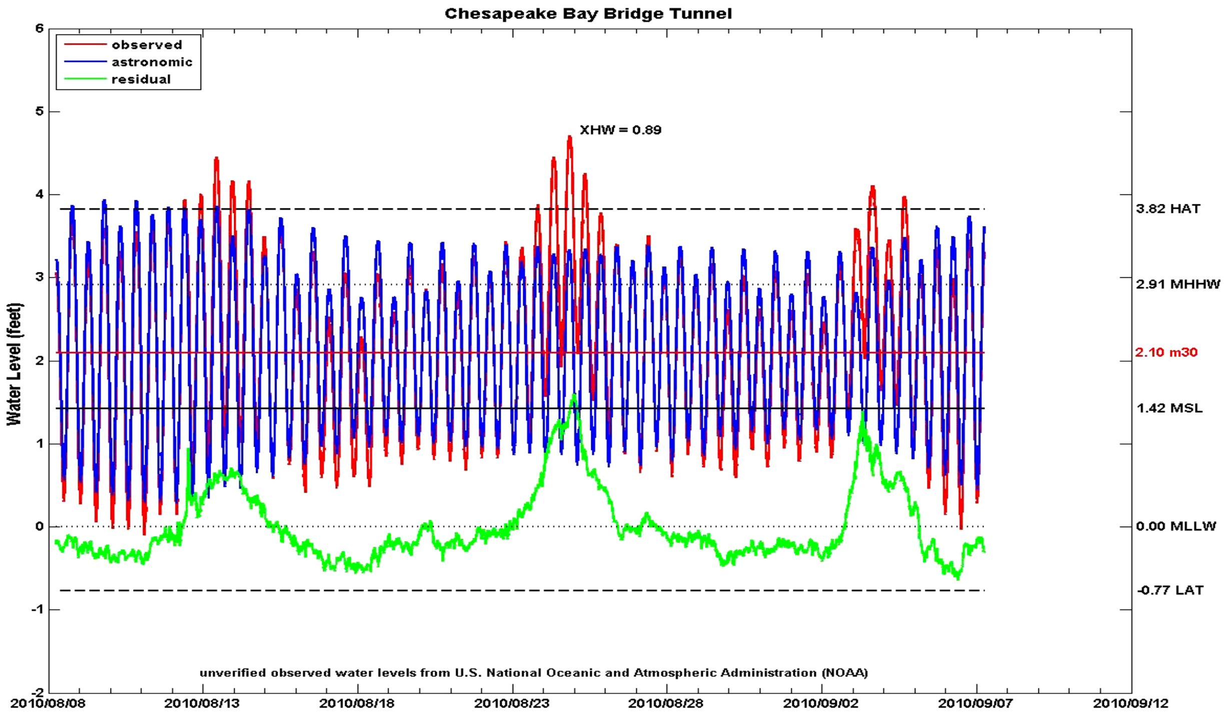


Figure 7. Thirty-day water level plot at the Chesapeake Bay Bridge Tunnel (CBBT) from August 8 to September 7, 2010. XHW = 0.89 feet is the highest extratidal high water (XHW) height measured above HAT. Note that Hurricane Earl (2010/9/03) did not produce this one!

