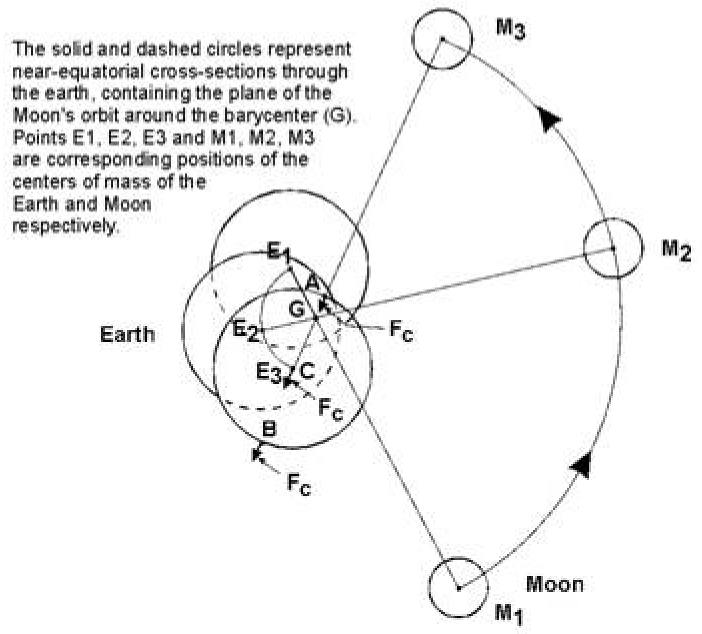
Tides, Sea Level and Water Currents

Contents

Basic Theory

A brief introduction to the tidal forces is contained in Our Restless Tides, by the National Oceanographic and Atmospheric Administration (NOAA) in the United States. The approach is fairly conventional, with basic graphics. An example of one such graphic is:



From "Our Restless Tides" NOAA

Figures such as the one reproduced above serve an important purpose, but there are alternative approaches that some may find preferable, particularly with the easy availability of web-based animation software. A very informative on-line tutorial "Introduction to ocean tides" is available (after you register) through "Meted", a cooperative online learning group. Another online introduction to tides that uses animated images is that of Professor M. Tomczak of Flinders University. Additional related references are listed at the Scripps Institution of Oceanography.

Most introductions, including Our Restless Tides and Professor Tomczak's website, explain tides in terms of a balance between gravitational and centrifugal forces. It is such an explanation that led to the figure above. Alternatively, introducing the concept of the "tidal potential" many of the complexities (such as illustrated in the figure above) of the force balance can be avoided. The Canadian Tidal Manual (Warren, 1983), online (in pdf format), discusses both approaches. This text requires slightly more advanced mathematical knowledge, but only by understanding the tidal potential can one understand the theoretical basis for the harmonic method of tidal analysis. It is more than twenty years old, but the theory has not gone out of date.

Finally, Pugh (1987) and Pugh (2004) have chapters on tidal theory written in a modern, textbook style.

Tidal Terminology

The National Tidal Centre hosts the comprehensive NTC glossary with an emphasis on Australian terms (for example, the tidal datums favoured in Australian jurisdictions). The Australian Hydrographic Service (AHS) glossary, the Manly Hydraulics Laboratory (MHL; NSW Dept of Commerce) glossary, and the Maritime Safety Queensland (MSQ; Queensland Department of Transport) site contain a number of pertinent definitions in an Australian context. The Land Information New Zealand (LINZ) site contains a concisely worded, but limited selection of tidal definitions, and NOAA's tidal glossary defines tidal terms in the context of US usage. It also defines a number of oceanographic terms, such as "Kuroshio Current". The International Hydrographic Organisation (IHO) Hydrographic Dictionary, available for a fee, is a large compendium of all sorts of hydrographic and oceanographic terminology, including tidal.

Analysis and Prediction

The purpose of tidal analysis is to represent the water level or current time series by a set of harmonics, or sine waves, each of them having a specific amplitude and phase. The set of amplitudes and phases are known as the tidal constants. While the **Australian National Tide Tables (ANTT)** publishes 22 constants plus a mean level for each port, the official predictions created by the NTC uses 112 (given that there is at least one year of observations available for analysis). The definitions of four of the major constants are given below, these four constants can be used to classify the tidal character of a site (see section 1.3.3 Tidal Classification). There are two main methods for analysis: the harmonic method, and the response method. As the latter is used almost exclusively as a tool of scientific research, only the harmonic method will be discussed.

