

PREPARING FOR A STORM TIDE: WHERE IS YOUR HAT?¹

Warnings given for an approaching hurricane or tropical storm about to make landfall include two primary elements: *wind velocity* and *storm surge*. While the risk of damage from high winds is straightforward, the risk of flooding due to a storm surge is not: the storm surge is only one of the components that will determine the maximum height reached by rising water levels. To distinguish it from a storm surge, the maximum height observed is called a *storm tide*.

A storm tide and a storm surge are not the same thing. Why is this important? It's important because storm surge taken alone represents a "static" risk. For example, a storm surge computer model will always produce the same answer given the same input, whether the year is 2006 or 1933 or 1066. The risks posed by storm tides are not at all static but change with time. In most coastal regions of the world, sea level is rising and storm frequency appears to be increasing as the result of global warming. Storm tides are quite sensitive to these effects as this article will show.

Certain government agencies speak of *the 100-year storm* when defining flood zones in the United States. By that they mean that every year carries the same 1-in-100 chance of encountering that storm, not that anything else is changing from one year to the next. This is far from true. Not only do we find mean sea level increasing by almost three feet per century relative to the rapidly subsiding land around New Orleans, Louisiana, but we also have an ongoing game of chance or joint probability involving storm surge, astronomical tide and the most recent stand of sea level at the time of the storm. Many combinations are possible and a wide range of storm tide heights can occur as a result.

Some examples are presented here to demonstrate the utility of a simple vertical reference commonly used outside the United States called *Highest Astronomical Tide (HAT)*. As the name implies, HAT marks the highest elevation that can be reached by a predicted (astronomical) tide. Derived through tidal analysis, it's an extreme prediction that does not occur every year. HAT is a natural datum for storm tides because it marks the elevation at which normal water levels end and abnormally high levels begin.

Want to know where HAT is located on your waterfront property? All it takes is a series of water level measurements suitable for analysis. Those who build coastal structures can then determine their elevations relative to HAT and by using this datum, determine the projected risk from storm tides. Storm tide height comparisons from one storm season to the next and from one location to the next can be made easier by measuring each storm tide by its height above the highest level reached by astronomical tides: HAT. The term *Extratidal High Water (XHW)* is proposed for storm tide heights referenced to HAT. As you will see, water levels cannot exceed HAT and become extratidal in the absence of both a storm surge and an accompanying mean water level that deviates from the tidal datum of Mean Sea Level (MSL), the parent datum referencing the predicted tide². An *Extratidal Low Water (XLW)* can also occur below *Lowest Astronomical Tide (LAT)*.

¹ Article revised 11 February, 2007. See note at end of final page.

² Predicted heights can also refer to other vertical datums that are offset from MSL by a fixed amount.

