# CHAPTER 5

# Datums and Vertical Control

## 5.1 Vertical datums

It is apparent that the elevation of something can only be expressed relative the elevation of something else, whether the reference elevation be that of the centre of the earth, the mean surface of the sea, the orbit of a satellite, or simply a bolt set in bedrock. The chosen zero to which other elevations are referred is called a *datum of vertical reference* or simply a *vertical datum*. The latter term is most commonly used, but it must not be misinterpreted to mean that the datum is vertical. The plural of "datum" is "datums" in this context, to distinguish it from the word "data" that signifies any set of observed values of a parameter. If the datum is defined over an area, it is called a *datum surface*.

A distinction must usually be made between the concept chosen to define a vertical datum and the realization of the concept in practice. For example, two agencies may both choose mean sea level as their reference surface, and they may independently determine a value for the elevation of the same benchmark. Because of differences in technique and errors of observation, the two values would almost certainly differ. The two datums would then be said to differ by that amount at the location of the benchmark, even though they profess to have the same ideal reference surface. It is not unusual to have elevations assigned to the same benchmark by several survey organizations.

## 5.2 Equi-geopotential or level surfaces

These are surfaces along which no work is done by or against gravity in moving from one point to another. The concept of a force potential was introduced in section 2.4, and equi-geopotential or level surfaces are simply surfaces of constant potential in the earth's gravity field. Gravity acts everywhere perpendicularly to level surfaces, and they are the surfaces to which all water levels would eventually conform in the absence of all forces other than gravity. The *geoid* is the level surface that most closely fits the mean surface of the world's oceans. The term "Mean Sea Level (MSL)" is frequently loosely used, without clear definition of its intended meaning; for our purposes, the surface of MSL will be defined as identical to the geoid. By this definition it is clear that the mean elevation of the sea surface at a particular location need not be the same as the elevation of MSL, since the elevation of MSL (the geoid) could be determined only by fitting a level surface to observations of the mean level of the sea surface over the whole of the ocean. The local mean water level (MWL) departs from MSL in the ocean because of surface slopes caused by prevailing wind stress patterns, persistent anomalies in the distribution of precipitation, evaporation, freezing, melting, heating and cooling, and by the deflection of ocean currents by the Coriolis force.

## 5.3 Geopotential, dynamic, and orthometric elevations

The difference in geopotential between two level surfaces equals the work done in raising a unit mass from the lower to the higher surface. Since this amount of work equals the vertical distance between the two surfaces times the average gravity along the vertical path, division by a standard value of gravity (e.g. the average value of gravity at sea level for a specified latitude) gives a number equal to the linear vertical separation of the two surfaces at a location where gravity equals the standard gravity. This number is the difference in *geopotential elevation*, and is quoted in units such as geopotential metres. All points with the same geopotential elevation above the geoid (MSL) must, by definition, lie on the same level surface, since the geoid is itself a level surface. To perform geopotential levelling in the field requires a knowledge of the value of gravity along the path of the levelling. To obtain differences in geopotential elevation, all instrumentally observed differences in elevation along the line must be multiplied by the ratio of the local gravity to the standard gravity.

The concept of *dynamic elevation* is precisely the same as that of geopotential elevation, the only difference being that geopotential levelling uses an observed value of local gravity in correcting the instrumental differences in elevation, whereas dynamic levelling uses a value calculated from a gravity formula involving latitude and altitude only. Local gravity anomalies can thus introduce local errors into dynamic levelling, in addition to any instrumental errors committed. The errors introduced by the anomalies tend to cancel out as the anomalies are passed, and do not accumulate over a long line of levelling.