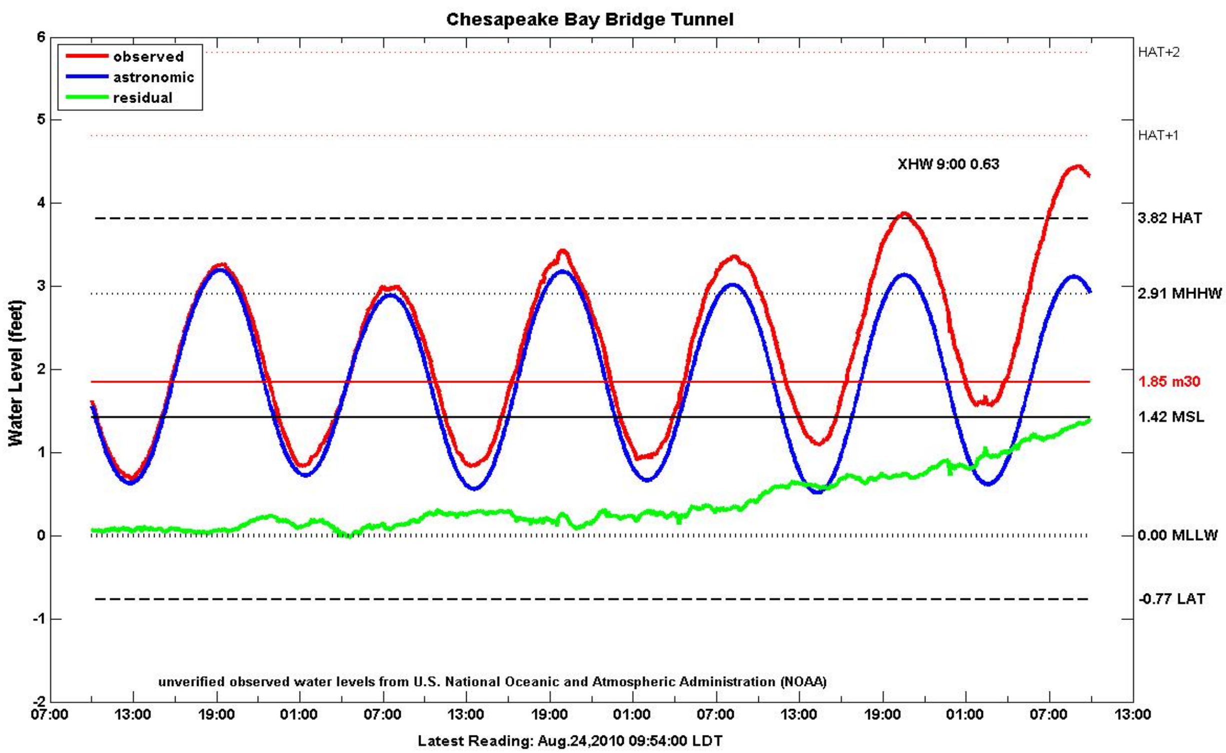


Figure 8. Three-day water level plot at the Chesapeake Bay Bridge Tunnel (CBBT). Tick marks on the bottom axis divide 24-hour times into 3-hour intervals. The date and time of the last reading received from the station (Aug.24, 2010 09:54 LDT) is shown in the caption below the bottom axis. Both local standard time (LST) and daylight savings time (DST) are used as appropriate. The time (09:00 LDT) and height (0.63 feet) of latest extratidal high water (XHW) are also displayed.

IV. VIMS Real-time Storm Tide Observation and Forecast System (***Rstofs***)

Rstofs is a 36-hour storm tide forecast that combines Tidewatch observational data with extratropical storm surge (ETSS) forecasts provided by the National Weather Service Meteorological Development Laboratory (NWS/MDL) in Silver Spring, MD. Using a hydrodynamic model driven by surface wind observations and forecasts, ***MDL*** generates ETSS forecasts for numerous locations, including the nine in Tidewatch. These are updated every six hours with each forecast providing modeled storm surge at hourly intervals for the next 96 hours after the forecast release.

Rstofs, like Tidewatch, is updated at half-hour intervals. The latest ETSS forecast is then used to extend the Tidewatch residual (green curve) 36 hours ahead and derive a 'total' water level forecast by adding it to the astronomic tide (blue curve) predicted ahead using tidal harmonic constants that we have derived for each station. The extended residual and 36-hour forecast are denoted by the dash-dot lines in Fig. 9 below at Back River, Dandy Haven, VA.

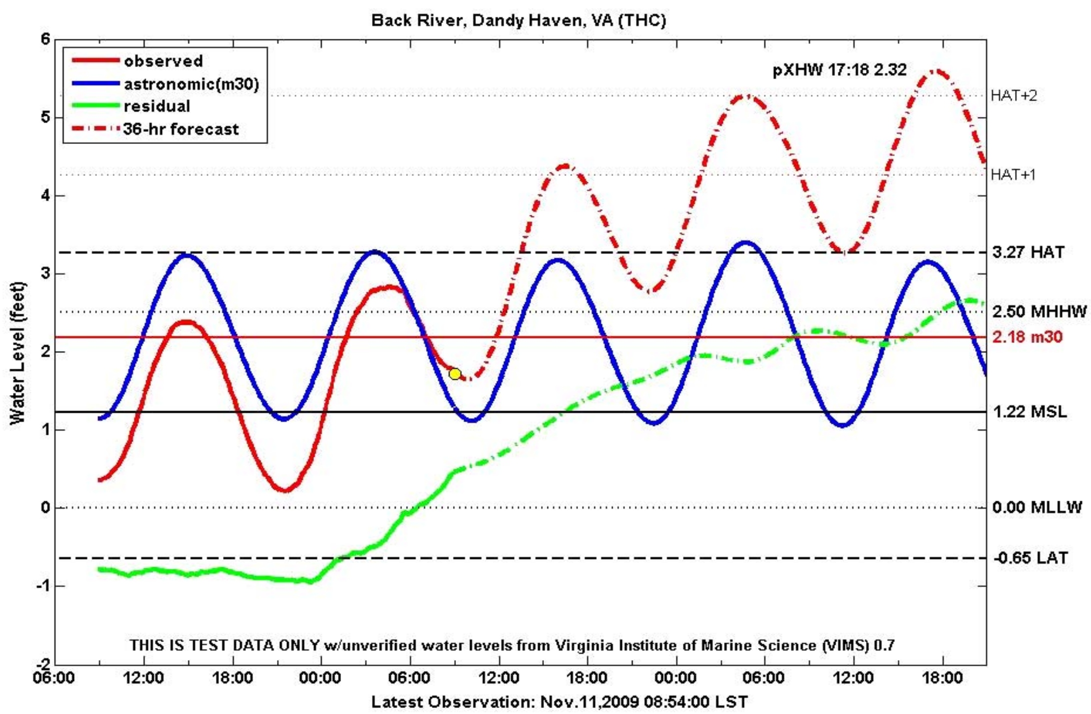


Figure 9. ***Rstofs*** forecast for Back River, Dandy Haven, VA, November 11, 2009.