Hurricane ISABEL and the “Storm King” of Chesapeake Bay

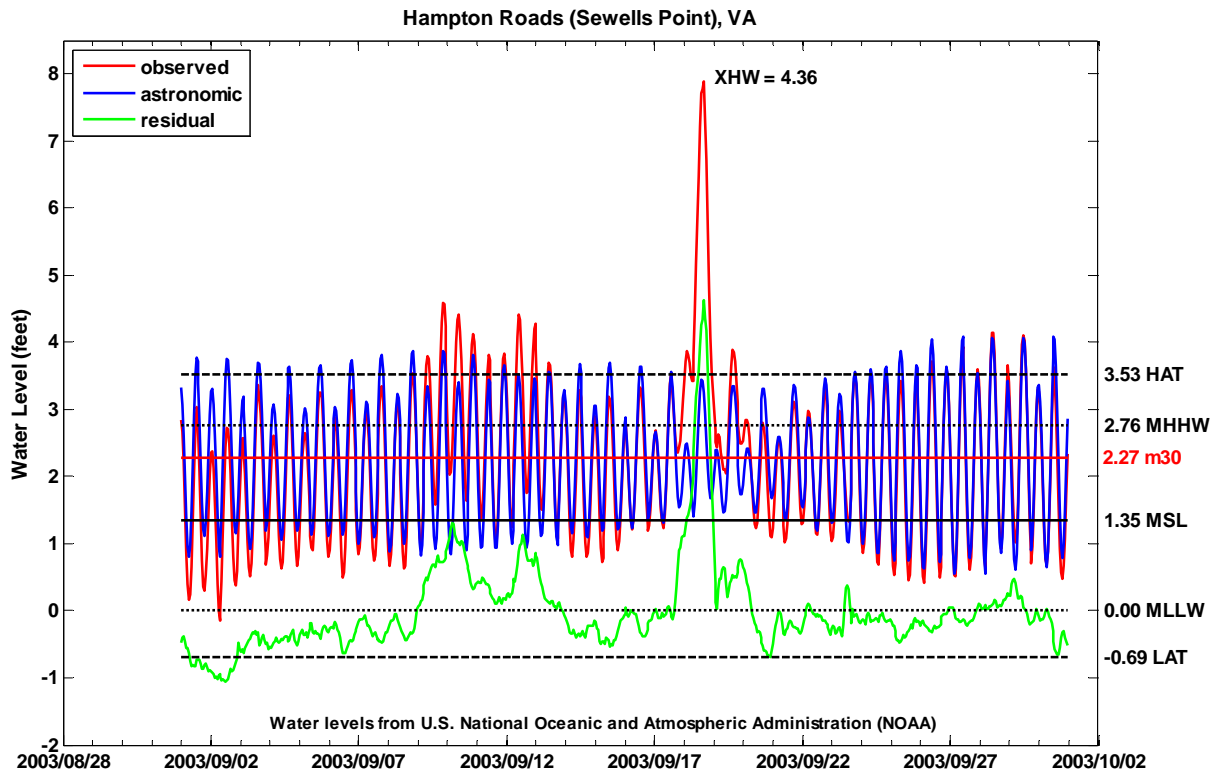
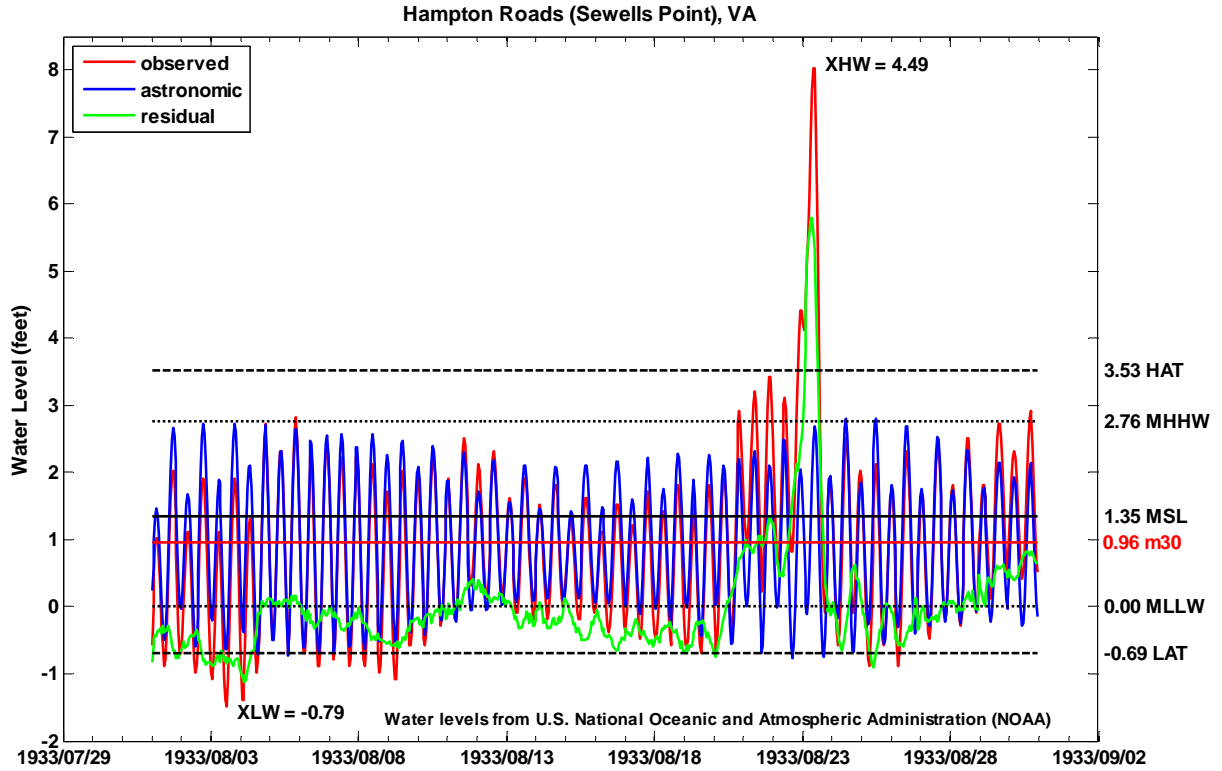
Hurricane ISABEL made landfall on September 18, 2003, producing severe coastal flooding in North Carolina, Virginia and Maryland. The Chesapeake Bay response to this event brought immediate comparison with the “Storm King” hurricane of August 23, 1933 which produced the highest observed water level on record in Hampton Roads: *8.02 feet (2.44 m)* above the tidal datum of Mean Lower Low Water (MLLW)³. The comparison seemed well-justified as ISABEL produced a peak water level of *7.89 feet (2.40 m)* above MLLW at Hampton Roads and may have exceeded this height at locations farther inland.