The name given to the concept of vertical linear distance above the geoid is *orthometric elevation*. Although this may at first seem to be the most straightforward definition of elevation, it will be seen to have some drawbacks. The average shape of a level surface on the earth is that of an oblate spheroid, with its centre at the earth's centre and its axis of revolution along the earth's axis. The family of level surfaces are concentric, but they are not all the same shape; their spheroidal shape becomes progressively flatter with distance from the centre of the earth. This progressive flattening is illustrated in Fig. 41, and simply follows from the definition of geopotential and the fact that gravity is greatest at the poles and decreases with latitude, being least at the equator. The decrease of gravity with latitude results from the increasing outward centrifugal force near the equator and from the flattened shape of the earth itself, which is probably also attributable to centrifugal force during the earth's formative period. The oblateness of all surfaces in Fig. 41 is greatly exaggerated to illustrate the principle, since if drawn to scale at this reduction, all level surfaces would be indistinguishable from spheres. Local gravity anomalies cause local increases or decreases in the separation between neighbouring level surfaces, but no attempt has been made to illustrate this in Fig. 41.

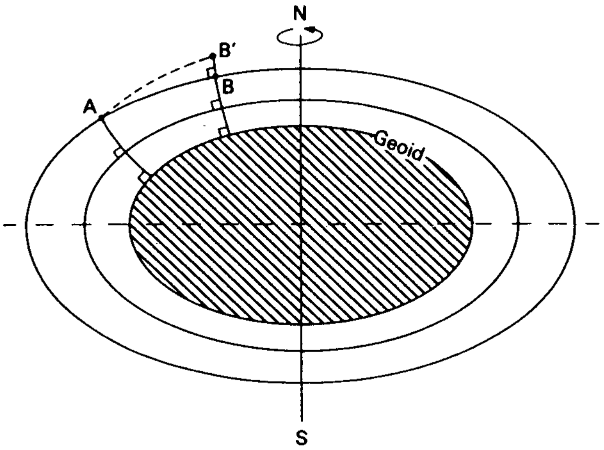

FIG. 41. The geoid and higher level surfaces, illustrating correction required to obtain orthometric elevation.

To demonstrate the correction to instrumental differences in elevation that is required to obtain orthometric differences, consider a line of levelling run from south to north along a level surface from *A* to *B* in Fig. 41. Since the levelling is along a level surface, there would be no difference in elevation detected instrumentally; however, because the level surfaces converge toward the north, *B* is at a lower orthometric elevation than is *A*. The orthometric correction to the instrumental difference observed in levelling from *A* to *B* is the height *BB'*, where *AB'* lies along a surface that is parallel to the geoid. The amount of the correction is calculated from formulae involving latitude, altitude, and the north – south extent of the line. The formulae for the dynamic and the orthometric corrections are based on the same model of earth gravity, making the two systems mutually convertible. Local gravity anomalies introduce local errors into orthometric levelling, but, as in dynamic levelling, the errors tend to cancel out as the anomalies are passed, and do not accumulate over a long line of levelling.

The greatest objection to an orthometric system of elevations is that points on the same level surface are not given the same elevation if they are at different latitudes. This is particularly disturbing for hydraulic and hydrodynamic studies on lakes and rivers. As an example, the orthometric elevation of the level surface of Lake Winnipeg (no wind, etc.) would be about 0.08 m less at the north end than at the south end. When working at sea level there is no orthometric or dynamic correction to apply, because both corrections are approximately proportional to the altitude. In small local surveys, such as between the control benchmarks and a water level gauge, there would probably never by any need to correct the instrumental differences to either the dynamic or orthometric system, because the ranges of elevation and latitude would be too small to generate a significant correction.