Constant	Definition
Major Diurnal Constants	
O^1	Principle Lunar diurnal constituent
K^1	Principle Lunisolar diurnal constituent
Major Semi-Diurnal Constants	
M^2	Principle Lunar semidiurnal constituent arising from the Earth with respect to the Moon
S^2	Principle Solar semidiurnal constituent arising from the Earth with respect to the Sun

Tidal analysis

The harmonic method is based on the concept of the tidal potential (see above). It is difficult to find books that set out in detail the process of analysis for the tidal constants, which are based on a simultaneous linear regression for each of the amplitudes and phases (which may number over 100). Warren (1983) and Pugh (1987) both contain a brief overview. The **Manual for Tidal Heights Analysis and Prediction** (Foreman, 1977) is essentially the operating manual for the "Foreman package" of tidal analysis and prediction and is one of the best practical guides. The PSMSL site presents some of the finer points of tidal analysis in the "Task-2000" discussion, and refers the reader to the analysis method outlined in Murray (1964) which described the current PSMSL practice (which is also the basis for present-day NTC practice). The International Oceanographic Commission website "Ocean Portal", which is devoted to the dissemination of ocean-related information, describes a number of tidal packages and invites the reader to review them.

Prospective tidal analysts should be aware that a set of constants derived using one analysis package may not provide accurate results with all prediction packages. This problem was discussed in Interpretation of tidal constituent Sa as well as in the Task-2000 report.

Tide prediction packages

Given a set of amplitudes and phases for a particular port from an analysis, the prediction of sea level is much simpler than the analysis that created them. The Scripps website listed above lists dozens of software packages that perform this function. Most generally contain a limited default set of constants for ports in the region covered, and it is also fair to say that most or all of those on the Scripps site are limited in the total number of constants they can accept (and hence limited in accuracy). For tidal information at Australian regional ports, Seafarer Tides, from the AHS (CD available online), is useful, having tabulated predictions for high and low water each day of the year for over 80 standard ports in Australia, PNG, Solomon Islands and East Timor. It incorporates a graphical representation of the tidal curves and predictions at 20 minute intervals for each location.

Tidal classification

The characteristic features of tides, such as whether there are two or only one high and low per day, vary widely around Australia. Various classification schemes have been developed, and one of the most common of these is the "form factor", F, defined by F = (K1 + 01)/(M2 + S2), see section 1.3 for definitions the four major constants. The ANTT describes the classification of tidal types as follows:

"All tides are composed of both semi-diurnal and diurnal components, the latter introducing inequality in successive heights of high or low water and also in the times. When this diurnal inequality reaches a certain limit, it becomes more informative to list the average heights of the higher and lower high and low waters rather than the average spring and neaps values. The division between diurnal and semi-diurnal tides is arbitrary. In these tables the following criterion is used:

When (K1 + 01)/(M2 + S2) is less than or equal to 0.5, the tide is considered to be semi-diurnal. When (K1 + 01)/(M2 + S2) is greater than 0.5, the tide is considered to be diurnal. In some areas these formulae are unsatisfactory and a more detailed study of the harmonic constants is necessary to determine tidal characteristics".

Analysis of tidal currents

Tidal currents are analysed in terms of their separate (east-west and north-south) components. An introduction to tidal currents can be found on the NOAA website, and the NOAA glossary gives further detailed definitions, such as the meaning of "rotary" versus "rectilinear" currents. Many users find it useful to distinguish between the terms "tidal currents" and "tidal streams", with the latter being used to imply the major axis of flow denoted on nautical charts. Warren (1983), and Pugh (1987) give additional details.

Long term sea level variability

Long-term sea level changes are an important reason for the necessity of permanent continuous tide gauge installations. The topic of sea level rise in the context of the "enhanced greenhouse effect" is nicely summarised, with good illustrations, in the United States Environmental Protection Agency's (EPA) booklet Greenhouse Effect and Sea Level Rise: A Challenge for this Generation, available in pdf format online. The potential impacts in the Australian region are discussed in Chapter 2 of Climate Change: An Australian Guide to the Science and Potential Impacts, available online on the Australian Greenhouse Office website in pdf format. The CSIRO also has an online fact sheet, and finally, Wikipedia's entry for sea level contains useful information and good graphics.