A more detailed comparison, however, shows that the “Storm King”, a presumed “100-year storm”, is in no danger of losing its title to ISABEL or any other storm the region has experienced in the last 100 years. The peak water levels noted above are correctly known as storm tides, the observed water level extremes referred to a fixed vertical reference on land, usually one of the tidal datums defined by the U.S. National Ocean Service (NOS), a division of the National Oceanic and Atmospheric Administration (NOAA), at the tide stations it operates in the United States and certain other countries. Storm tides are examples of the “total tide”: the sum of the astronomical tide (the everyday change in water level due to gravitational interactions between the earth, moon and sun), the storm surge (the transient change due to the effects of the storm), and long-term change (sea level rise, seasonal and decadal change). The infinite number of ways in which these three components can combine dictates the final outcome: the storm tides that residents of the coastal zone will experience.

What makes the “Storm King” so formidable? Rated as a category 3 hurricane on the Saffir-Simpson scale, the *5.8 foot (1.8 m)* storm surge produced by the 1933 storm was a foot greater than the *4.8 foot (1.5 m)* storm surge produced by ISABEL, a category 1 hurricane by the time of her arrival in Virginia. The 1933 storm also encountered more extreme astronomical tides (spring tides nearly in phase with the storm surge). ISABEL matched the August 1933 storm tide through the third component: a net sea level change of approximately 1.3 feet in the seventy years between August 1933 and September 2003. The graphs on the following page show how this occurred, but to fully understand sea level change, a brief explanation of the tidal datums shown on the right side of the graphs is needed along with a precise definition of what is called the sea level anomaly.

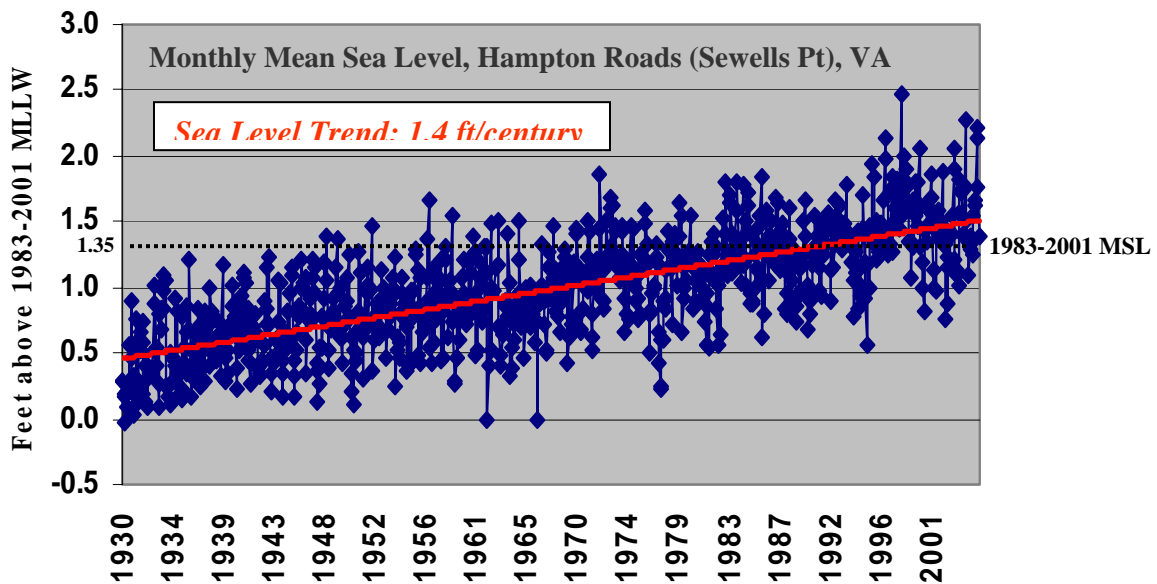
Tidal Datums - A set of commonly used tidal datums appears on the right side of the above graphs along with their respective elevations in feet. Three of them (MHHW, MSL and MLLW) are defined by NOAA/NOS and two others – Highest Astronomical Tide (HAT) & Lowest Astronomical Tide (LAT) - are based on the definitions previously stated and are used in the United Kingdom and most other countries outside the United States. In the United Kingdom, LAT has been used as the chart datum (vertical reference for depth soundings) because predicted tides never fall below it, yet it is not so low that it results in unduly shallow depths being shown on nautical charts (to paraphrase the Admiralty Manual of Hydrographic Surveying).