## 5.4 Geodetic Datum

Geodetic Datum (GD) is the reference surface to which the Geodetic Survey of Canada refers elevations. It is referred to as a sea-level datum because it professes in concept to be the geoid, which is also called Mean Sea Level. In practice, of course, it can only be an approximation to the geoid, and its physical location is precisely defined only with reference to Geodetic benchmarks in a region. Geodetic Datum exists only as a concept in regions not yet included in the Geodetic network of vertical control. Elevations above the Geodetic Datum are always quoted in the orthometric system. Geodetic Datum (i.e. the elevations of the benchmarks in the network) is based on a 1928 adjustment of the Canadian levelling network, in which the mean water levels at the gauging stations of Halifax, Yarmouth, Pointe-au-Père, Vancouver, and Prince Rupert were all held fixed at zero. Since the mean sea surface is known not to be a level surface (section 5.2), Geodetic Datum is seen to have departed immediately from the precise concept of the geoid. It was realistically reasoned, however, that the errors introduced by equating MWL to MSL were less than those incurred in long lines of land levelling.

## 5.5 International Great Lakes Datum (1955)

International Great Lakes Datum (1955), or IGLD, is a datum established by the Canada – U.S. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrological Data, to provide a unified datum for use in hydraulic and hydrological studies on both sides of the border along the Great Lakes and St. Lawrence River. The establishment of IGLD also met the need for a revision of datums in the Great Lakes region caused by the cumulative effect of crustal movement over the years. Crustal tilting in the Great Lakes basin appears capable of raising one end of a lake with respect to the other end by as much as one metre in three hundred years. IGLD may be referred to as a sea-level datum, but, in recognition of the fact that sea level varies from place to place, it was defined as the level surface passing through the mean water level at the outlet of the system. In practice, this was determined as the mean level at Pointe-au-Père over the period from 1941 to 1956, and extended throughout the system by a network of over-land levelling and water level transfers. Dynamic elevations are used in the IGLD system because it was wished to have the same elevation quoted for all points on the same level surface, since water surfaces seek level surfaces, not surfaces equidistant above the geoid. The geopotential system would have been more desirable still, but insufficient gravity information was available at the time. The standard gravity used to convert geopotential numbers into dynamic elevations is the average sea-level value of gravity at 45° latitude. The length of a dynamic metre at a particular location therefore equals the length of a linear (or orthometric) metre times the ratio of the standard to the local gravity, a ratio that is very close to unity in the region served by IGLD. The distinction in units can usually be ignored when dealing with the small instrumental differences in elevation encountered in small local surveys.

Because the physical location of a datum is defined locally by the elevations of benchmarks that move with the earth's crust, crustal movement has continued to distort IGLD with respect to level surfaces since its establishment (as it has all datums in the region). In the interest of consistency within the system, the elevation of a new benchmark should be established only by transfer from a nearby original benchmark, on the assumption that the difference in crustal movement between two nearby locations is small. Eventually, the distortion within the system may become intolerable, and a complete re-levelling and readjustment of the network undertaken. New elevations would then be assigned to all benchmarks, and the new datum would be identified by its date of adjustment.

## 5.6 Hydrographic charting datums

Depths and elevations shown on hydrographic charts must be below and above specified datum surfaces. For purposes of navigational safety, depths are referenced to a low water datum and elevations to a high water datum, so only rarely could there be less depth or less clearance than that charted. Water level gauge measurements and tide height predictions must also refer to specified datums. It is universal practice to reference the water levels and the tide predictions to the same datum as that used for charted depths, so addition of the observed or predicted water height to the charted depth will give the appropriate total depth.

*Chart datum* (CD) is the datum to which depths on a published chart, all tide height predictions, and most water level measurements are referred. It was agreed in 1926 by member states of the International Hydrographic Organization that chart datum "should be a plane so low that the tide will but seldom fall below it." The wording indicates that the resolution was formulated with only tidal waters in mind, and, since the word "seldom" was left undefined, it provides but a qualitative instruction for the choice of chart datum. The following three criteria place somewhat more restriction on its choice: chart datum should be

1) so low that the water level will but seldom fall below it,
2) not so low as to cause the charted depths to be unrealistically shallow, and
3) it should vary only gradually from area to area and from chart to adjoining chart, to avoid significant discontinuities.