Although the ETSS forecast is updated every six hours, it is adjusted every half-hour to match the ***Rstofs*** residual which we update half-hourly, thus making maximum use of the latest observational data. The residual, found as observed minus astronomic water level, is measured up until the time of the latest observation - and continues thereafter as the green dash-dot curve derived from the ETSS forecast. It then gives the forecast water level (red dash-dot line) when added to the astronomic tide. Note that the highest *predicted* extratidal high water (pXHW 17:18 2.32) is marked on the graph as the third of three XHW high waters expected. Multiple XHW occurrence is typical of large northeasters.

Navigating the ***Rstofs*** Web Page

To access the ***Rstofs*** site online, go to http://sura-vims-pe6600-1.vims.edu/~drf/RSTOFS/. Authorization is required to enter this site; *Rstofs* is a new system whose forecast guidance material is still undergoing test and evaluation. Prior to implementing a fully operational service, it is our plan to interact with a limited number of users whose requirements and mandates will help determine the final configuration of ***Rstofs***. Contact John Brubaker (brubaker@vims.edu), David Forrest (drf@vims.edu) or John Boon (boon@vims.edu) to obtain information on becoming an active participant with assigned user ID and password.

The screenshot shown below (Fig. 10) illustrates the present configuration of ***Rstofs*** *version 1*. Three-day graphs with 36-hour forecasts for nine locations form a column on the left and, where available, the corresponding ***MDL*** extratropical water level forecast is shown in the column on the right (via link to http://www.nws.noaa.gov/mdl/etsurge/). Links provided in the lower left corner below each ***Rstofs*** graph can be used to view the corresponding 30-day graph in Tidewatch.

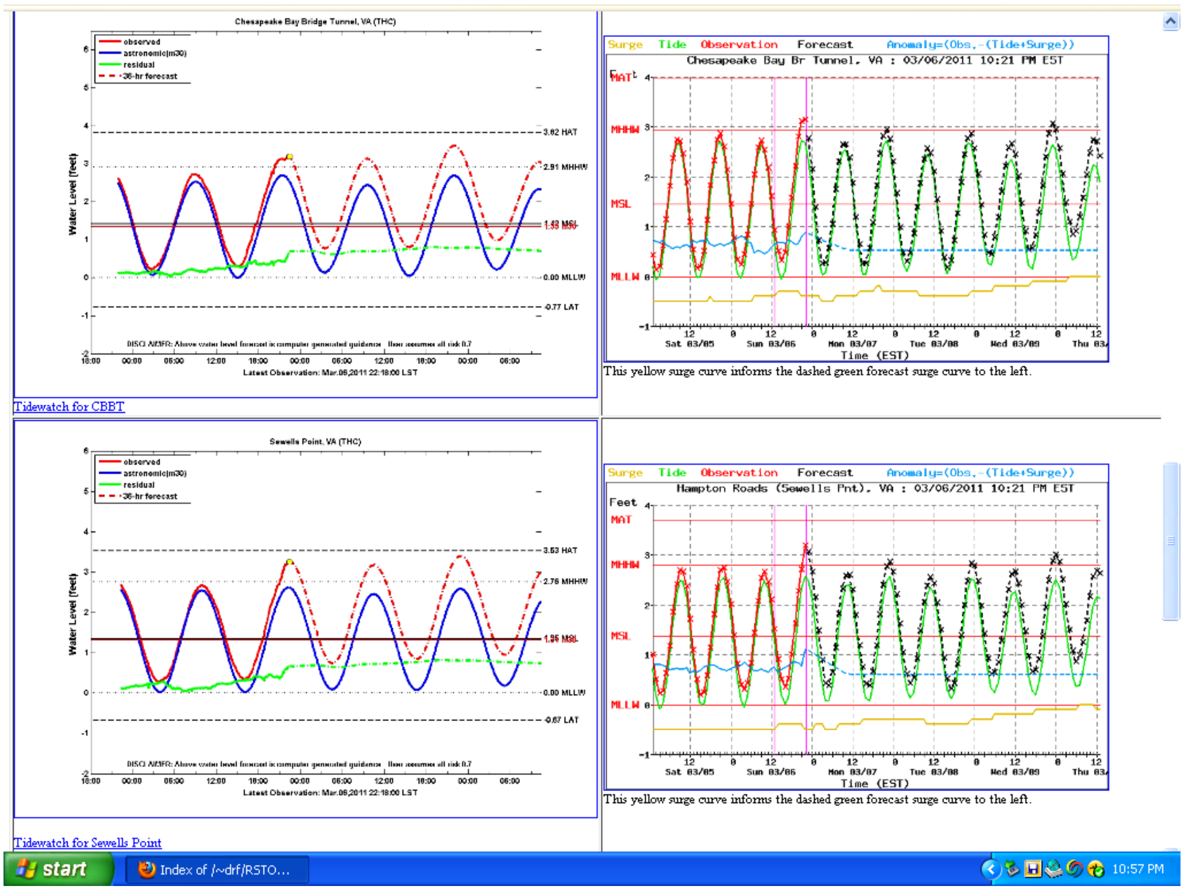


Figure 10. Screenshot of web page showing layout of ***Rstofs*** and ***MDL*** graphics.