³ MLLW – average of the daily lower low waters observed over the 1983-2001 National Tidal Datum Epoch.
MHHW – average of the daily higher high waters observed over the 1983-2001 NTDE.



Of the datums shown above, only MSL is actually used for tracking sea level change. At U.S. tide stations, it represents the accepted mean sea level elevation measured above a fixed but arbitrary point on land called the station datum (STND). NOAA defines MSL as the *arithmetic mean of the hourly heights measured over the National Tidal Datum Epoch (NTDE)* and it periodically revises the 19-year NTDE in response to changing sea level. Past revisions include 1924-1942 MSL, 1941-1959 MSL, 1960-1978 MSL and most recently, 1983-2001 MSL. As previously noted, all other datums are simply offsets from MSL that reflect local tidal characteristics (tidal range). HAT and LAT represent the extremes of the predicted tide, a function of the tidal harmonic constants determined at a tide station rather than an average over the NTDE. A 19-year wait is not required for them, just good tidal constants!

Sea Level Anomaly – NOAA’s update of MSL roughly every 20 years is one of the few government standards to explicitly recognize that sea level is changing. Because a new NTDE is time-consuming and costly to devise, MSL serves as a “temporary” benchmark against which sea level change month-to-month and year-to-year can be measured. A plot of *monthly mean sea level (mmsl)* for each calendar month over seventy-five years at Hampton Roads reveals an upward linear trend with an average rise rate of approximately 4.3 mm/year (1.4 feet per century) relative to 1983-2001 MLLW as shown below.



Although the fit of the red line to the above mmsl data convincingly supports a linear trend of rising sea level at Hampton Roads, there is still a considerable amount of scatter above and below the trend. The Sea Level Anomaly (SLA) is defined as the vertical difference between a selected mmsl value and MSL. As such, it consists of both the sea level trend and the observed monthly deviation from that trend.

Extratidal High Water: A Qualified Measure of Risk

An Extratidal High Water (XHW) includes any high water level that exceeds the limits of the local astronomical tide as defined by Highest Astronomical Tide (HAT). However,

storms can cause water levels to drop as well as rise and for some applications, an extratidal water level below Lowest Astronomical Tide (LAT) may be significant as well. During a storm event, there can be numerous instances of extratidal high water and of course the maximum XHW level recorded is usually the one of interest.

A standard for comparison - A typical XHW is produced by a sea level anomaly coupled with a storm surge in combination with the astronomical tide. To compare storms such as ISABEL in September, 2003, and the August 1933 hurricane, it is necessary to adjust for the change in sea level between these events. This can be done using the sea level anomaly (SLA) values shown in the following table:

Storm	SLA	XHW (unadjusted)	XHW (adjusted)
Sep2003	0.92 ft	4.36 ft above HAT	3.44 ft above HAT
Aug1933	-0.39 ft	4.49 ft above HAT	4.88 ft above HAT

Without its SLA of plus 0.92 feet (2.27 less 1.35), ISABEL’s XHW would be reduced from 4.36 feet to 3.44 feet above HAT. Without its SLA of minus 0.39 feet (0.96 less 1.35), the August 1933 XHW would increase from 4.49 feet to 4.88 feet above HAT. Two points can now be made:

- Adjusted for the SLA, the XHW levels from August 1933 and September 2003 compare in the ratio 4.88 to 3.44 or 1.4 to 1.
- Had the “Storm King” occurred in 2003 in combination with the SLA and the astronomical tides for September 18th of that year, its XHW would have reached a height of approximately 5.8 feet above HAT (4.88 plus 0.92).