On most Canadian coastal charts the surface of lower low water, large tide, or LLWLT (see section 5.7), has been adopted as chart datum, but the term "lowest normal tide," or "LNT," has been retained on the charts since it encompasses a variety of other choices for chart datum on some older charts. On United States charts, chart datum is taken as mean lower low water (MLLW), a surface somewhat higher than LLWLT. It has been agreed by the two countries that on charts covering both Canadian and U.S. waters Canadian chart datum is to be used on the Canadian side of the boundary, and U.S. datum on the U.S. side, regardless of which country publishes the chart. This policy causes a discontinuity in chart datum along the international boundary, but preserves the principle that charts of the same waters should all have the same chart datum, and that it should be the same datum as used for tidal predictions in those waters.

The choice of a chart datum is usually more difficult on inland waters than on coastal waters because inland waters lack the stabilizing influence the huge ocean reservoir exerts on the mean water level. Whereas a 2-month water level record at a coastal location provides sufficient tidal information to determine a reasonably accurate chart datum, many years of record may be necessary to provide the information on seasonal and secular fluctuations in mean water level required to determine chart datum on lakes and rivers. Shorter-term fluctuations, such as those due to seiches and wind set-up may also be considered in setting chart datum, but information on these can be obtained over a fairly short record period. Dry and wet periods in many drainage basins (e.g. the Great Lakes basin) seem to occur in almost regular "cycles" of several years, causing corresponding periods of low and high water levels in the drainage systems. The chart datums must be set with low-stage years in mind, and may appear to be pessimistically low over several years of high stage. There are a fortunate few inland waters for which chart datum is easily chosen – those in which the minimum water level is controlled during the navigation season. A guideline sometimes used in setting inland chart datums is that the water level may fall below the datum 5% of the time, but this may not be severe enough if the water level undergoes large fluctuations. A preferred guideline is that the daily mean water level should never fall more than 0.2 m below the chart datum during the navigation season.

It should by now be apparent that chart datum need not be a level surface even over the extent of a single chart. Along a river, chart datum must slope with approximately the slope of the water surface of the river at low stage. Even along the coast, where there is no appreciable slope of the mean water level, the surface of chart datum must slope down from regions of small tidal range toward regions of larger tidal range to accommodate the lower low waters. On most lakes, however, it is common to adopt a single level surface as chart datum over the whole lake.

*Sounding datum* is simply the datum to which soundings are reduced when compiling a "field sheet" during a hydrographic survey. It may or may not remain as the chart datum. While a sounding datum may be chosen rather arbitrarily to facilitate an immediate start for a sounding survey, it is imperative that its elevation and the elevation of the zero for any water level records be referenced to permanent benchmarks on shore. This is required to permit adjustment of the soundings to the final chart datum, and to permit recovery of the chart datum in future surveys of the same region.

The *datum for elevations* on a chart is the surface to which the charted elevations of prominent targets (lights, beacons, steeples, chimneys, etc.) and clearances under obstacles (bridges, power lines, etc.) are referred. It is usually the same high water datum used to define the shoreline on a chart. On most Canadian coastal charts the surface adopted as datum for elevations is higher high water, large tide, or HHWLT (see section 5.7). On Canadian charts of non-tidal inland waters, however, for reasons that are no longer apparent, the low water chart datum is also used as the datum for elevations, while a high water surface is used to define the shoreline.

### 5.7 Special tidal surfaces

It is found useful to define and name several average tidal elevations that can be used in comparing tidal characteristics from place to place. Some of these have already appeared in the preceding text. From a single gauge site only one elevation can be determined for each definition, but it is proper to think of each elevation as only one spot on a continuous tidal surface over the whole ocean. The tidal surfaces presently in vogue in Canada are listed and discussed below.

MWL — mean water level — average of all hourly water levels over the available period of record.
HHWLT — higher high water, large tide — average of the highest high waters, one from each of 19 years of predictions.
HHWMT — higher high water, mean tide — average of all the higher high waters from 19 years of predictions.
LLWMT — lower low water, mean tide — average of all the lower low waters from 19 years of predictions.
LLWLT — lower low water, large tide — average of the lowest low waters, one from each of 19 years of predictions.
LNT — lowest normal tide — in present usage it is synonymous with LLWLT, but on older charts it may refer to a variety of low water chart datums.

Of the above tidal surfaces, MWL is the only one whose elevation is determined in practice by straightforward application of the definition. The others are at present calculated from semi-empirical formulae involving the harmonic constants of the major tidal constituents. Today's high-speed computers, however, possess the capability of generating nineteen years of prediction and applying the definitions directly with no great difficulty. Another possibility is to generate only one year of predictions, that being a year in which the moon experiences its average excursions in declination (nodal factors, $f$, near unity), and to take the appropriate averages and extremes from that year of predictions only. These options are under consideration, but in the meantime the semi-empirical method of calculation gives values that have been shown to simulate the definitions very well. Figure 42 illustrates these tidal surfaces and their relation to the charting datums and other charted features.

A variety of other tidal surfaces are defined and used by hydrographic agencies in different countries. Chart datum for United States charts on both the Atlantic and Pacific coasts is now determined as mean lower low water (MLLW), which is defined as the average of all the lower low waters over a specified 19-year period. Previous to 1980 the chart datum for U.S. Atlantic coast charts was defined as mean low water (MLW), the average of all the low waters over an earlier specified 19-year period. Because of the small diurnal inequality on the east coast and because of a difference in sea level between the two 19-year periods, the change from MLW to MLLW has made only a minor change in east coast chart datums, one that is not reflected in the charted depths. The discontinuity in datums between adjoining U.S. and Canadian charts remains. Chart datum for British charts is now defined by the tidal surface of lowest astronomical tide (LAT), which is the lowest water level predicted in a 19-year period. Partly because this is difficult to determine, and partly to accommodate older charts, the definition of chart datum is relaxed to permit it to be 0.1 m above a rigorous LAT. A tidal surface used to define chart datum on many older British Admiralty charts, including some in Canadian waters, is mean low water springs (MLWS). It is the average of all available low water observations at the time of spring tide, and applies only where the diurnal inequality is small. While it is no longer in general use, MLWS provides a simple example of how the harmonic constants may be used to approximate the elevations of tidal surfaces. MLWS is approximated as the height of MWL above chart datum minus the sum of the amplitudes of the semidiurnal lunar and solar constituents, or, symbolically,

$$\mathrm{MLWS} = Z_o - (M_2 + S_2).$$

The semi-empirical formulae used to approximate LLWLT, etc. are much more complicated, and will not be given here.