Station locations for both ***Rstofs*** and ***MDL*** forecasts are shown in Fig. 11. Note that ***MDL*** forecasts for Gloucester Point, VA and Portsmouth, VA do not include observed water levels as these stations are no longer active. Caution should be used in utilizing forecast information at either station.

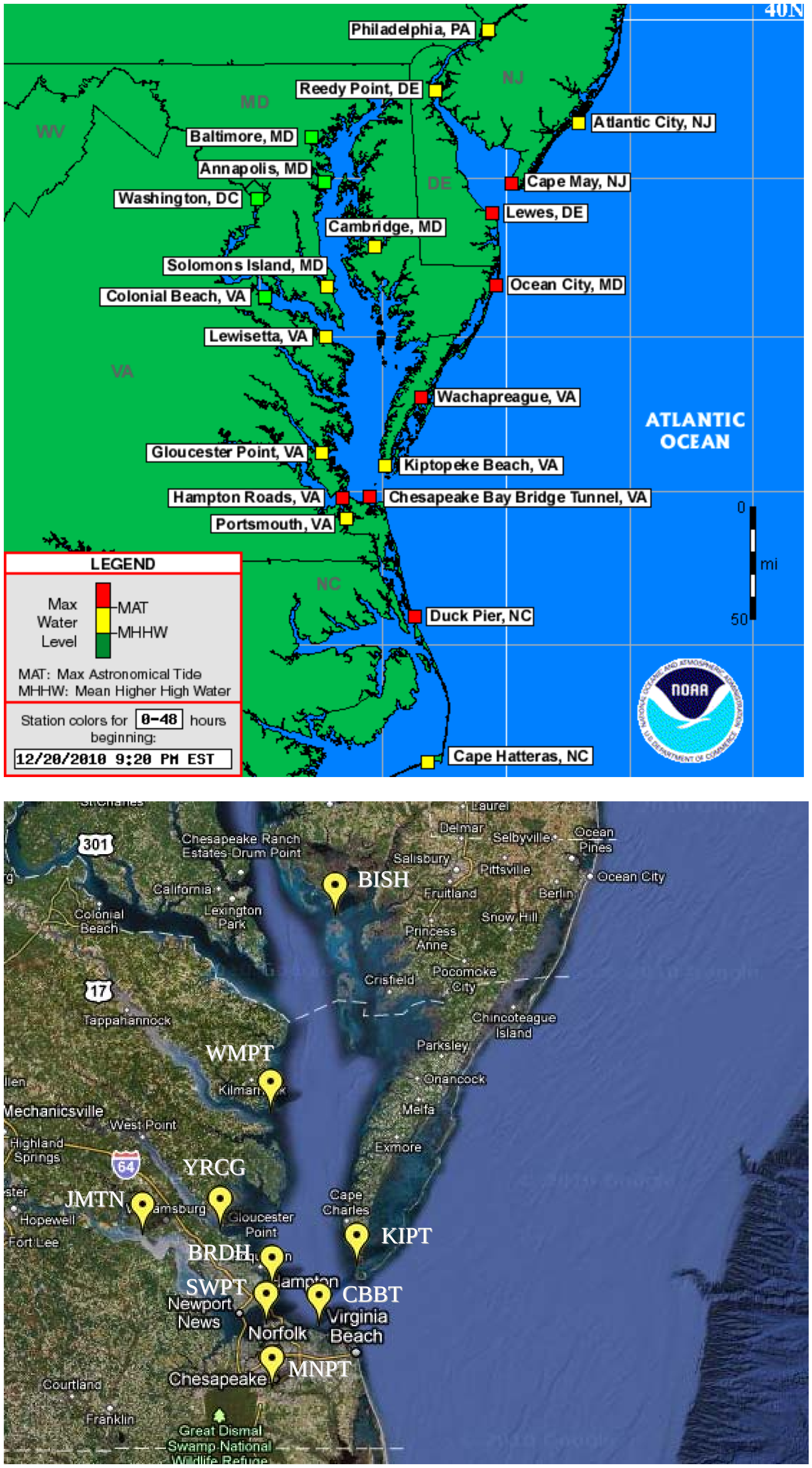


Figure 11. Location of ***MDL*** (upper map) and ***Rstofs*** (lower map) forecast stations.

V. Tools for Providing Guidance

Three-day graph: ***Rstofs'*** primary tool for storm tide guidance is the three-day water level graph of the type shown in Fig. 9. This graph contains the immediate information needed to evaluate the present water level situation and the situation likely to develop over the next 36 hours. It is updated half-hourly at all stations except BRDH which is updated hourly.

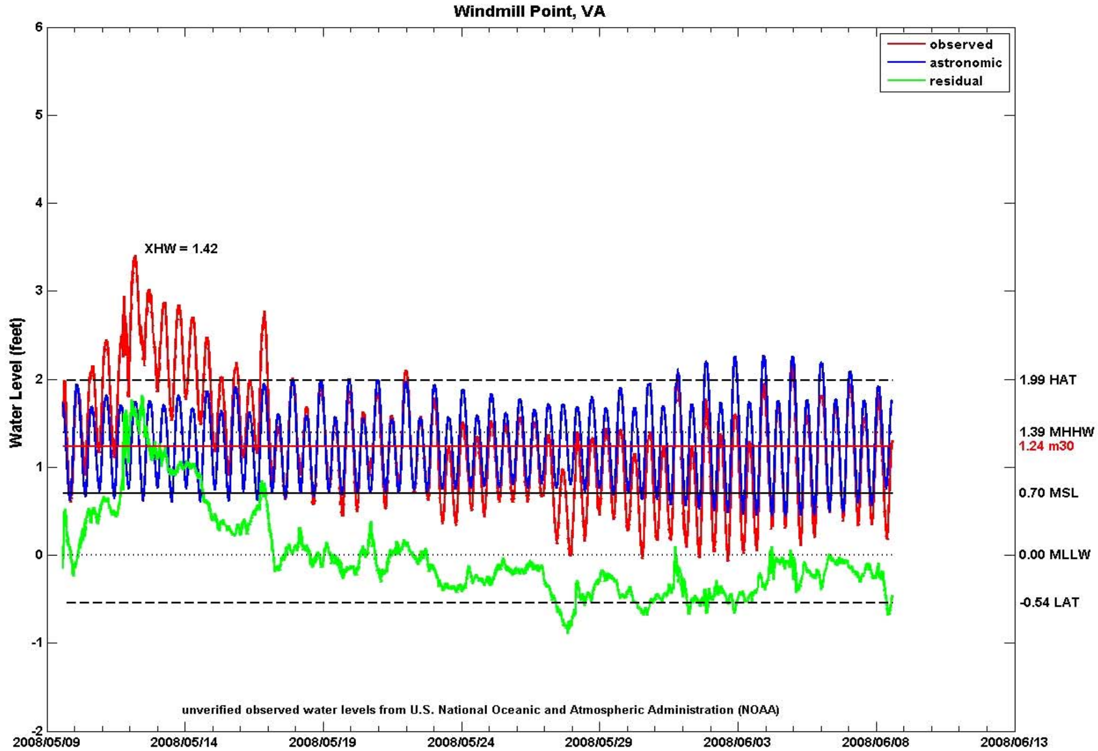
- High Water Time and Height – The time and height of the next three high waters expected is information of obvious importance to residents and property owners. This is especially the case for extratropical storms which are capable of producing a series of damaging high waters spanning more than one day. Although ordinarily a lesser threat than a named hurricane, these normally unnamed storms can still flood parked cars and introduce several inches to a foot or more of water inside homes and businesses. Given adequate warning, owners can move cars and take steps to protect homes and other infrastructure.

- Height in feet above HAT – We suggest highest astronomic tide (HAT) as the preferred tidal datum for referencing storm tide heights. An example from spring 2008 may help to show why. A storm on May 12, 2008 produced a storm tide of 1.64 feet above HAT at Money Point (MNPT) and 1.42 feet above HAT at Windmill Point (WMPT), a difference of 0.22 feet (see Fig. 12). If referenced to chart datum, the same storm tide height would be 5.54 feet above MLLW at MNPT and 3.41 feet above MLLW at WMPT, a difference of 2.13 feet, nearly ten times as great. Although other factors are involved, including differences in storm surge height and time of arrival, much of the 'inflation by datum' is due to the difference in tidal range at these two stations; e.g., a diurnal range of 3.22 feet at MNPT compared to only 1.39 feet at WMPT. The better choice, we believe, is to use HAT as a baseline when selecting a metric for flooding actually experienced. Persons standing near this baseline on May 12, 2008 would have experienced water up to their knees at both MNPT and WMPT. This would not be true using any other datum as a baseline, including a geodetic datum such as NAVD88.

Thirty-day graph: A graph showing water levels over the past 30 days approximately a lunar month is useful in a number of ways. As explained on p. 11, comparing short-term mean sea level (m30) with epochal mean sea level (MSL), gives a quick indication of the *sea level situation* (i.e., the sea level anomaly, m30-MSL). If the sea level is elevated at one location in lower Chesapeake Bay, it tends to be elevated at other locations as well due to the influence of deep ocean processes. In addition, forecasters should not overlook the *subtidal situation* which is indicated by the residual (green curve). If it is trending towards a low, it may offset the effect of a raised sea level – or add to it if trending towards a high.

- Raised (lowered) sea level means the astronomic tide is raised (lowered) relative to the usual datum of prediction, MSL, by the amount m30-MSL.

- Residual (subtidal) change is an irregular wave oscillating around zero level. When a storm surge arrives, it adds to the current position of the wave, high or low.



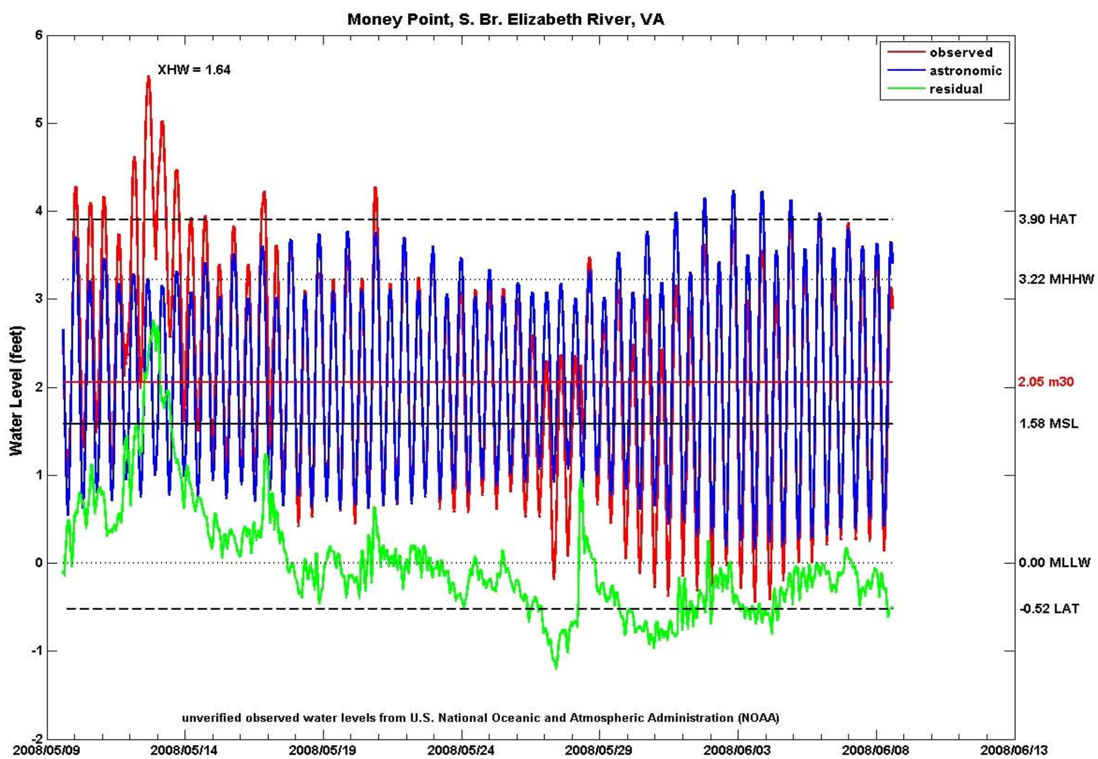


Figure 12. Storm tide of May 12, 2008, at Windmill Point, VA (WMPT, upper graph) and Money Point, VA (MNPT, lower graph). The extratidal high water (XHW) height of 1.42 feet above HAT at WMPT is close to the XHW height of 1.64 feet above HAT at MNPT, evidencing a similar flooding experience on this day at both locations despite the difference in diurnal range: 1.39 feet at WMPT compared to 3.22 feet at MNPT.

Extratropical storm, November 11-13,2009 – This strong nor'easter - called 'Nor'Ida' by some because of the influence of Hurricane Ida's remnants – produced exceptional extratidal water levels over a three-day period. Figure 9 shows one of the early forecasts made on the morning of November 11, just before the storm's arrival at BRDH; Figure 13 illustrates the situation 24 hours later.

The upper graph in Fig. 13 presents a three-day window on water level variation. Note that as the water levels continue to rise, the 'feet-above-HAT' scale on the right expands to cover the highest storm tides appearing in the 36-hour forecast. In this case, all three high waters in the forecast are expected to be above HAT + 3 feet and one is expected to be above HAT + 4 feet which past experience has indicated will produce flooding on a scale comparable to Hurricane Isabel.

The lower graph in Fig. 13 shows a residual curve that had been trending downward for the past seven days prior to the storm's arrival on November 11, reaching a low of about one foot below 'zero' at this time. The zero in this instance is the average of the residual 'wave' representing the *subtidal variation* over the past 30-days[1]. This drop in water level was enough to effectively cancel out the *sea level anomaly* (m30-MSL) which was also about one foot but trending in the positive direction. The forecaster should recognize that the residual could just as easily have been zero or rising above zero. If the subtidal variation and the sea level anomaly had each attained a positive value before the storm, their sum would have meant that the *storm surge* would have begun rising from a possibly much higher elevation when it arrived in Hampton Roads on November 11.

The above statement assumes no interaction between the meteorological events driving the subtidal variation and the event producing the storm surge superposed on it. Additional study is needed to verify this assumption - or to determine if there is interaction and the form it may take. But in the interim it makes good sense to bring up the 30-day graph and view both the subtidal change and the sea level anomaly to analyze the situation about to unfold.

Figure 14 shows a 3-day Tidewatch graph for Money Point (MNPT) during the November 2009 storm. A record high of HAT + 4.69 feet was recorded, slightly higher than the storm tide recorded during Hurricane Isabel at this station. Below the figure is a table (Table 1) comparing the extratidal high water extremes recorded at MNPT and seven other stations in the lower bay during the November 2009 storm. Note that BRDH is ranked second behind MNPT if height above HAT is used as the reference; it falls to fourth position if MLLW is used as the reference, replaced by two nearby stations with a larger tidal range (CBBT and SWPT).

Figure 15 shows the effect of the November 2009 storm on the shoreline at the south end of Cedar Island, one of the barrier islands on the Virgina eastern shore region.

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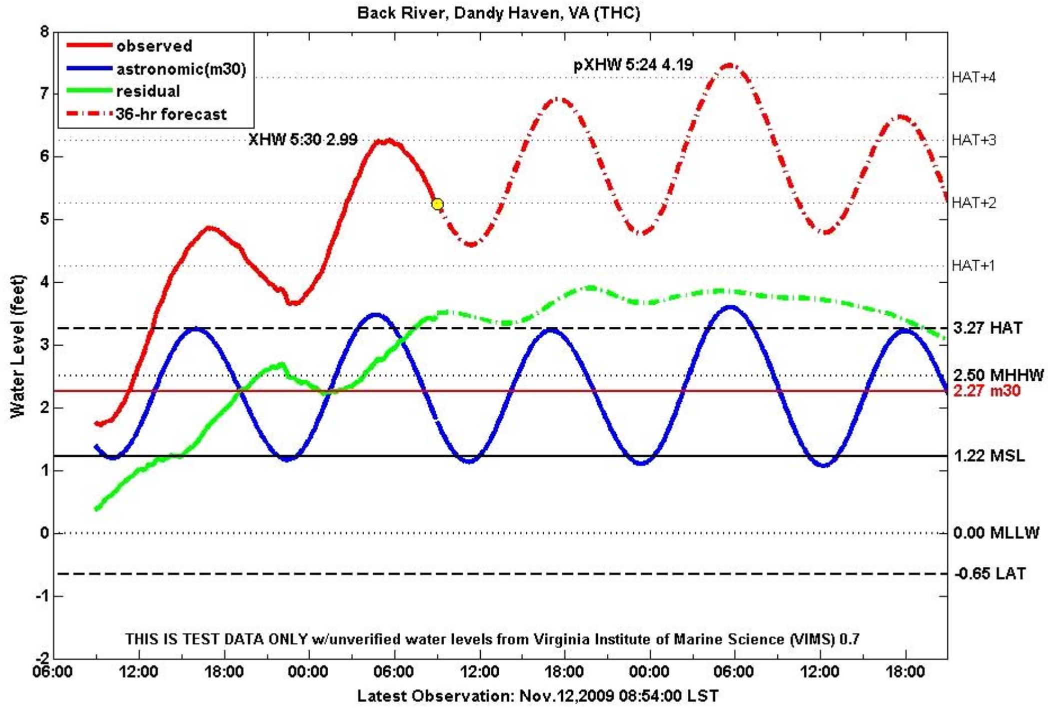
[1] Since both the observed water level and the astronomic tide over the past 30-days each have the same mean (m30), their average difference (the residual mean) must be zero. The residual in this case behaves like a wind wave whose average height over time is the still water level or 'zero' level at the measurement station.



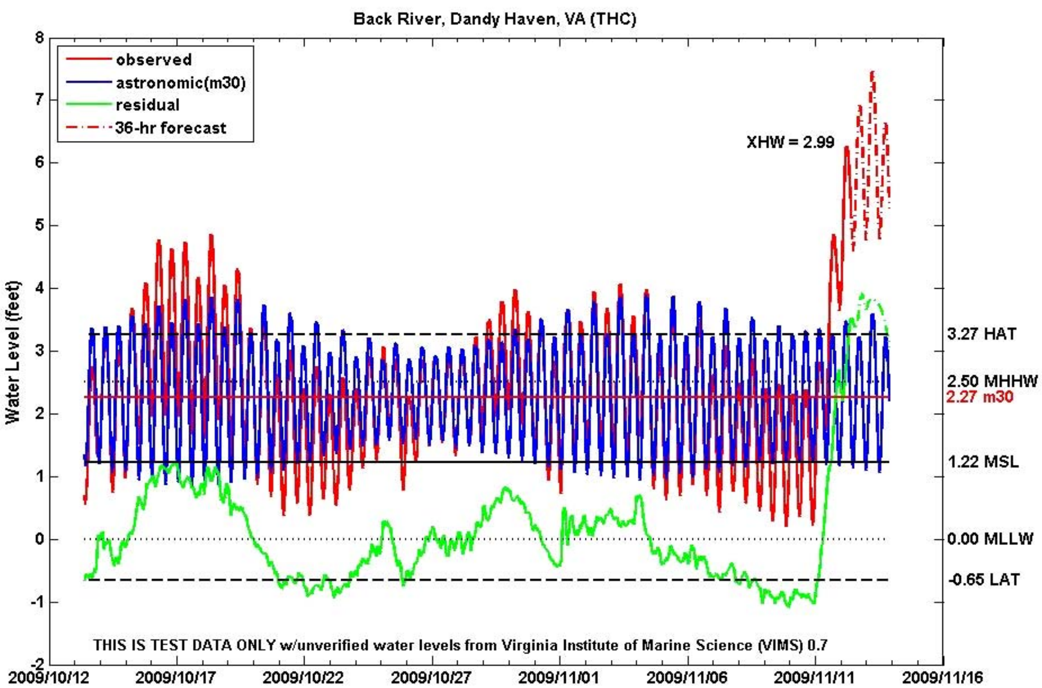


Figure 13. Storm tides of November 11-13, 2009 at Back River, Dandy Haven (BRDH). Three-day graph (upper graph) forecast three successive high waters above HAT+3 feet. Thirty-day graph (lower graph) shows storm surge began when residual water level was nearly 1 foot below the 30-day mean, offsetting a sea level anomaly of +1.05 feet. The maximum water level forecast was 4.19 feet above HAT, compared with 4.22 feet above HAT as later observed.

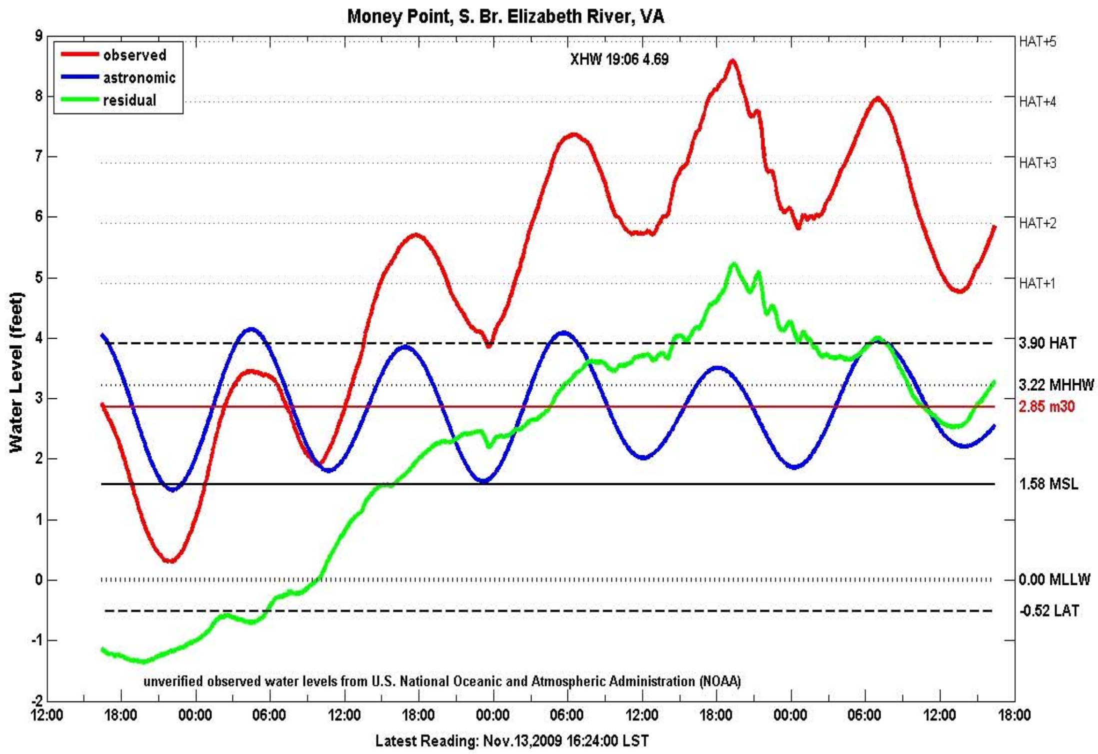


Figure 14. Storm tides of November 11-13, 2009 at Money Point (MNPT) from VIMS Tidewatch.

Table 1. Ranking of extratidal high water extremes in Virginia, November 2009 storm.

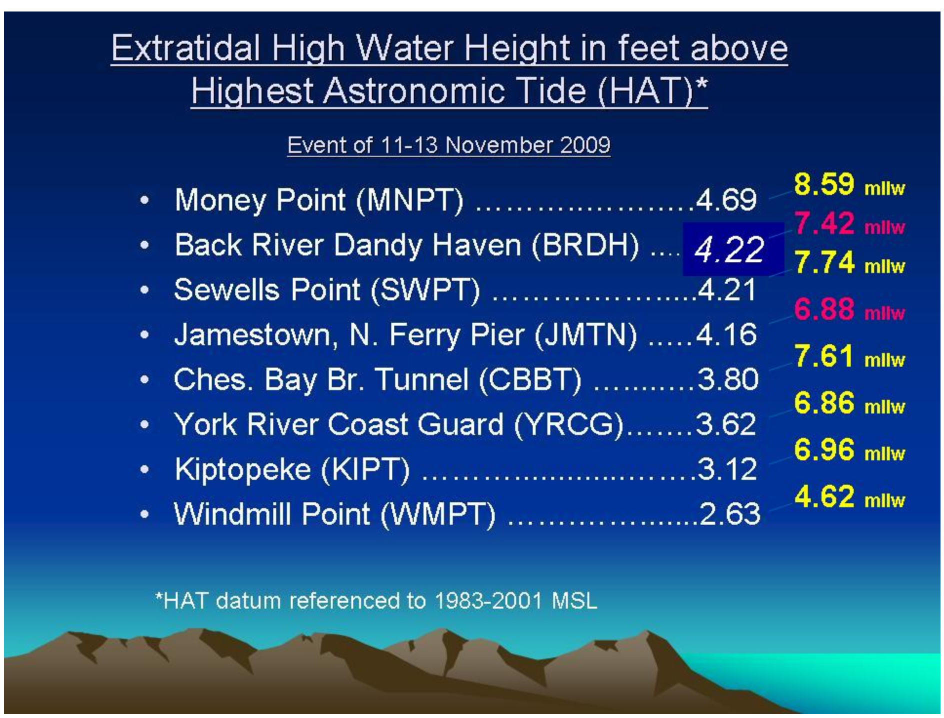


Figure 15. Shoreline erosion at the south end of Cedar Island, eastern shore of Virginia.

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