Recent Observations – The year 2006 has been called a “quiet” year in which none of the more dire hurricane forecasts have come to pass. What kind of XHW, then, can one expect in a quiet year? Three recent events provide an answer that isn’t so quiet.

Tropical depression ERNESTO occurred on September 1, 2006 and an unnamed northeaster later occurred on October 7, 2006. Both of these storms caused flooding at various locations in lower Chesapeake Bay and its major river tributaries. The flooding was unexpected as neither storm was accompanied by an advisory warning for extreme water levels. Of the two storms, ERNESTO produced a slightly higher storm surge at Hampton Roads – approximately 3.6 feet as compared to 3.4 feet for the October 7 northeaster. The northeaster, however, produced XHW = 2.96 feet above HAT as compared to XHW = 1.98 feet above HAT during ERNESTO at Hampton Roads – a difference of almost a foot.

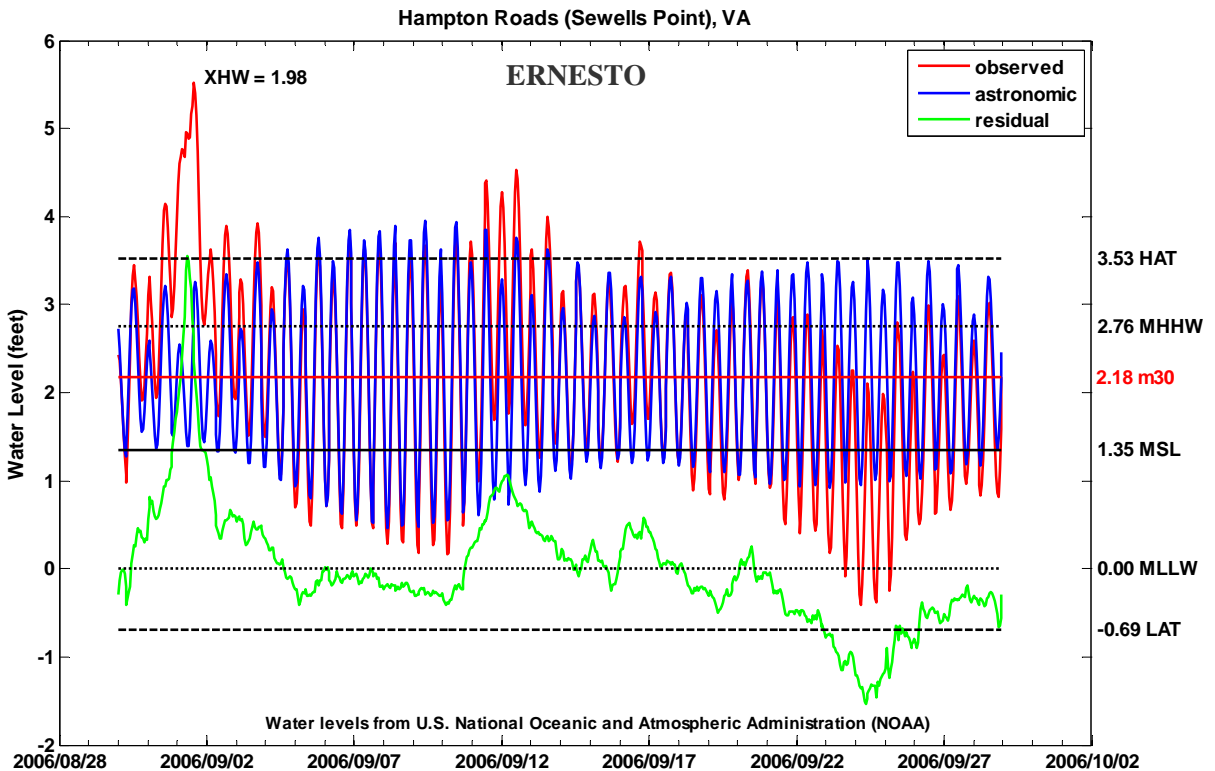
The reason for this difference is easily seen in the two graphs shown on pages 6 and 7. ERNESTO occurred during neap tides of minimum range and its storm surge peaked near