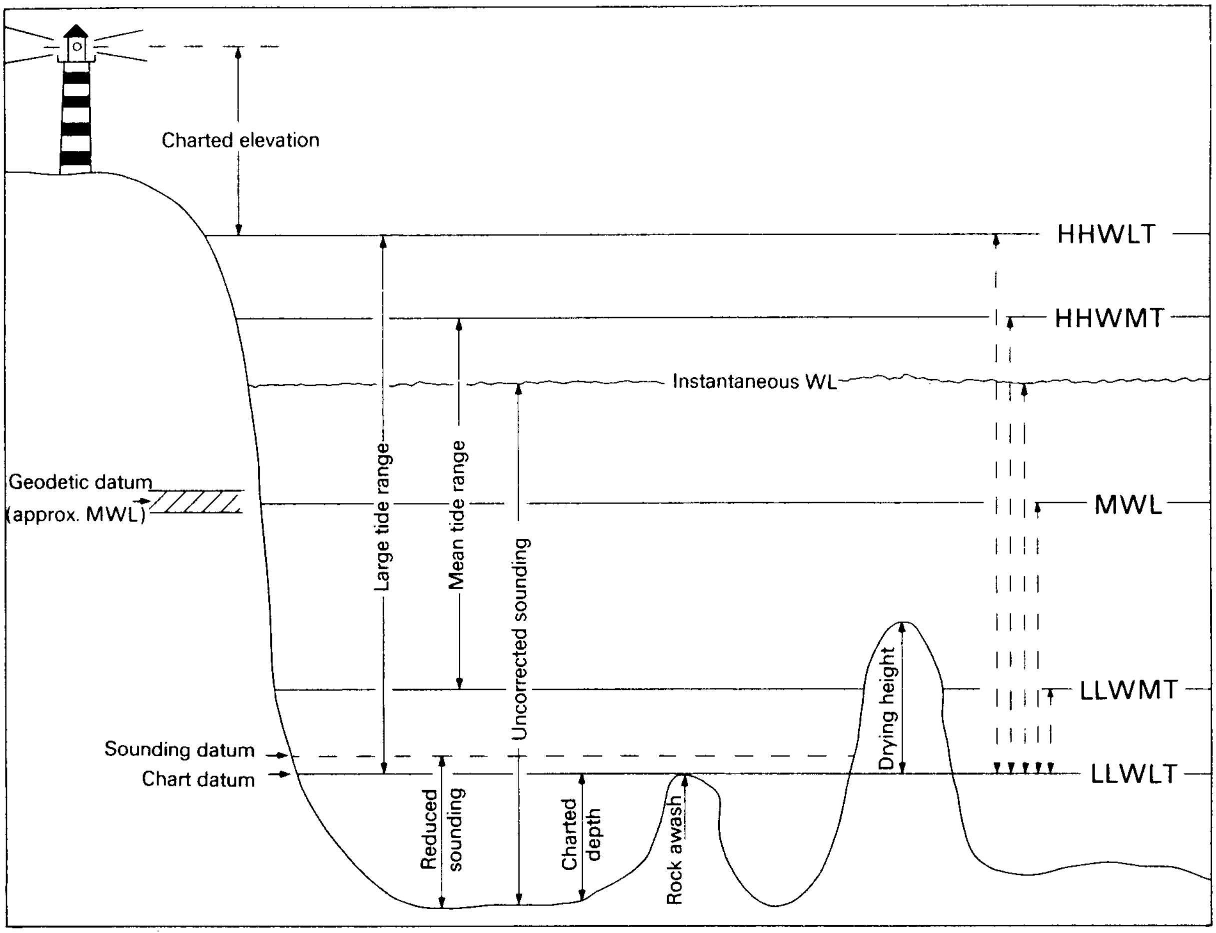

FIG. 42. Relation between tidal surfaces, charting datums and physical features.

## 5.8 Land levelling and water transfers

Anyone who installs or operates a water level gauge must ensure that the zero of the gauge is always accurately referenced to local benchmarks. This is done by standard spirit levelling around the closed network of benchmarks and gauge. It is convenient if one of the local benchmarks is a Geodetic benchmark, but if no Geodetic BM is accessible within a kilometre of the gauge, the task of tying the gauge and its BMs into Geodetic Datum is left to the Geodetic Survey of Canada, the experts in long-distance overland levelling.

Water transfers were mentioned in section 5.5 in connection with the establishment of IGLD. They provide a means of transferring elevations across large expanses of water, on the assumption that the slope of the water surface can be estimated from the hydraulic and meteorological factors. Installation of water level gauges is usually essential for accurate water transfer because reasonably long records are required to average out seiche activity and to span a variety of meteorological conditions, whose effects may then be evaluated. Water transfers are used most frequently over large lakes, because on the average their surfaces approximate very closely to level surfaces. Water transfers of chart datum along the sloping surface of a river may also be carried out, but since the transfer is not along a level surface, elevations may be determined only with respect to the sloping chart datum, not with respect to sea level. In performing a water transfer along a river, interpolation should be made between two reference gauges, because the slope of the river may not be the same with respect to the slope of the chart datum at all stages. Water transfer of sounding datum from gauge to gauge along the sea coast is also a common practice, as described in Chapter

6. This is also the transfer of a sloping rather than a level datum, and is based on the assumption that the tide curves at the neighbouring stations have the same shape, but that one may lag the other in time and have a different vertical scale (i.e. different range). Only where the tide has a small diurnal inequality are the assumptions likely to be valid. It is partly for this reason that it is referred to here as a transfer of sounding datum, rather than of chart datum, because the final chart datum would almost certainly be based on an analysis of the full tidal record available at the end of the survey, rather than on the preliminary water transfer.