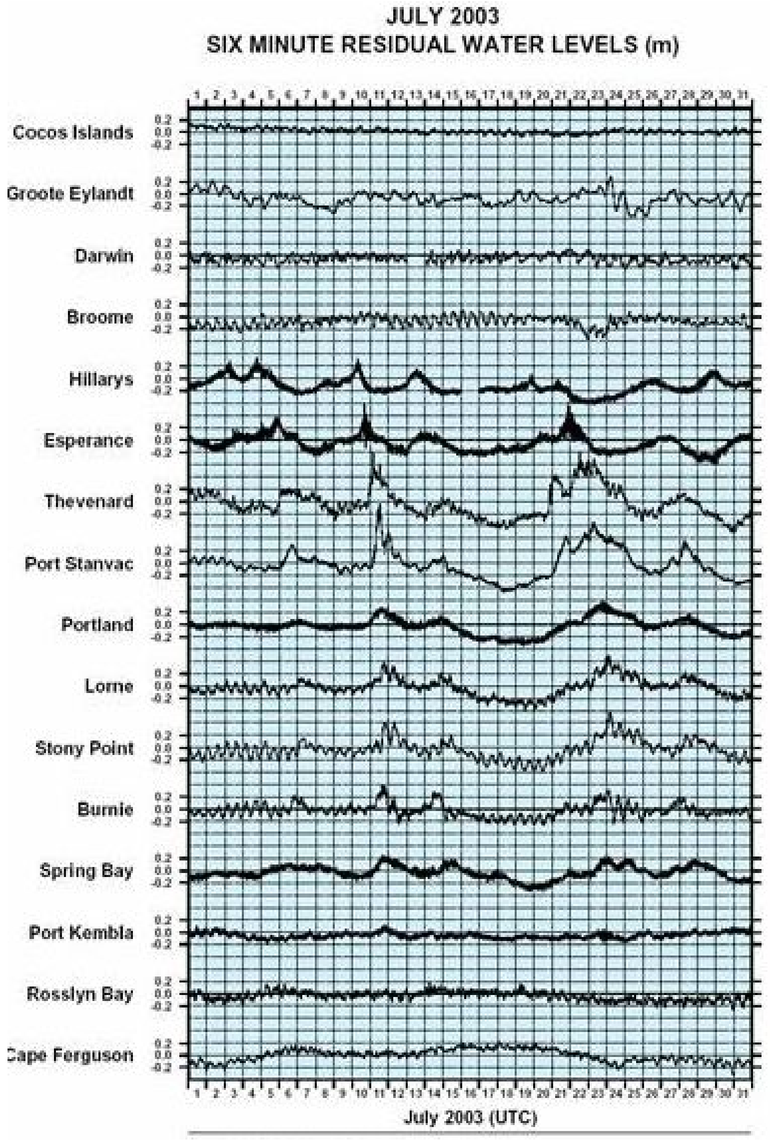
Environmental Effects on Sea Level

Water levels at the coast are governed by environmental (weather-related, ocean wave, etc.) effects as well as by the astronomical tides. Perhaps the most familiar and dramatic example along the coasts of Australia is the storm surge, a large volume of water driven up to the coast by the combined effects of wind and atmospheric pressure. The effects of wind and atmospheric pressure are described in Section 2.3 of the IOC (Intergovernmental Oceanographic Commission) Training Manual Vol. I (1985). This section also discusses the difference between tropical and extra-tropical surges.

Weather-related effects

The appendices of the NSW Coastline Management Manual contains descriptive reviews of coastal processes and the effects on beaches of storms and other weather-related events. The climate-related information is primarily focused on NSW, but the majority of the information is more general. Warren (1983) (Chapter 4) describes wind set-up of sea level at the coast, wind-driven currents, atmospheric pressure effects, storm surges, seiches, precipitation, and runoff, written for the purposes of the tidalist. Pugh (1987) also covers most of those topics. Some nice illustrations and discussion of coastal processes can be found in Chapter 4 of Shelf and Coastal Oceanography by Prof. M. Tomczak.

What starts out as a storm surge, can under certain conditions become a free wave known as a coastally trapped wave (CTW) or continental shelf wave. In Australia such waves were intensively studied in the 1980's as part of the Australian Coastal Experiment, which focused on the continental shelf of southeastern Australia. However, the largest and most prevalent CTWs in Australia occur along the southern Western Australia coast and along the Great Australian Bight.