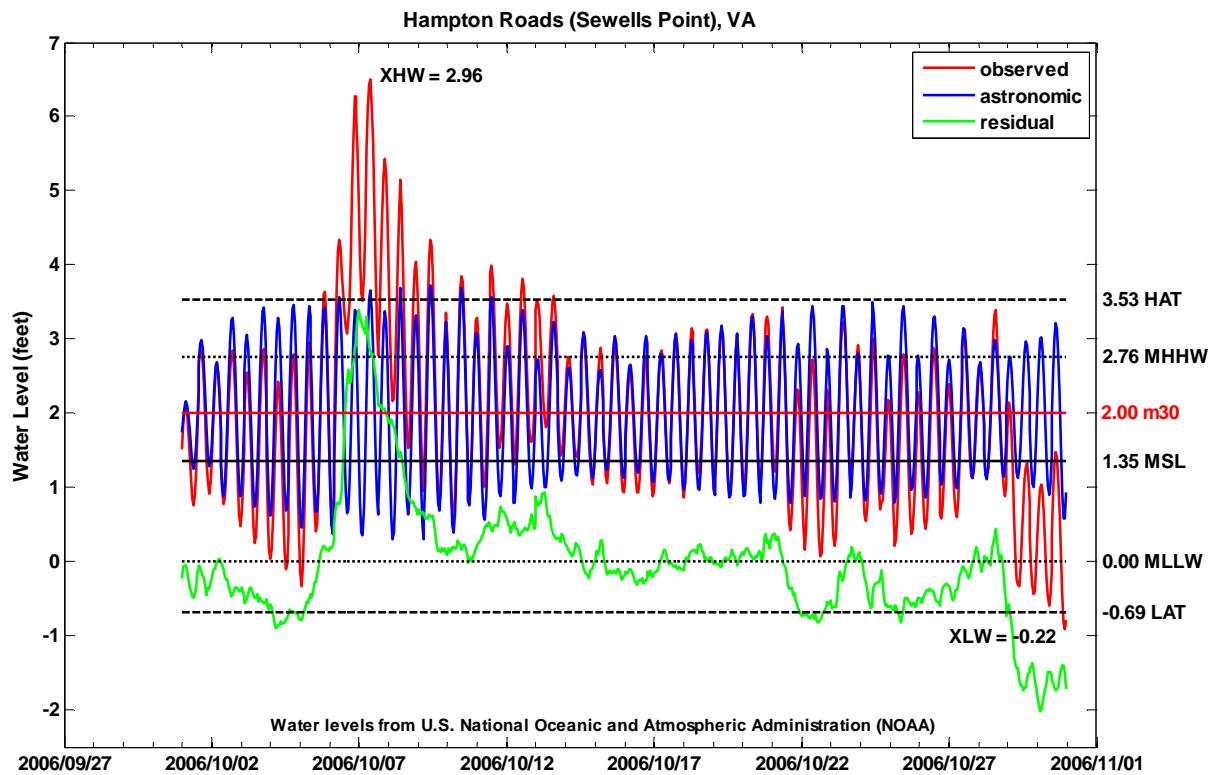
a low astronomical tide. In contrast, the northeaster occurred during a perigean-spring tide of greater than usual range and its storm surge peaked near a high tide.

Given that ERNESTO in September and the northeaster in October occurred within a month of one another, it's no surprise to find that their SLA values are similar. But it is very interesting to note in the table below that the adjusted XHW for a mere northeaster in October 2006 amounted to almost half the adjusted XHW produced by the "Storm King" of August 1933. Northeasters deserve our respect.

Storm	SLA	XHW (unadjusted)	XHW (adjusted)
Sep2006	0.83 ft	1.98 ft above HAT	1.15 ft above HAT
Oct2006	0.65 ft	2.96 ft above HAT	2.31 ft above HAT

What type of flooding attends water levels reaching 1.15 feet and 2.13 feet above HAT? At Gloucester Point, VA, both of the above storms forced several inches of salt water inside the River's Inn Restaurant, the adjoining ship's supply store and a yacht broker's office on a pier at the York River Yacht Haven. This case and others raise a question as sea level continues to rise and hurricanes become more frequent: Shouldn't there be a new and smarter strategy for designing structures to withstand the extratidal high waters that are most likely to occur over time? Or a strategy not to build in high risk areas?

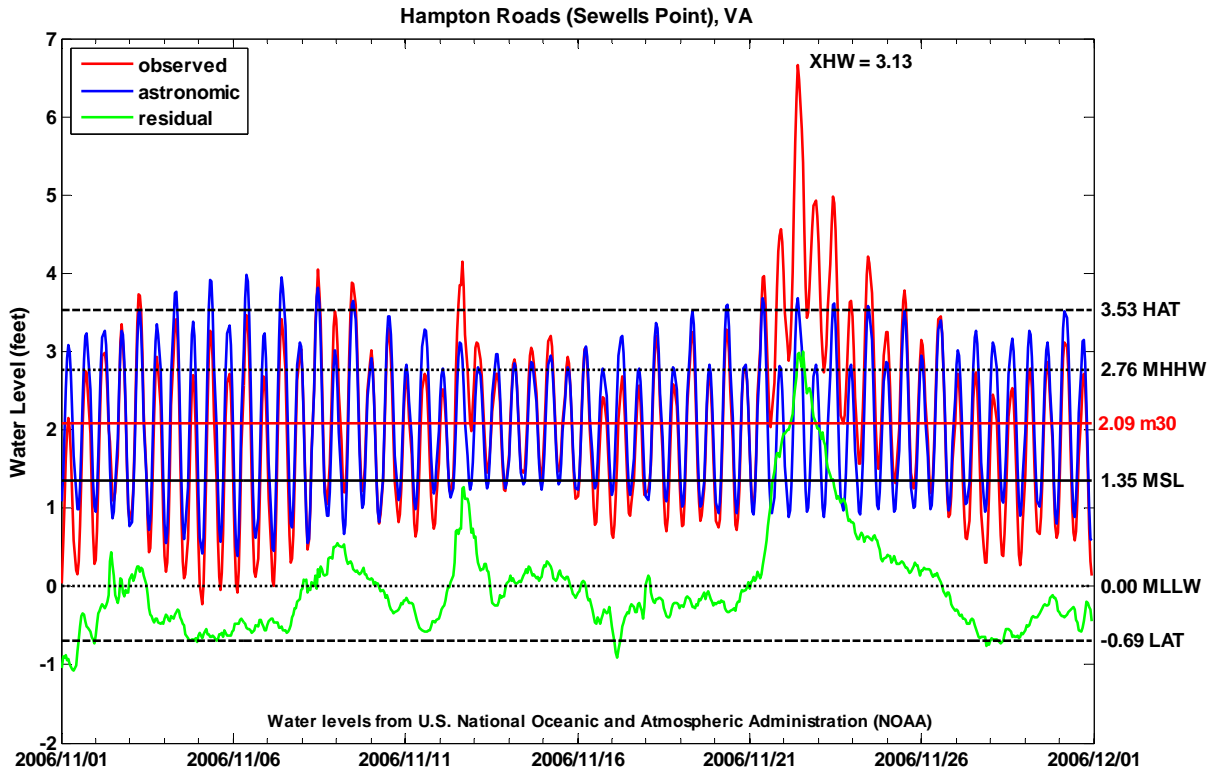




Another one!

As this article was about to be posted on the Web, yet another northeaster found its way into Chesapeake Bay. Some “quiet” year! The “Thanksgiving” northeaster produced a storm tide of 3.13 feet above HAT, the largest XHW for the year at Sewells Point in Hampton Roads.





NOTE: This article was revised February 11, 2007, to correct the elevations of Highest Astronomical Tide (HAT) and Lowest Astronomical tide (LAT) at Hampton Roads. The computations made for the original article did not include the seasonal tidal constituents S_a and S_{sa} in the astronomical tide formula that determines HAT and LAT. In the lower Chesapeake Bay region, this correction significantly increases the predicted range of the astronomical tide by raising the elevation of HAT and lowering the elevation of LAT relative to MSL. This has the effect of making determinations of extratidal water level more conservative and less likely to be overstated.