## 5.9 Purpose and importance of benchmarks

The purpose of permanent Hydrographic benchmarks is to identify locally the elevation of the physical surface that is chart datum. Since all other charting datums and tidal surfaces are referred to chart datum, the Hydrographic BMs are the fundamental references for vertical control in charting and water level gauging on navigable waters. While other agencies, such as the Geodetic Survey, frequently tie the Hydrographic BMs into their networks and provide elevations for them on their own datums, it remains the elevation of the BM above chart datum that is basic to charting and gauging procedures. Only the responsible Hydrographic agency may assign or alter the elevation quoted for a BM above chart datum. Although it is not necessary for charting purposes, it is desirable that chart datum be referenced to Geodetic Datum, so that the Geodetic elevation of chart datum can be supplied to engineers and surveyors and documented on the charts. Subsequent re-adjustment of the Geodetic network could provide new Geodetic elevations for the Hydrographic BMs and chart datums, but would not affect the quoted elevations of the BMs above chart datum. On the Great Lakes, where chart datum is defined on each lake as a fixed elevation above IGLD, it is necessary that the Hydrographic BMs be tied in to IGLD as part of the procedure for establishing datum for charting. Ultimately an adjustment will need to be made to all BMs in the IGLD network, to correct for the crustal movement since 1955 and to incorporate new levelling. This will provide new IGLD elevations for Hydrographic BMs and chart datums, but will not change the BM elevations relative to chart datum. These can be changed only if a new chart datum is defined, and the charts revised accordingly.

As part of the installation procedure of any water level gauge, a minimum of three BMs are established in the immediate vicinity (½ km) of the gauge, with no two in the same feature or structure. The elevation difference between the preliminary gauge zero and each of the BMs is then determined by accurate spirit levelling. When the elevation of chart datum is finally chosen with respect to the preliminary gauge zero, the BM elevations are converted and recorded in the BM descriptions as elevations above chart datum. If the water level gauge is to continue in operation, its permanent zero would be set to chart datum. The BMs provide for the recovery of chart datum in future surveys and for consistency in the setting of gauge zero for all water level measurements at the same site.

One BM at a site is insufficient because there would be no comparison by which to test its stability over the time since its installation. Two BMs are insufficient because if one is found to have moved with respect to the other, there would be no way to know whether one, the other, or both were unstable. Three BMs provide the possibility of identifying one unstable member of the group. This is why three is the minimum required number of control BMs at each gauge site. More than three BMs is, of course, desirable because there is no guarantee that two BMs may not be found to have been unstable. When a BM is found to be unstable, it must be destroyed and replaced by a new one in a different location. The elevation of the new BM above chart datum is determined by levelling from the remaining stable BMs. The elevation and description of the new BM are recorded, along with notice of the destruction of the unstable BM.

It is worth noting that chart datum may be precisely (a few millimetres) related to other datums, such as GD and IGLD, only at gauge sites where those datums have been tied in to the Hydrographic BMs. This is true for the following reasons: firstly, because away from the gauge sites the chart datum is determined only to the accuracy to which the soundings are observed and corrected, and secondly, because chart datum at each sounding site is determined in effect by water transfer from the gauge site along the water surface, and the shape of the water surface with respect to the geoid is not determined as part of the sounding survey. It is thus not possible to define the continuous surface of chart datum in terms of its accurate elevation above Geodetic or other survey datums, the relation being accurately known only at gauge sites.