Sea level residuals based on data from SEAFRAME stations of the Australian Baseline Array

The effect of CTWs on coastal sea level is clearly visible in the preceding figure. A typical case begins somewhere in the vicinity of Hillarys, WA on 10 July. Onshore winds with peak gusts of 25 m/s (about 50 knots) drove water forward onto the shelf, sending sea levels at the tide gauge to about 30 cm above the predicted tidal value and initiating a CTW. CTWs travel along coastlines over the continental shelf. In the southern hemisphere the direction of travel is such that the coastline is to the left of the wave, so the CTW propagated southwards from Hillarys. It was evidently reinforced over the following days by onshore or north-westerly winds. The wave rounds the southwest corner of Australia, then turns to the east, successively raising sea levels by a half-metre or so at Esperance, Thevenard, Port Stanvac (Adelaide), Portland, and Lorne, finally entering Bass Strait a day or two after leaving Hillarys.

A second CTW appears to be generated in the Bight itself on the 21st, with large residuals observed first at Esperance, and then stations to the east.

Shallow water effects

As the tide enters shallow waters, the tides associated with one or another of the major components often interact to produce "compound tides". Another effect is in the lagging of the tide wave through friction. Murray (1964) wrote:

"Ports which are situated in shallow water may have distorted tidal profiles, and this distortion may take many forms. In some cases, the distortion takes the form of a short period of rising tide and a long period of ebb, and at some places this can take the extreme form of a bore, particularly at spring tides. At other ports, the shallow water effects may cause double high or low waters, or perhaps a stand of tide lasting several hours; again the effect can vary considerably between spring and neap tides."

An introductory-level discussion is contained in Warren (1983). Many, but not all, shallow water effects on tides can be accounted for by use of the full 112-constituent analysis.

When tidal waters flow into coastal lagoons, or other partially impounded water bodies, the return flow frequently takes on a different character. For example, the flood currents are often more vigorous and the rise of water level in the lagoon more rapid than its fall. The connection of the lagoon to the ocean often takes the form of a long, narrow channel, which acts like a low-pass filter, reducing the amplitude of the higher tidal frequencies and the tidal effects within the lagoon. The time of high and low waters in the lagoon is also phase-lagged behind that of the ocean. The more restricted the connecting channel, the longer the hydrodynamic turn-over time, or residence time, within the lagoon. More restricted lagoons also tend to have greater salinity variations due to river input, which fluctuate with rainfall, and they also tend to be more prone to problems with sedimentation, pollution, and eutrophication. Consequently, there have been many instances of channel deepening and widening worldwide. These frequently have led to improved water quality, fish breeding, and other positive effects; however, careful study is required to predict the full ecological consequences in advance.

Tsunamis are well-known for their destructive impacts on many coastal areas. These also are essentially shallow-water phenomena since the generating wave is barely discernible in the open ocean. Recordings of tsunami are rare in Australian waters, but not unknown (see the Geoscience Australia factsheet). IOC Vol.1 states:

"A tsunami is a wave generated by seismic activity and as such falls outside the two categories of forces responsible for normal sea level changes, tides and the weather. Not all submarine earthquakes produce tsunami. The important element is a vertical crustal

movement which displaces the sea bed. The tsunami wave characteristics will depend on the amplitude of the displacement and the dimensions of the sea bed involved. Horizontal displacements of the seabed will be relatively ineffective. The waves travel at a speed given by (water depth • gravitational acceleration)$^{1/2}$. Amplitudes in deep water are small, probably not more than 1 metre. The Pacific Ocean and its coastlines are the most vulnerable to tsunami because of the seismically active surrounding plate boundaries. As the wave approaches shallow coastal waters its amplitude increases and there are multiple reflections and refractions which combine to give very large local amplitudes. A network of reporting tide gauges in the Pacific enables warnings of tsunami arrival to be given some hours in advance."

Tidal Datum Epoch

The tidal datum epoch (TDE) is the interval recommended for the calculation of datums. It is normally longer than 18.6 years in order to include a full lunar nodal cycle. The Permanent Committee for Tides and Mean Sea Level (PCTMSL) recommended that a 20-year TDE, 1992-2011 inclusive, be adopted for the determination of Lowest Astronomical Tide and Highest Astronomical Tide (LAT and HAT). The MSQ document "Tidal Reference Frame for Queensland", details the implementation of the epoch in Queensland.

Internationally, there are different but equivalent ways of defining the epoch. For example, to account for slow variations of sea level relative to land, NOAA intends to re-compute the U.S. National TDE (NTDE) every 20-25 years. (The "current" epoch is the 19-year period ending 31 December 2001.) The NTDE is used in the US for the computation of not only LAT and HAT, but also mean sea level and most other tidal datums. The NOAA site gives additional information.

Tidal Planes and Levels

The terms "tidal planes", "tidal datums", and "tidal levels" will be used interchangeably , although some authors draw a distinction - for example, a "plane" implies a two-dimensional surface extending over a given region.

Harmonics-based definitions

The following definitions, based on the tidal harmonics, are taken from the ANTT. The harmonic definitions can be considered convenient simplifications. The Intergovernmental Committee on Surveying and Mapping (ICSM), Tidal Interface Working Group (TIWG), has produced a 103-page compendium of terms related to the legal definition of the land-sea boundary in Australia. It can also be found as a summary. In the following, Z0 represents the mean sea level, and the other symbols are the usual harmonic constants.

For semi-diurnal ports:

Mean High Water Springs: MHWS = $Z_0 + (M_2 + S_2)$

Mean High Water Neaps: MHWN = $Z_0 + |M_2 - S_2|$

Mean Low Water Springs: MLWS = $Z_0 - (M_2 + S_2)$

Mean Low Water Neaps: MLWN = $Z_0 - |M_2 - S_2|$

For diurnal ports:

Mean Higher High Water: MHHW = $Z_0 + (M_2 + K_1 + O_1)$

Mean Lower High Water: MLHW = $Z_0 + |M_2 - (K_1 + O_1)|$

Mean Higher Low Water: MHLW = $Z_0 - |M_2 - (K_1 + O_1)|$

Mean Lower Low Water: MLLW = $Z_0 - (M_2 + K_1 + O_1)$

Observations-based definitions

The harmonic-based definitions are not universally accepted, in part because they assume that M2, S2, O1, and K1 are the dominant four components, which is not always the case. For this reason, many authorities (e.g., MSQ and NOAA) adhere strictly to observation-based definitions of the tidal planes. The TIWG list of standard terms in the table below gives observation-based definitions from the Australian Hydrographic Office tidal glossary. Variations of the definitions may apply in current legislation.

	Purpose	**Definition**
HAT	Landward limit of the tidal interface Chart datum for high tide (clearances) Limit of landward extent of tidal water under normal atmospheric circumstances.	Highest Astronomical Tide: The highest level of water which can be predicted to occur under any combination of astronomical conditions.
MHWS (and MHHW)	Tidal datum for cadastral (boundary) purposes for some jurisdictions (eg New Zealand, Queensland)	Mean High Water Springs (MHWS): The average of all high water observations at the time of spring tide over a period time (preferably 19 years). Applicable in semi-diurnal waters only. Mean Higher High Water

		(MHHW): The mean of the higher of the two daily high waters over a period of time (preferably 19 years). Applicable in mixed and diurnal waters.
MHW	Common law datum for cadastral (land boundary) purposes. Used in Australia unless amended by legislation (as in Queensland for example) Frequently used as the coastal limit on topographic mapping	Mean High Water (MHW): The average of all high waters observed over a sufficiently long period.
MSL	Average limit of the tides	Mean Sea Level (MSL): The arithmetic mean of hourly heights of the sea at the tidal station observed over a period of time (preferably 19 years).
MLWS (and MLLW)		Mean Low Water Springs (MLWS): The average of all low water observations at the time of spring tide over a period of time (preferably 19 years). Applicable in semi-diurnal waters only. Mean Lower Low Water (MLLW): The mean of the lower of the two daily low waters over a period of time (preferably 19 years). Applicable in mixed and diurnal waters.
MLW	Has been used as the limit of Australian States as the definition of 'low water'.	Mean Low Water: A tidal level. The average of all low waters observed over a sufficiently long period.
LAT	Chart low water datum. Baseline for the purposes of defining Australia's maritime boundaries in compliance with the UN Convention on the Law of the Sea.	Lowest Astronomical Tide (LAT): The lowest tide level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions.