PART II
Instruments and Procedures

CHAPTER 6

Establishment of Temporary Water Level Gauge

6.1 Introduction

From the viewpoint of a field hydrographer, the immediate function of a temporary water level gauge is to provide the information necessary for the transfer or establishment of sounding datum (and, eventually chart datum) and for the reduction of soundings to this datum. If properly recorded and documented, however, the information from such gauges may serve other functions as well, such as provision of harmonic constants for tidal prediction and of information on short-term water level fluctuations. Since the hydrographer may not know to what use the water level and benchmark information may be put in the future, the care expended in installation and operation of a gauge should not be limited to that necessary to achieve the required accuracy of sounding reduction. This is why some of the accuracy standards recommended below may at first appear to be unnecessarily severe: they should, however, be readily achievable with the exercise of moderate care. As discussed in section 3.6, every effort should be made on tidal waters to obtain at least one month of water level record, to permit proper tidal analysis of the data. One of the fringe benefits that may accrue to the field hydrographer as a result of added care in the installation and operation of gauges is the improvement of cotidal charts for use in future surveys of the same or nearby areas.

6.2 Stilling wells

A stilling well is a vertical enclosure with only limited access to the outside water; its purpose is to damp out most of the rapid vertical oscillation of the water surface whose elevation is being measured. A stilling well is always required for use with a float-type water level gauge because rapid rise and fall of the float may cause its suspension cable to slip over, or even jump off, the pulley wheel. Other problems that may be cured by installation of a stilling well are excessive "chatter" in a pen-on-paper record, and excessive scatter among readings taken at fixed intervals by a digital recorder. A small portable stilling well is useful when it is wished to level to the water surface, as is required in checking the zero setting of a submerged pressure gauge. Such a portable well could be simply a length of metal or plastic pipe sealed at one end except for a small intake hole far enough above the sealed end to avoid obstruction. With the well set vertically in the shallow water near shore (secured by rocks or other temporary supports), a levelling rod may more easily and accurately be held on the water level inside the well than on that outside.

A much more substantial stilling well than that described above is required for use with an automatic recording gauge. It may be constructed from wooden planks, metal or plastic pipe, sections of culvert, etc. It must be vertical and have sufficient cross-sectional area to accommodate the float and counter-weight clear of the sides of the well at all water level stages; it must extend from below the lowest to above the highest water levels anticipated (including wave action outside the well); except for the small intake hole, it must be water-tight over the portion of its length that may be submerged; and it must be sturdily constructed and mounted to withstand wave action without significant motion of the well. Particular care should be given to strengthening the bottom of the well, since a sudden surge (up or down) in the water level outside the well creates a pressure (in or out) against the bottom of the well of 0.1 atmospheres per metre of surge.

The intake opening should be so placed as to be submerged at all times, but should not be so close to the bottom of the well that it could become blocked by the accumulation of silt inside or outside. It is sometimes difficult to find a location that is both convenient and suitable for construction of a stilling well. For example, the vertical side of a pier provides a convenient surface to which to attach a stilling well, and the pier can provide easy access to the gauge; but in regions with large tidal range (e.g. Bay of Fundy), the area around the pier may dry out at some low water stages. In such a case, it may be feasible to dig the bottom of the well down below the low water stage and feed it through the siphon action in a hose running from deeper water off shore to the inside of the well; the hose or pipe may pass through the wall of the well at any convenient spot near the bottom of the well, but it must be assured that the end of the hose inside as well as that outside the well remain submerged at all times. A similar arrangement may be used when silting is a problem near the bottom of the well, feeding the well through a hose or pipe whose outside end is secured in deeper water where silting is not a problem.

The damping action of a stilling well is a function of the ratio of the cross-sectional area of the inside of the well to that of the intake, the larger the ratio the greater the damping. Figure 43, shows for different intake ratios, the rate of adjustment of the water level inside a well to a sudden and sustained surge in the outside level. While the decay rate of the level difference is not strictly exponential, it is nearly enough so over much of the curves to make the concept of a response time meaningful. Taking the response time of a well as the time required for the inside water level to adjust half way to a sudden and sustained surge in outside level, Fig. 43 provides the following response times for wells of various intake ratio, R:

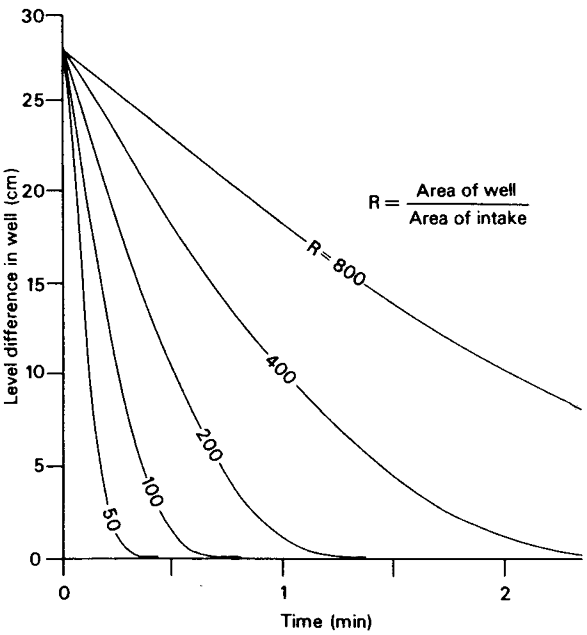

FIG. 43. Response of water level in stilling well to sudden and sustained surge of outside water level, for various intake ratios.

6 seconds for $R = 50$
11 seconds for $R = 100$
22 seconds for $R = 200$
45 seconds for $R = 400$
90 seconds for $R = 800$

The data for Fig. 43 was obtained by measurement in a section of plastic pipe whose cross-sectional area was 900 cm^2 and whose wall thickness was 3 mm. The wall thickness and the roughness of the intake surface may influence the response times somewhat. It is recommended that the area of the intake be 1/100th that of the well ($R = 100$), or that the diameter of the intake be 1/10th that of the well. If a long intake pipe or hose is employed, the pertinent intake area is the smallest cross-sectional area along its length. Since friction in a long intake pipe increases the response time of the well, the cross section of a very long pipe or hose may need to be greater than that indicated by $R = 100$. Figure 44 illustrates the damping effect of a well with $R = 100$ on waves of ½-metre amplitude and periods of 12 hours, 6 minutes, and 6 seconds, respectively. These three periods were chosen to represent a possible tide wave, harbour seiche, and surface swell. The well is seen to damp out the high frequency waves effectively, while passing most of the intermediate frequency seiche, and all of the low frequency tide signal.

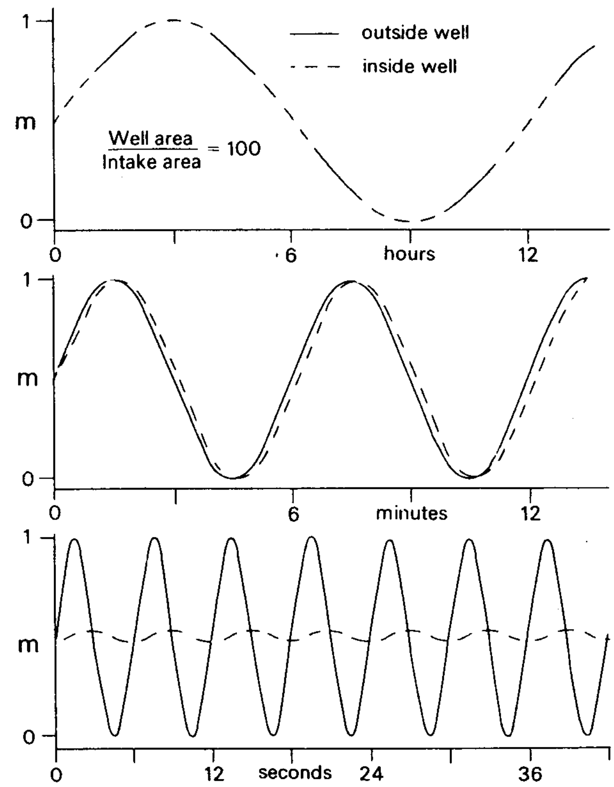

FIG. 44. Damping effect of stilling well with intake ratio of 100, for oscillations with period (a) 12 hours, (b) 6 minutes and (c) 6 seconds.

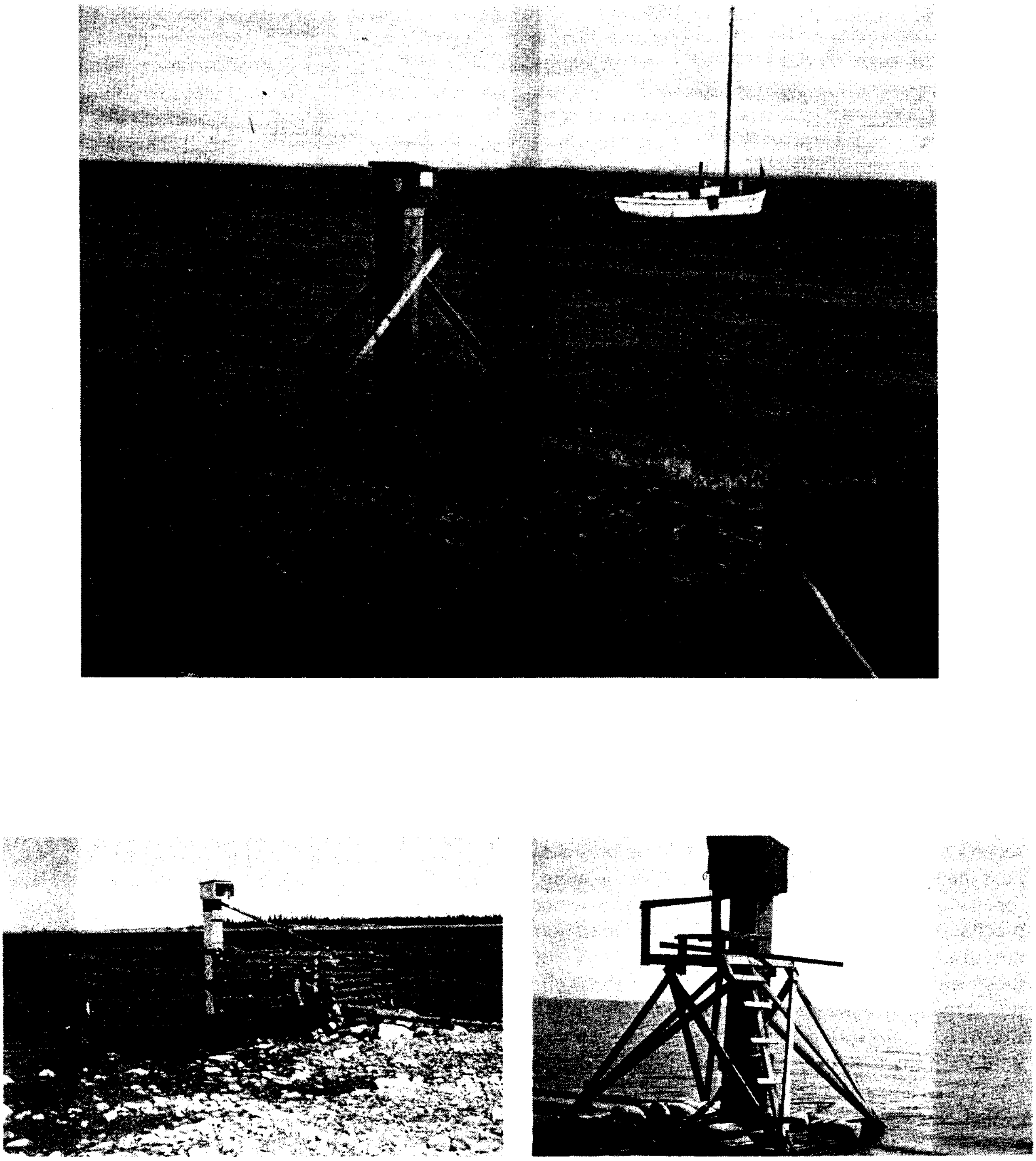

PLATE 8. Various makeshift structures to support temporary water level gauges. The gauge shelters shown house float gauges mounted over stilling wells constructed of wooden planks. (Photos by Canadian Hydrographic Service.)

Detailed instructions for the installation of stilling wells are not given here because each situation presents its own challenges, and some ingenuity may be required to assure that the well is vertical, rigid and motionless, accessible, protected from damage by boats berthing nearby, and free from excessive silting, while still being deep enough to have its intake below the lowest water level. Figure 45 illustrates schematically the use of a stilling well in conjunction with a float-actuated water level gauge.

6.3 Gauge shelters

Most installations will require construction of some sort of protective shelter for the gauge against the weather and interference from curious passers-by. At permanent gauge sites, a small walk-in gauge house is usually provided, but at temporary sites, an enclosure large enough to accommodate the gauge itself is sufficient. It is conveniently constructed from plywood, with a door hinged at the bottom so it can be dropped down out of the way or secured horizontally by hooks and chains to form a working surface. If there is a stilling well, the gauge shelter may be fastened securely to the top of the well for support, with a weather-tight connection between the well and the shelter. Holes drilled in the floor of the shelter should be no larger than necessary to accommodate passage of the leads or cables from the sensor in the well to the gauge recorder. An inspection hatch should be provided near the top of the well to give access for cleaning, repairing, or replacing the float or other sensor mechanisms. Large holes in the floor of the shelter are discouraged, because of the propensity for loose articles to fall through them into the well, possibly fouling the sensor mechanism. Figure 45 illustrates a typical gauge shelter in conjunction with a stilling well and float gauge. When a gauge site is in an area inhabited or travelled by the public, particular care should be given to neatness of construction, including the painting of the gauge shelter and any supporting framework. When unattended, the shelter should be securely padlocked. A notice attached to the shelter indentifying the installation as a water level gauge and briefly describing its function will satisfy most people's curiosity, and, it is believed, decrease the likelihood of meddling.

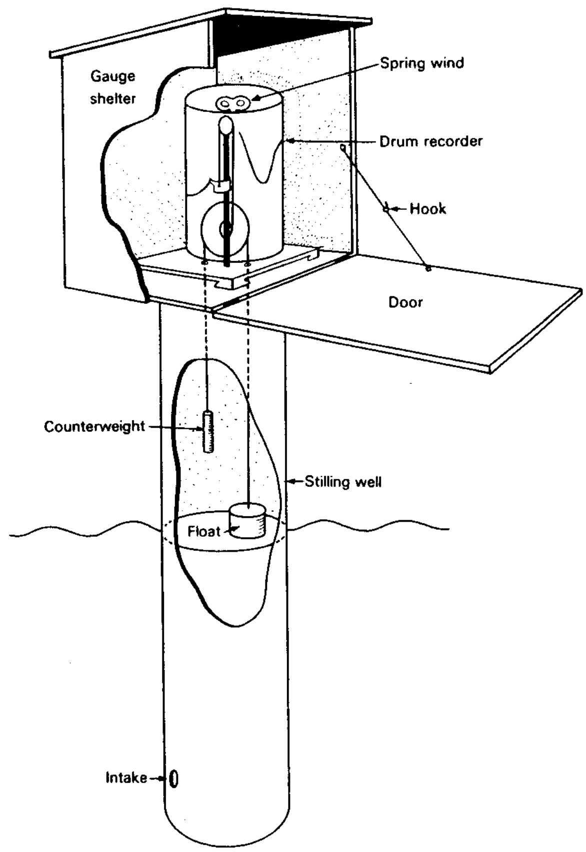

FIG. 45. Float gauge, stilling well, gauge shelter and drum recorder.

6.4 Float gauges

The float gauge has long been the standard instrument for the precise measurement of water levels. It provides a direct measurement of the water level, and so does not require calibration over its range of operation, although its zero adjustment must be regularly monitored. Its major drawback is the rigid requirement for a stilling well, provision of which may be a problem at many locations. Figure 45 illustrates in principle the operation of a float-actuated water level gauge (float gauge). The illustration does not pretend to represent any particular make or model of instrument, and the drives, linkages, etc. encountered on actual equipment may differ considerably from the simple ones shown.

The water level information is transmitted from the float to the recorder by the thin cable which is attached at one end to the float, passes over the pulley on the recorder, and is attached at the other end to the counterweight. The float is usually cylindrical in the centre and spherical at the ends; it is hollow, and the level at which it floats may be adjusted by the addition or removal of lead shot. When deployed, the water line on the float should come about half way up the cylindrical section, to assure a linear change in buoyancy with change in depth. Increasing the cross-sectional area of the float increases the sensitivity of the gauge to changes in water level, but a practical limit is set by the size of the well and the inspection hatch. The counterweight must be heavy enough to keep sufficient tension in the float cable to prevent if from slipping on the pulley, but not so heavy as to lift the float too high up in the water. It should be solid and made all or mostly of lead, to minimize its loss of weight to buoyancy if it is submerged over part of the range. Since the float will ride slightly lower in the water when the counterweight is submerged than when it is in air, a small but systematic error can thus be introduced into the readings near high water with respect to those near low water. At permanent gauge installations an effort is made to avoid this source of error, either by mounting the gauge high enough above the highest water level that the counterweight need never reach the water, or by providing a separate water-tight dry well to accommodate the counterweight. These refinements are not required for temporary installations, but if the range of water levels is small, it should be a simple matter to mount the gauge high enough and to cut the float cable to a length that would keep the counterweight out of the water. The float cable should be strong but light. It is particularly important that it be light when the range of the tide is large, because the effective weight of the counterweight is increased by the weight of cable on its side of the pulley, and decreased by the weight of cable on the float side. Further details concerning the installation of a particular model of float gauge should be obtained from the instrument manual accompanying it or from the agency issuing the equipment. A variety of types of recorder may be used in conjunction with a float gauge, and some of these are discussed below; in Fig. 45 a drum-type paper chart recorder is shown.

6.5 Pressure gauges — diaphragm type

The hydrostatic pressure at depth h in a column of water is ρgh, where ρ is the mean density of the water in the column above the depth h, and g is the acceleration due to gravity. Gravity may be considered constant for the purpose of water level measurement, but differences in water density from place to place may be important, particularly if large differences in salinity occur. The difference in density of ocean water at 0°C and of fresh water at 25°C is about 3%, 2½% being due to the salinity difference, and ½% due to the temperature difference. Clearly, if water levels are to be interpreted from hydrostatic pressure measurements, different calibration scales would be required for fresh and salt water. Use of pressure sensors instead of float gauges to measure water levels at temporary locations for the control of hydrographic surveys has become almost standard practice. This is because installation of the pressure gauge is much simpler, especially if no wharf is available. A stilling well is not normally required with a pressure sensor, any damping that is required usually being supplied by the design of the sensor head itself and by the natural damping of the pressure signal of short waves with depth (see section 1.4). Figure 46 illustrates the damping of the pressure signal from a 6-

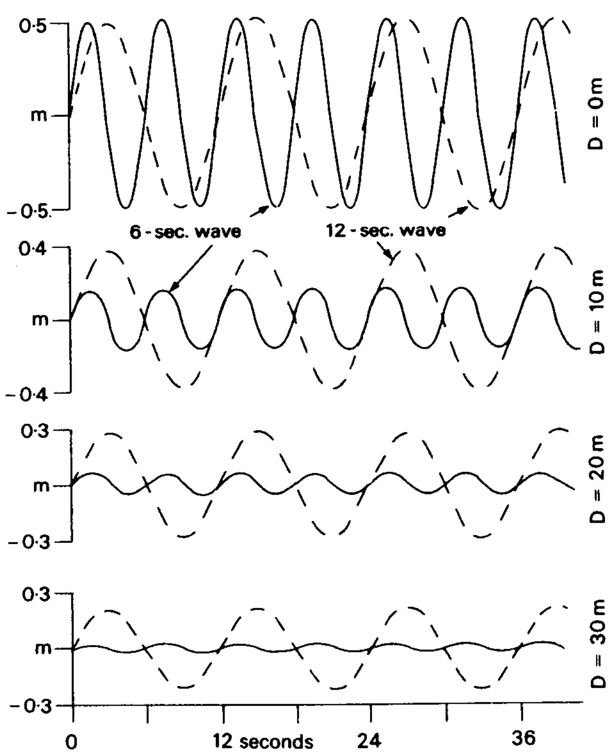

FIG. 46. Damping of pressure signal with depth, for 6-second and 12-second sinusoidal waves.

second and a 12-second sinusoidal wave at depths of 10, 20, and 30 metres. The vertical scale in Fig. 46 is shown in metres, after conversion from pressure units. There is, of course, no damping of the pressure signal from long waves (tides, seiches, etc.).

Figure 47 shows schematically a diaphragm-type pressure gauge assembly. The pressure sensor is a flexible rubber diaphragm that forms one face of a hollow air chamber; the outside of the diaphragm is exposed to the water pressure through holes in a protective housing. Adjusting the size of the holes controls the damping of the response much as in a stilling well. The air chamber behind the diaphragm has an air-tight connection through a small (1-2 mm inside diameter) capillary tube to the inside of a Bourdon tube, bellows or aneroid chamber at the recorder site on shore. These devices translate changes in differential pressure (inside vs. outside) into a motion which can be conveyed by various linkages to a recorder. A Bourdon tube uncoils slightly as its internal pressure increases, a bellows extends lengthwise, and an aneroid lid becomes more convex. The gauge depicted in Fig. 47 has a bellows linked to the pen arm of a drum-type recorder, but other arrangements are possible. The diaphragm housing must be securely mounted face down on some supporting structure below the lowest water level, such that it may not move (especially not vertically) during the recording period. If a wharf is available, the attachment may be to one of its pilings, but since the sensor may be 200 m or more from the recorder, a small rock crib or other support can usually be constructed in a reasonably protected location on firm bottom off shore. The principle of operation of this type of pressure gauge is that the static air pressure is uniform within any closed system (except for the negligible weight of the vertical column of air). Thus, as long as all seals are tight, the pressure inside the bellows equals the pressure at the diaphragm, which consists of the hydrostatic pressure due to the column of water plus the atmospheric pressure at the water surface. Since the pressure outside the bellows is the atmospheric pressure, the pressure difference to which the bellows responds is the hydrostatic pressure due to the column of water above the diaphragm.

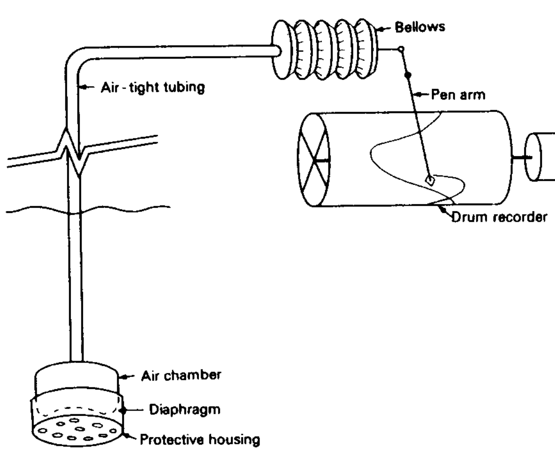

FIG. 47. Diaphragm-type pressure gauge, bellows pressure transducer and drum recorder.

6.6 Pressure gauges — bubbler type

Bubbler gauges (also called gas purge gauges) are not as frequently used as diaphragm gauges at temporary gauge sites in Canada, but they have many of the same advantages, e.g. they do not require a stilling well and the pressure sensor can be installed a considerable horizontal distance from the recorder. Figure 48 shows schematically a bubbler-type pressure gauge assembly. The pressure sensor is simply the orifice at the underwater end of a long flexible air-tight tube. The tube may be larger than that of a diaphragm gauge because the volume of gas contained in the system is not a limiting factor; an inside diameter of 5 mm is recommended. At the recorder site on shore compressed air or nitrogen is continuously introduced into the system from a cylinder (A) through a reduction valve (B) that lowers the gas pressure to the working range of the recorder and other equipment. The pressure at the high and low side of the reducing valve is displayed on the needle gauges (C and D). The pressure at the low side (gauge D) must always exceed the greatest hydrostatic pressure that could be experienced at the orifice. The gas then passes through a flow control valve (E), which is a valve like that used in underwater breathing apparatus to maintain a steady flow of air regardless of changes in pressure at the downstream end. At this point the tube branches, one branch going to the recorder and the other continuing on to feed the orifice (F). At a convenient spot in the system below the flow control valve a bubble chamber (G) containing oil or water is inserted so the rate of gas purging can be monitored and controlled to about one bubble per second. As long as gas is issuing

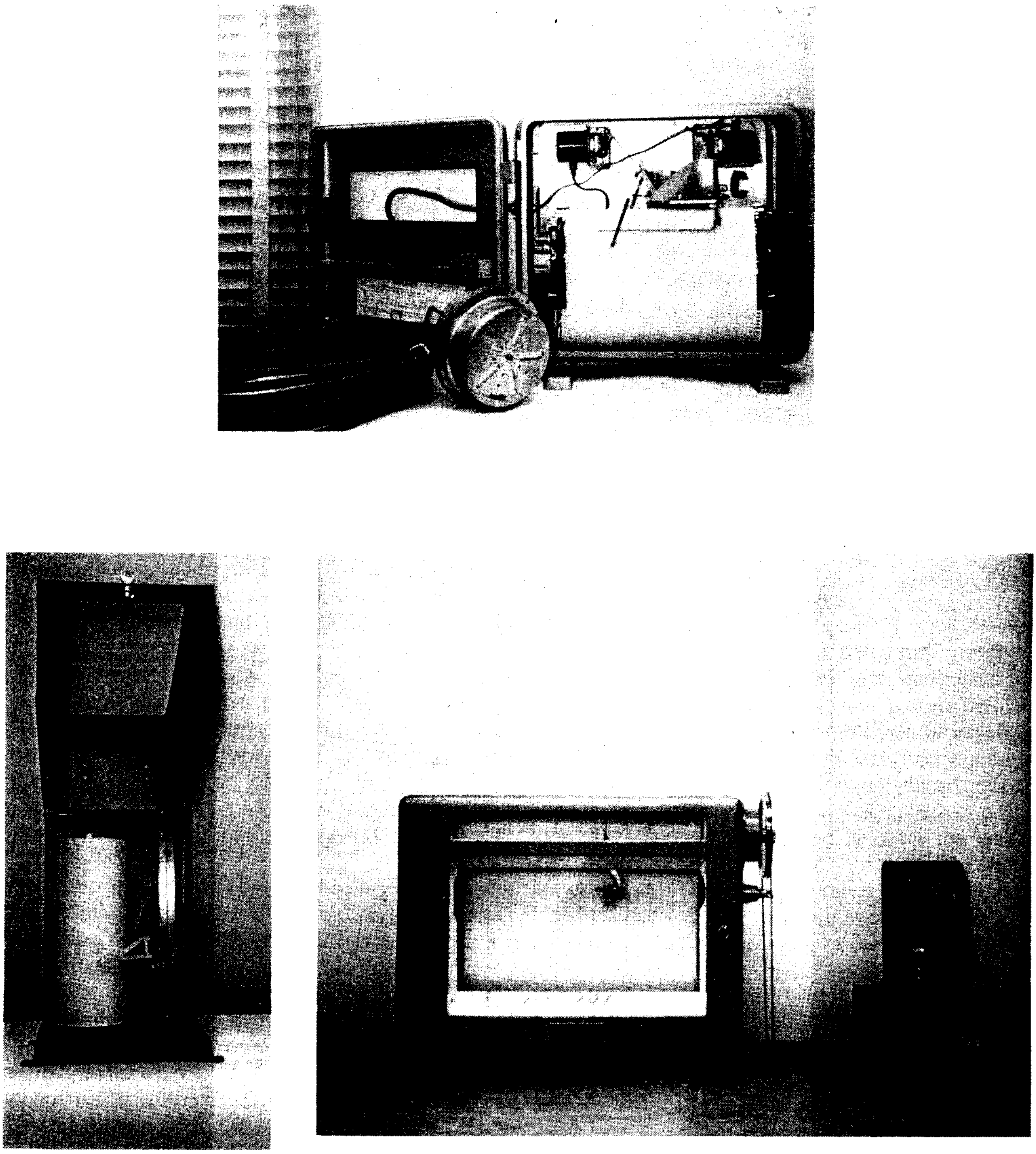

PLATE 9. (*Upper*) Diaphragm-type pressure gauge, showing diaphragm housing, coiled-up capillary tubing, and strip-chart recorder. (*Lower left*) Drum-type recorder for use with float gauge. (*Lower right*) Strip-chart recorder for use with float gauge, and (on right) a sight (electrical tape) gauge. (Photos by Canadian Hydrographic Service.)

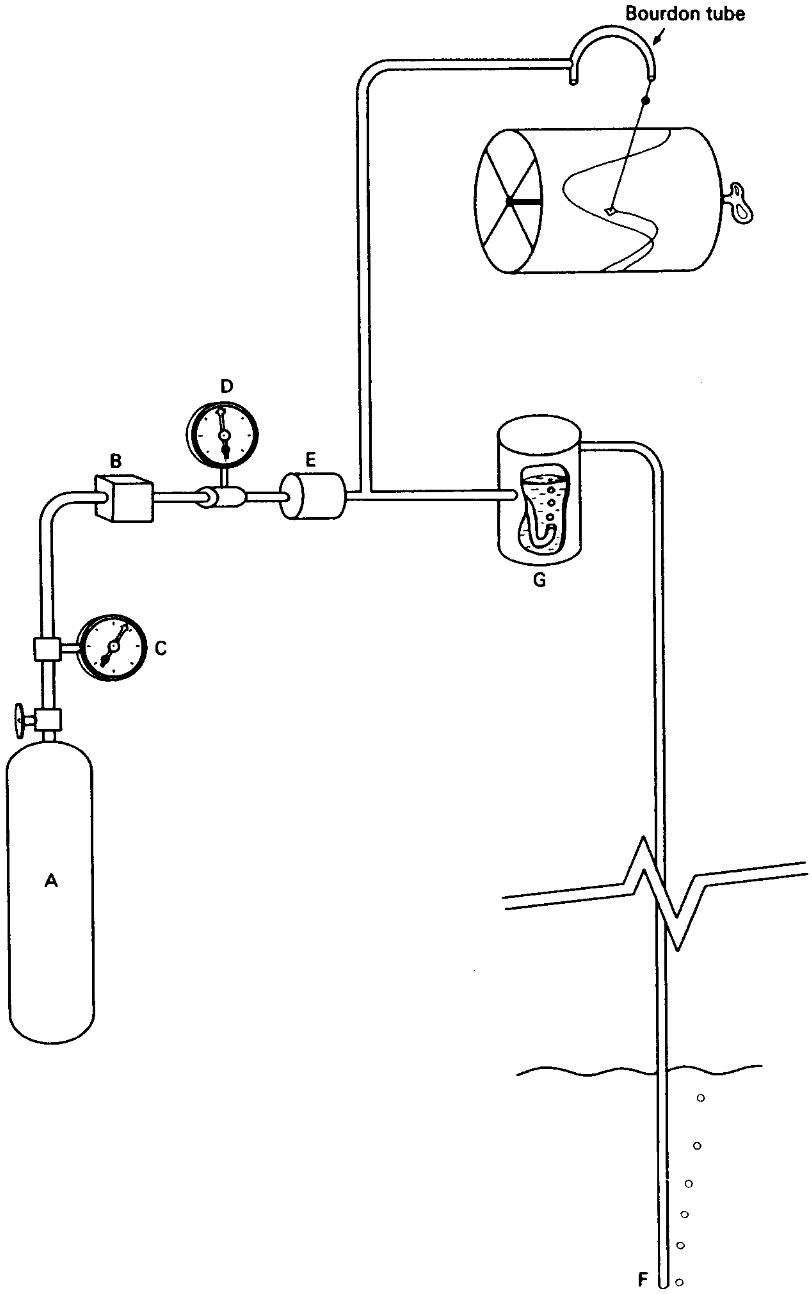

Fig. 48. Bubbler-type pressure gauge, Bourdon tube pressure transducer and drum recorder.

from the orifice at about this rate, the pressure throughout the system below the flow control valve will be sensibly uniform, and equal to the pressure in the water at the orifice. Again, various recorders could be used, but Fig. 48 depicts a Bourdon tube linked to the pen arm of a drum-type recorder. Since the outside pressure on the Bourdon tube is atmospheric, the pressure difference to which it responds is equal to the hydrostatic pressure due to the column of water above the orifice. If the flow of air is allowed to stop, water will flow through the orifice up the tube, giving a faulty reading; and if the flow of air is too rapid, there will be a slight pressure drop along the tube toward the orifice, giving slightly too high a reading. One cylinder of gas should operate the gauge for four or five weeks.

6.7 Pressure gauges — deep sea

These are gauges that are self-contained in their own protective case, which can be anchored on the sea bottom to record changes in pressure for periods up to a year and in depths up to several kilometres. The type most commonly used at present senses pressure by means of a quartz crystal which forms part of an electrical oscillator circuit. The resonant frequency of the crystal, and hence of the oscillator, depends upon the pressure applied to the crystal (and to a lesser extent upon the temperature of the crystal). By exposing the crystal to the external pressure through a pressure port in the case, the frequency of the oscillation is made to depend upon the pressure outside the case. The frequency response is not linear with the pressure, however, and the instruments must be calibrated to relate frequency to pressure. The oscillator frequency is recorded regularly at a pre-selected sampling interval. Most present models record data on magnetic tape, but solid-state memory banks may largely replace tapes in the near future, thus reducing the power requirement and eliminating a source of trouble in the moving tape drive assembly. Data storage space is usually the limiting factor determining the maximum record length attainable, the shorter the sampling interval, the shorter the record. In deep sea operation the gauge is unattended from the time of mooring to the time of recovery, and the record is not available for use until it is removed from the gauge and electronically translated. For use at shallower locations, however, most models have an acoustic transducer which may be engaged to transmit the readings as sound pulses that can be received by hydrophone in real time. Alternatively, if the mooring is not too deep, the readings can be transmitted by electrical cable from the gauge to an auxiliary recorder in a moored buoy, or even on shore. A system may soon be available whereby a gauge can be interrogated acoustically from a vessel and made to play back all or part of its stored data. Such features may give these gauges a role in the reduction of hydrographic soundings, but at present they are mostly used for the study of tides at offshore locations.

From the standpoint of water level measurement, there are two major difficulties with the self-contained gauges moored far from shore: the first is that they sense total pressure (hydrostatic plus atmospheric), and hence do not reflect the true water level unless the atmospheric pressure is separately measured and subsequently subtracted (see section 4.4); the second is that it is difficult or impossible to relate the zero setting of the gauge accurately to benchmarks on shore. For the determination of tidal constants at offshore locations, however, the self-contained gauges are most adequate, because neither a slight drift in the gauge zero nor the inclusion of the atmospheric pressure signal is likely to contribute any significant energy at the tidal frequencies. In fact, the total pressure displays a much cleaner tidal signal than does the hydrostatic pressure alone. This is because in the ocean the fluctuations in local atmospheric pressure are largely offset by corresponding fluctuations of the opposite sense in the water level (inverted barometer effect; section 4.4). In spite of their shortcomings in water level measurement, the deep-sea gauges may be useful in improving the accuracy of sounding reductions over shallow banks far from shore (e.g. the Grand Banks).

6.8 Staff gauges

A staff gauge is simply a graduated staff (usually marked in metres, decimetres, and centimetres) mounted vertically in the water with its zero below the lowest anticipated water level. It is usually constructed from prefabricated metal or wooden sections 1 metre long; the sections are placed end to end and fastened to a straight wooden plank or pole to achieve the length required to cover the local range of water level. If a wharf is nearby, the staff may be attached to one of the vertical wharf pilings. If there is no existing structure to which to attach the staff, it may be necessary to construct a stone-filled wooden crib or tripod with a wide base to provide a rigid support. On some types of bottom the pole supporting the staff may be driven into the bottom until it is firm, and secured vertically by at least three guy wires fastened to anchors. Sometimes, when the tidal range is large and the bottom slope is small, the intertidal zone is so broad that two staff gauges may be required, one near shore to be read during the upper part of the range, and one farther off shore to be read during the lower part of the range. It is even possible that more than two staff gauges could be required under rare circumstances (e.g. the tidal flats of the upper Bay of Fundy or Ungava Bay). When more than one staff gauge is used to cover the range of water levels, they should be related to each other so that there is a slight overlap in the part of the range that they cover, and so that they give the same reading in the region of overlap. Figure 49 sketches several possible staff gauge installations, but the hydrographer's ingenuity may produce others; all are satisfactory as long as the staff is rigid and steady and is convenient to read.

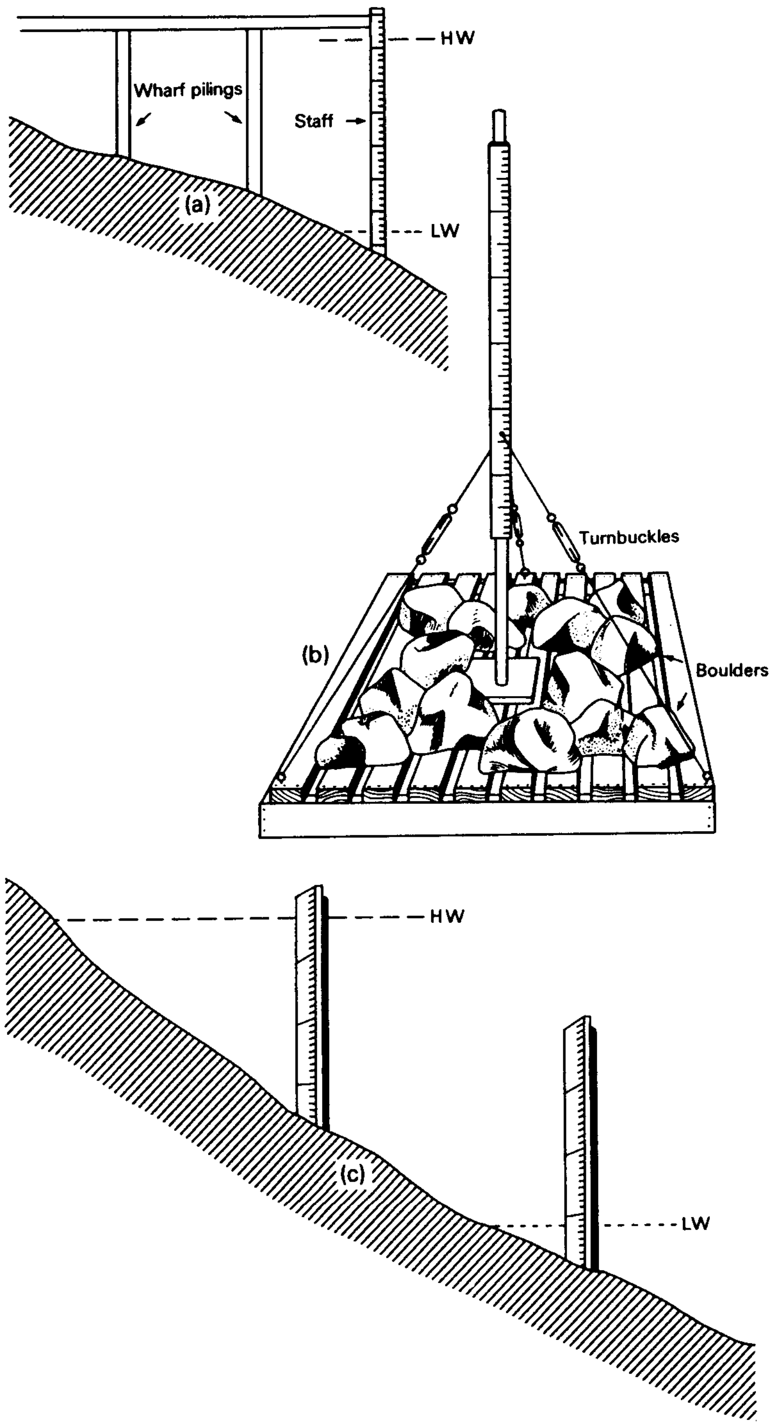

Fig. 49. Staff gauge installations (a) on wharf piling, (b) on submerged platform and (c) on long sloping beach.

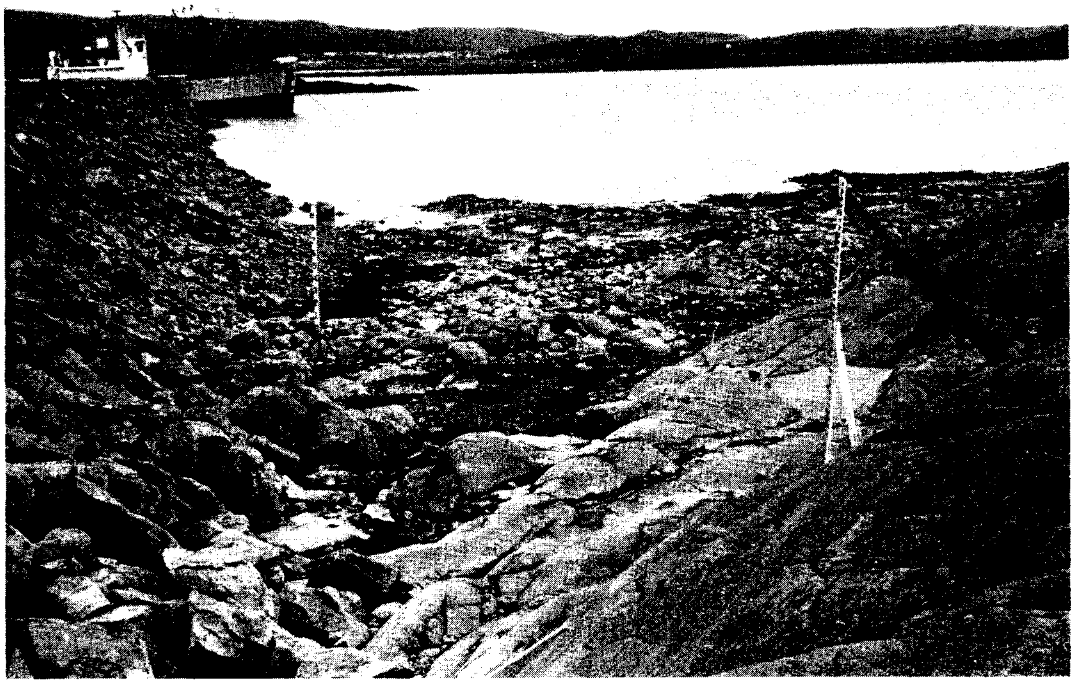

PLATE 10. Use of multiple staff gauges at Frobisher Bay, Northwest Territories, to span the large range of tide between low and high waters. (Photos by Canadian Hydrographic Service.)

A staff gauge is required at every gauging site. It may serve as the only gauge for a brief local survey at a location where the tidal constants are already known, or on non-tidal waters, although it would then require continuous monitoring during sounding. Where it is feasible to install an automatic gauge (float, diaphragm, etc.), a staff gauge is still required, against which to make checks of the accurate operation of the automatic gauge.

6.9 Sight gauges (electrical tape gauges)

A sight gauge is used to make spot readings of the water level inside a stilling well, usually as a check on the operation of the automatic gauge. It provides a more accurate check than can be obtained from a staff gauge, but may not be considered as a replacement for the staff gauge. This is because both the sight gauge and the automatic gauge read the level inside the well, and a comparison of their readings tells nothing about possible blockage of the well intake. At permanent gauge installations, comparisons are always made of the automatic gauge with both the staff and sight gauge. Use of a sight gauge at temporary installations is optional, but it does offer a convenient and accurate means of checking gauge zero and referring it to benchmarks.

A sight gauge is mounted on the floor of the gauge shelter, and consists of a graduated metal tape spooled onto a metal drum, with a plumb bob (or plummet) fastened to the running end so that the lower end of the plummet forms the zero point for the tape graduations. As shown in Fig. 50, the core of the metal drum is electrically connected in series with a low-voltage battery, a needle galvanometer, and with the water in the well (either through the wall of a metal well or through a wire on the inside of a non-metallic well). A flat-topped peg, called a "gnomon," is set alongside the tape on the shelter floor. To read the vertical distance of the water level below the gnomon, the tape is unrolled from the drum through a small hole in the shelter floor until the tip of the plummet touches the water surface, completing the electrical circuit through the water and causing the galvanometer needle to jump. At this instant the length of tape out at the level of the top of the gnomon is read. The tape is then slowly raised until the galvanometer needle drops back again, and another reading of the tape against the gnomon taken. The mean of the two readings should be taken as the distance of the water level in the well below the top of the gnomon at the central time of the operation. The gnomon must be mounted so as to be clearly in view through the open shelter door, to permit its elevation, and hence that of the gauge zero, to be referenced to benchmarks.

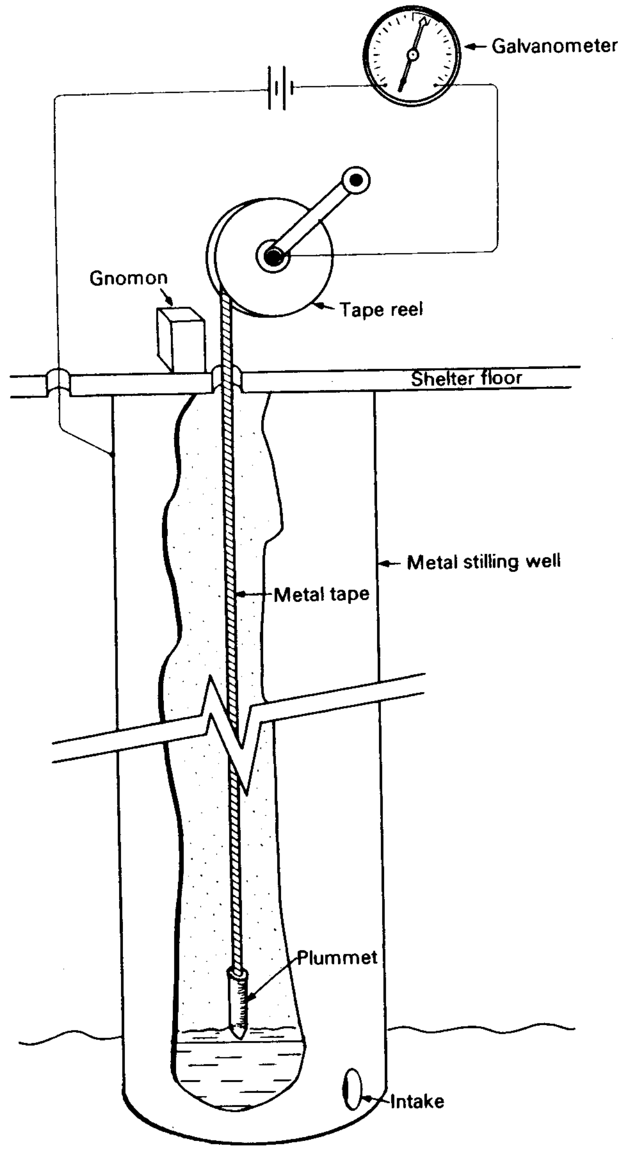

FIG. 50. Electric sight gauge, with metal stilling well.

6.10 Data recorders

The type of recorder most commonly used at present with automatic water level gauges at temporary locations provides a continuous pen-on-paper trace of the water level on a chart driven at a constant speed by a spring-wound clock. The movement of the pen is mechanically controlled by the movement of the float pulley or the pressure element (bellows, etc.). The drum-type recorder (Fig. 45, 47, 48) uses a single sheet of chart paper that fits exactly once around the drum, which is driven to rotate once per day. In non-tidal waters the chart on the drum recorder must be changed each day, to avoid confusing overlaps of the traces. In tidal waters, however, the chart may be used over several days because the daily advance of the tide (50 minutes per day) distinguishes one day's record from another. The strip-chart recorder uses a long strip of chart paper that feeds from a supply spool over a recording plate and onto a take-up spool. The chart is long enough to contain a full month of record, but segments may be documented for identification and cut off for use during the sounding survey, provided that the gauge is the responsibility of the sounding party. Segments of record may not be removed from gauges at permanent stations, whose records serve purposes other than sounding reduction.

At many permanent gauging stations data are digitally recorded on punched paper tape or in solid-state memory core that can be read remotely by telephone or locally in the gauge house. There are also tele-announcing gauges that can be interrogated by telephone to give the present water level and the trend (rising or falling) in plain language. There are obvious advantages to the application of similar technology to the temporary gauges; for example, to telemeter water level data by radio link to the survey vessel, either in real time or in blocks of specified length. Equipment of this type will probably soon replace the traditional equipment, and the hydrographer should keep abreast of such developments.

6.11 Selection of gauge site

The first consideration in choosing gauge sites for vertical control of hydrographic sounding surveys should be given to how well the water level fluctuations at the gauge sites reflect those in the survey area. This will depend not only upon the distance between the gauge and the survey area, but also upon the rate at which the tidal character may change in the region, the change in slope of a river along its length, the response of a lake to wind set-up and seiches, etc. If a survey is to cover a long stretch of coast-line, it may be desirable to have two gauges in simultaneous operation and to leap-frog them along the coast as the survey progresses. Two gauges may also be required in the survey of a long tidal inlet, since the tidal character can change significantly between the entrance and the head. More than one gauge is often required along a strait that joins two bodies of water of different tidal character because the tide must change character rapidly along the strait. The surface slope along a river may be different at different stages of flow, and so may not always be parallel to the slope of the low-water stage chosen as chart datum: for this reason, two gauges may again be necessary, one at the upstream end and one at the downstream end of the survey area, with no rapids, waterfalls, locks, or other datum discontinuities between them. The approximate location of temporary gauges should be planned before entering the field, and the Regional Tidal Officer should be consulted when advice or assistance is required.

The detailed local selection of a gauge site should be made with the following considerations in mind:

(1) Ease of installation: the existence of ready-made structures to which the automatic gauge and the staff gauge may be attached (wharf, fish stakes, bridge pilings, etc.); presence of firm bottom on which to construct support for gauges if no ready-made structure is available; presence of sufficiently deep water near shore to assure that the gauge does not "dry out" or the surrounding water become impounded in a tidal pond at low water; availability of materials from which to construct support structures; accessibility of the site by water and/or land; and suitability of nearby terrain or structures for establishment of benchmarks.

(2) Ease of maintenance and operation: natural protection provided against full impact of waves and current; likelihood of silting around gauge intake or sensor; possibility of damage from or obstruction to marine traffic; and accessibility of the gauge and recorder both by launch and by foot.

6.12 Benchmarks — general

Benchmarks are the fixed elevation markers against which the zero setting of the gauge is checked during its operation, from which hydrographers may recover chart datum for future surveys, and through which surveyors and engineers may relate their surveys and structures to chart datum. The function and importance of benchmarks, and the reason that a minimum of three is required at each gauge site, has been discussed in section 5.9. The benchmarks (BMs) should be in place by the time the gauge is to be set in operation. To minimize the length of the levelling lines, an attempt should be made to keep all three BMs within a radius of half a kilometre of the gauge. The primary consideration, however, is that they be solidly set in stable structures, bedrock, or firm ground. No two BMs should be in the same structure or within 70 m of each other in horizontal distance, to minimize the likelihood of two of them experiencing the same instability.

Outcrops of bedrock provide the most stable setting for BMs, but structures with substantial foundations that extend below the frost line (public buildings, water towers, bridges, etc.) are usually also excellent. Permission should, of course, be obtained before placing a BM in a private structure. A BM should never be placed in a hollow or depression in which water might collect and freeze, and care should be given to the final appearance of the BM, since this reflects indirectly on the credibility of the other aspects of the survey. As an aid to future recovery, BMs set in bedrock should, whenever possible, be set close to a distinctive feature in the rock or to some easily describable landmark. Existing BMs that may have been established by other agencies in the vicinity of the gauge may serve as reference BMs for the gauge if they meet the stability and accessibility standards. Indeed, the use of such BMs is encouraged, since it determines the local relation between chart datum and the other survey datum. Enquiries about existing BMs should be made to pertinent survey agencies before entering the field.

6.13 Benchmarks — standard type

The standard Canadian Hydrographic Service BM tablet is illustrated in Fig. 51. It is made of bronze, and has a cap 5.6 cm in diameter with a shank 6.4 cm long and 1.5 cm in diameter. In the lower end of the shank there is a slot about 1.5 cm deep to receive a bronze wedge, which spreads the prongs of the shank against the sides of the hole when the tablet is set in rock or concrete. On the face of the cap there is a groove about 3.0 cm in length. When the tablet is set into a vertical face (i.e. with the shank horizontal), the groove marks the BM elevation, and the tablet must be set so that the groove is horizontal. During levelling, a benchmark chisel inserted into the groove provides the horizontal surface on which to rest the levelling rod. When the tablet is set in a horizontal face (i.e. with the shank vertical), the BM elevation is the highest point on the slightly convex surface of the cap, and the flat bottom of the levelling rod may be rested directly on the face of the tablet.

The standard method for setting the tablet into a horizontal or vertical face of rock or concrete is to drill a hole with a rock chisel, slightly deeper than

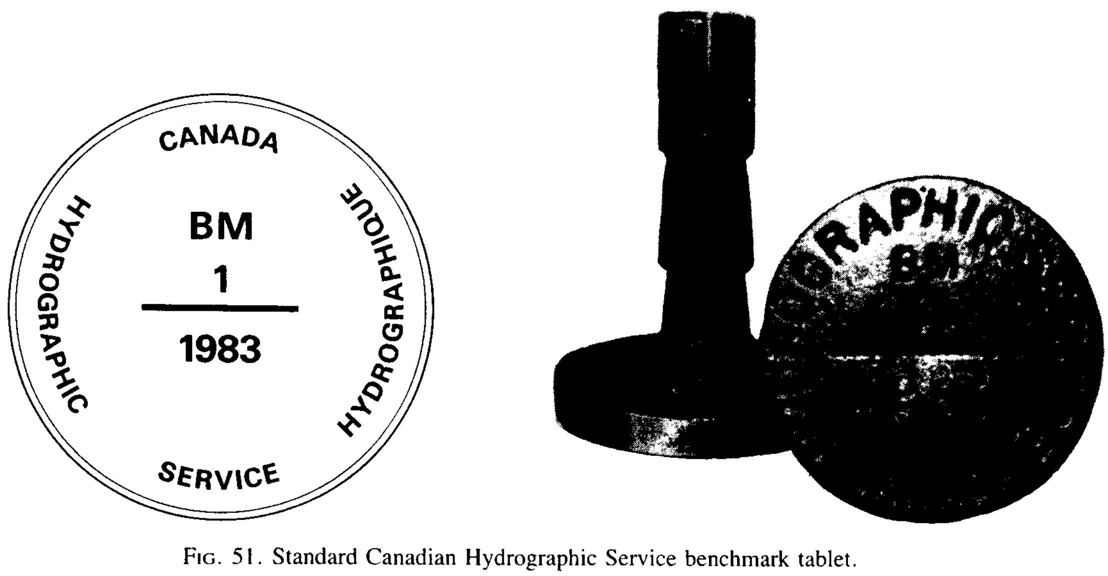

FIG. 51. Standard Canadian Hydrographic Service benchmark tablet.

the length of the shank of the tablet and slightly wider than its diameter. If the hole has the proper dimensions, the underside of the cap will come flush with the surface of the rock or concrete and the wedge will spread the prongs on the shank to grip the sides of the hole when the tablet is driven in. If the hole has been made slightly too deep, a small pebble may be placed in it to bear on the wedge. Under no circumstances may the shank be shortened to fit into a hole that is too shallow. Before finally setting the tablet, the hole should be cleaned out and filled with sufficient cement mix to squeeze into all the spaces around the shank and under the cap where it does not seat perfectly against the rock or concrete when it is wedged into the hole. Excess cement should be cleaned off, leaving the tablet neatly sealed against the penetration of water and frost. It is stressed that the purpose of the cement is to seal the small hollows left when the underside of the cap of the tablet is as nearly as possible flush with the original surface: cement is not to be used to fill in a space left because the hole was not drilled deep enough.

6.14 Benchmarks — special types

Benchmarks may be placed in suitable soil by fastening them to an iron pipe (called a "soil post"), when no rock or concrete structure is available. Figure 52 illustrates the setting of a soil post BM. A standard bronze tablet is welded to the top of a smooth iron pipe that is long enough to reach below frost level (2 or 3 metres). Holes are drilled through both sides of the pipe at its base, through which are fitted steel rods about 20 cm long to help anchor the pipe. The pipe must have an inside diameter large enough to accommodate the shank of the tablet, and an outside diameter no greater than that of the cap of the tablet. A hole of about 20 cm in diameter must be dug deep enough that only about 15 cm of the pipe protrudes. A post hole auger should be of assistance in this. Sufficient cement is placed in the bottom of the hole to encase the anchoring rods and seal the bottom of the pipe against the intrusion of ground water. Soil is then tamped in firmly around the pipe to fill the hole, with the surface soil mounded up around the pipe to allow for consolidation and shrinkage of the back-filled soil. The outside surface of the pipe should be smooth, so that frost heaving of the surface soil is less likely to affect the pipe. Soil posts should be placed on high ground with good drainage. Sandy soil is usually excellent for the installation of soil posts, but clay soil should be avoided, being too subject to frost heaving. If it is anticipated that soil post BMs may be required, a supply of pipes should be prepared before leaving for the field, having the tablets welded to the tops and the anchor-pin holes drilled near the bottoms. Rather than preparing a variety of lengths of pipe, one could prefabricate the pipes in short sections of three types — top sections, threaded on the inside at one end, and with the tablet welded to the other end; bottom sections, threaded inside at one end, and with anchor holes drilled at the other end; and insert sections, threaded inside at both ends. In the field, the sections could be fastened together with threaded plugs to form the desired length. The sections

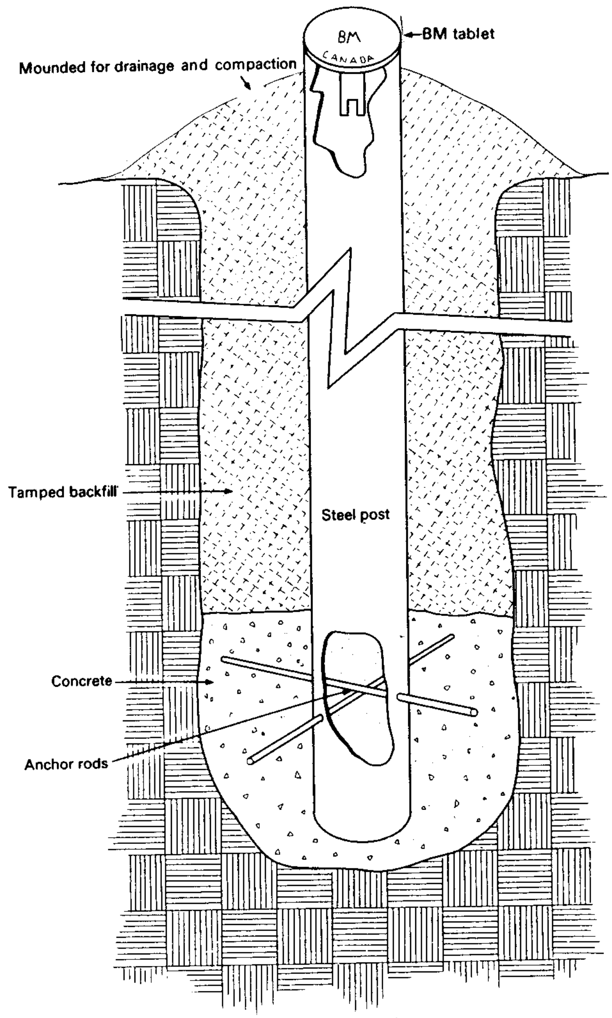

FIG. 5′. Soil post benchmark installation.

should be joined on the inside by threaded plugs, rather than on the outside by threaded collars, to preserve a smooth exterior.

Special techniques for setting BMs in areas of perma-frost, muskeg, and spongy soil do exist, but they are often laborious, and sometimes require special motorized equipment. If at all possible, gauge sites should be chosen to avoid the need for such difficult BM installations. The Geodetic Survey of Canada has a great deal of equipment and experience related to the installation of special types of BM. Sometimes, if a request is made before the final planning of their field season, a Geodetic benchmark party may be able to visit problem gauge sites to install special BMs. The Regional Tidal Officer should be consulted if BM installation problems are anticipated, and requests for assistance from the Geodetic Survey or other agencies should be made through him.

6.15 Benchmarks — descriptions

The face of each BM tablet must be stamped with the BM number and the year of its establishment (see Fig. 51). The stamping is done with metal dies before the tablet is set. Because Hydrographic BMs do not form a continuous network, but exist in discrete clusters around gauge sites, it is acceptable to repeat the same set of consecutive numbers (1, 2, 3, etc.) for the BMs at separate sites. If a BM has been lost or destroyed, its number must be retired, and the BM that is installed to replace it should receive the next number that has not been previously used from the numbering sequence at that gauge site. To enable a BM to be recovered and used at a future date, a description of its appearance and location must be recorded on the Temporary Gauge Data form (Appendix B), copies of which will be retained and updated by the Regional Tidal Officer. In all records, the BM name should appear exactly as stamped on the tablet, e.g. BM 1, 1983. The BM description consists of three elements:

(a) a verbal description,
(b) a sketch of the immediate vicinity, and
(c) photographs of the BM and surrounding area.

The verbal description should tell the type of BM, its number, how and in what it is set, its distance and direction from any easily identifiable marks (e.g., the corner of a building), and any other information that might assist in its recovery. The sketch should be kept as simple as possible, but must include at least the following basic information: true north direction, distance scale, high water line, drying areas and their type (e.g. rock, sand, shingle), prominent structures or features and their names, and distances between BMs and from BMs to structures or features. Two photographs should be taken, one a close-up to show the tablet and the surface or structure in which it is set, and the other a more distant view of the BM in relation to its surroundings, particularly identifiable features such as buildings, boulders, the shoreline, or even trees. In the second photograph, someone should point to or hold a levelling rod on the BM so there is no doubt as to its location.

If a previously occupied gauge site is revisited and the original BMs are located, their catalogued descriptions should be checked for accuracy and for possible changes that may have occurred at the site. Necessary revisions to the descriptions are to be noted on the Temporary Gauge Data form. If an old BM is found to have been destroyed, it is to be replaced with a new one, bearing a different number from the one that was destroyed. If an old BM is determined to be unstable, as demonstrated by a shift in its elevation with respect to the surrounding BMs, it is to be destroyed and replaced by a new BM with a new number. Notice of the destruction of BMs and the descriptions of BMs planted to replace them must be reported on the Temporary Gauge Data form, so that this information can be kept up to date in the benchmark catalogues.

6.16 Levelling — General

Levelling is an essential part of the gauge installation procedure, whose function is to establish the elevations of the BMs with respect to each other and with respect to the staff gauge and the automatic gauge zeros. When sounding datum is decided upon relative to the gauge zero, its elevation can thus be referenced to the BMs. When chart datum is ultimately confirmed, the catalogued elevations of the BMs above chart datum will depend for their accuracy upon the levelling done during the gauge installation, and from time to time during its operation. Because of the importance of levelling, the basic principles and procedures are discussed here, but a novice may wish to refer to a manual of surveying or civil engineering for a more detailed

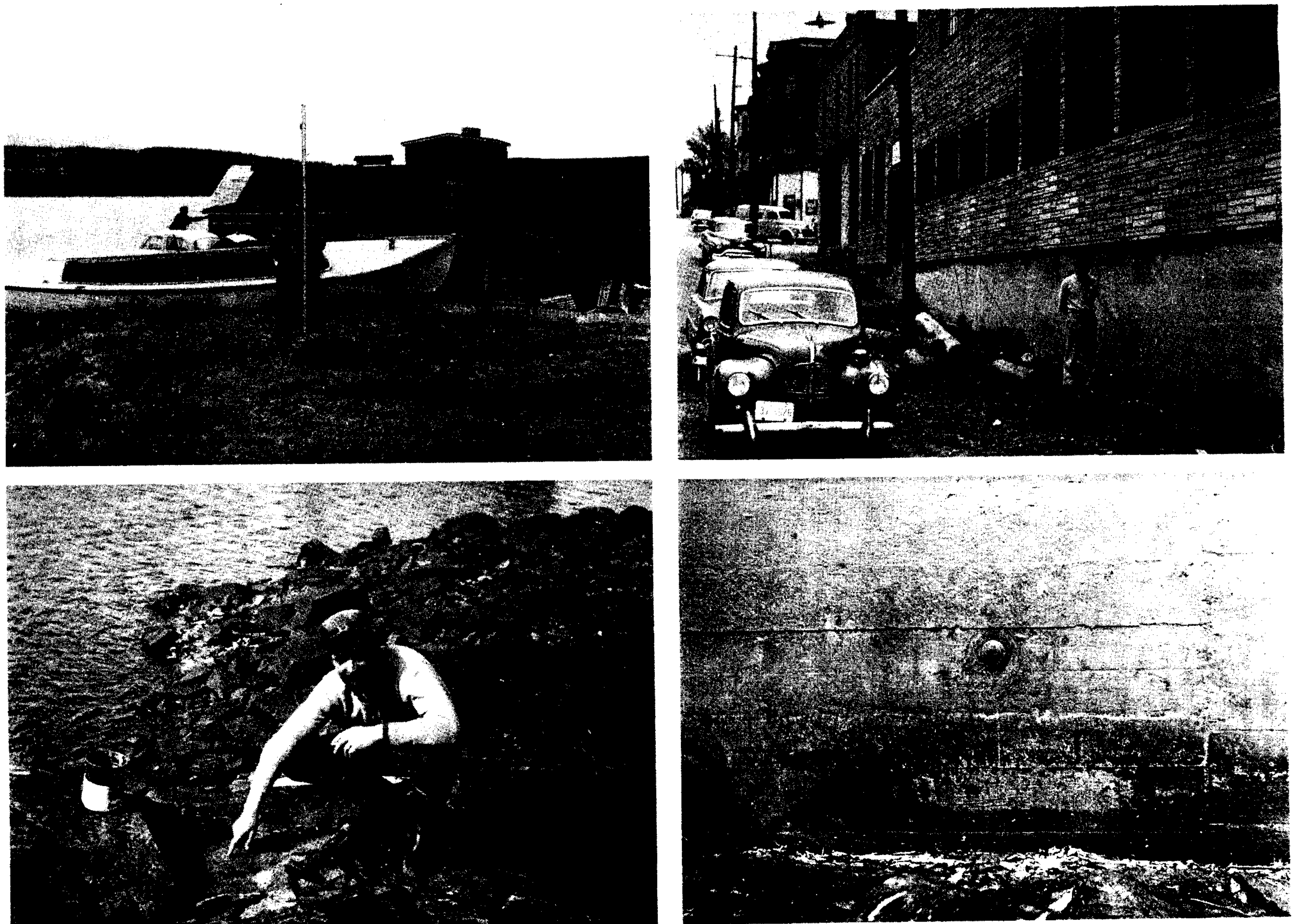

PLATE 11. Benchmark photographs, used to aid in recovery of the benchmarks on future surveys. Location of the benchmark may be indicated by someone pointing to it or holding a levelling rod on it when photographed. Photo in lower right is a close-up of the benchmark whose location relative to its surroundings is shown in the upper right photo. (Photos by Canadian Hydrographic Service.)

treatment. The three systems for calculating elevations above sea level that were discussed in section 5.2 (geopotential, dynamic, and orthometric) should be understood by the hydrographer, but need not concern him in connection with the local gauge site levelling. This is because there would be no significant difference in the three systems over the short distances and the small elevation differences involved, and it is acceptable to use the observed values directly. If the Hydrographic BMs are later tied by another agency into a more extensive levelling network, their elevations above that agency's datum will be measured in one of the three systems of section 5.2, but this will not change their quoted elevations above chart datum, for which the Canadian Hydrographic Service alone is responsible.

6.17 Levelling — method and terminology

The traditional method of levelling employs a levelling instrument (or simply a "level") with a viewing telescope, which is set up on a tripod between two points whose difference in elevation is to be determined. With the optical axis of the telescope horizontal, a reading is made on a graduated rod resting vertically on one of the points; the rod is then placed vertically on the second point, the telescope is swung around in the same horizontal plane, and another reading is taken on the rod. The difference in rod readings gives the difference in elevation between the points, the larger rod reading corresponding to the lower point. If the distance between the two points is large, if the difference in their elevations is greater than the length of the rod, or if they are not both visible from a single instrument set-up, the process must be repeated in steps, using intermediate points called *turning points* between the ends of the line. This is illustrated in Fig. 56. If the levelling is proceeding from BM1 to BM2, the sightings on the rod when it is closer to 1 are called *backsights*, and those when it is closer to 2 are called *foresights*. The difference in elevation from 1 to 2 should always be measured twice, once by running the line from 1 to 2, and again by running it from 2 to 1. The discrepancy between the values obtained is called the *closing error*, or the *closure*. This method of levelling has long been referred to as "spirit levelling" because the horizontality of the telescope was set with reference to the bubble in a vial containing alcohol, called a spirit level. Many of today's levelling instruments have a system of optics suspended on fibres to eliminate the need for the literal spirit level, but the name persists. A more apt descriptive name for the method is *differential levelling*.

6.18 Levelling — equipment

In addition to the levelling instrument itself, the following items are required for the performance of proper differential levelling: instrument tripod, levelling rod, rod level, benchmark chisel, and portable turning point. The tripod usually is mated to the particular levelling instrument. Most have telescoping legs, and care is required to see that all wing nuts are tight after the tripod is set up. The base plate on which the instrument sits sometimes has a small spherical level, whose bubble should be approximately centred when the tripod is set up. If there is no spherical level, the rough levelling can be accomplished by sighting along the surface of the base plate at the horizon. On uneven terrain it is permissible to clamp the legs of the tripod at different lengths to obtain a more stable set-up.

The levelling rod may be made of wood, with a metal foot plate and with a graduated invar metal scale mounted on its face, the zero of the graduations being at the base of the foot plate. There is on most rods a sliding section that can be extended and clamped, to double the usable length of the rod; in using this, one should be certain that the extended section is fully seated and securely clamped against its stops. While it may be wise to carry a spare rod, the same rod should be used over a complete line of levelling. This is so that if the base of the foot plate does not coincide with the zero of the graduations, this zero error will cancel out in the difference between foresights and backsights.

It is important that the levelling rod be held no more than a few degrees off the vertical when it is being read. To aid the rodman in this endeavour, a rod level is supplied. It is a piece of metal about 10 cm long, with a right-angle groove along its full length, and a small spherical level mounted at one end. The rodman holds the rod level with one hand against the corner edge of the rod, just below eye level, and swings the rod until the spherical level bubble is centred; the groove in the rod level, and hence the rod itself, should then be vertical. The observer can tell from the vertical cross-hair in the telescope if the rod is off vertical to one side or the other, but he can not tell if it is off vertical fore-and-aft: this is why rodmen are sometimes asked to sway the rod slightly back and forth so the observer can take the lowest reading, which should be the reading obtained when the rod is vertical. Use of the rod level provides a much easier solution, especially when three-wire levelling is called for, as described below.

A benchmark chisel is a flat piece of metal about 3 cm wide and 30 cm long, with a knife-edge at one end to fit into the horizontal groove of a BM tablet that has been set in a vertical face. The other end of the chisel is bent in a right-angle to form a handle, and a small level vial is mounted on the face of the chisel to indicate when it is horizontal. When the chisel is set into the groove of the tablet and is horizontal, it forms the base on which the levelling rod is rested while being read. If the rod is not extended and if it is not windy, the rodman alone can usually perform this operation; otherwise, two men may be required, one to hold the rod and one to hold the chisel.

A portable turning point is a metal plate that is placed on the ground to provide a rest for the levelling rod at intermediate points (turning points) in the levelling between terminal points. It is usually an aluminum plate about 20 cm in diameter, with three pointed feet on the bottom and a small raised pedestal at the centre on the top, on which to rest the rod. The purpose of the feet is not to raise the plate off the ground, but to prevent if from slipping sideways, and on soft ground the feet should be pressed down so that the underside of the plate is bearing on the ground over most of its area.

6.19 Levelling — instruments

Two types of levelling instrument are in general use today, the "spirit level" and the "automatic (or self-levelling) level." We will examine first the characteristics they have in common. Both have three foot-screws and a small spherical level on the base of the instrument, by which to level it on the tripod. Both have a reticle with one vertical cross-hair and three equally-spaced horizontal cross-hairs (or fine lines etched on glass). Their telescopes have an objective lens to focus the image of the rod onto the plane of the reticle, and an eyepiece through which to view the reticle and rod image. Some instruments have azimuth locking screws, which must be loosened when the instrument is being swung through a large horizontal angle, and tightened when the azimuth tangent screw is to be used for precise aiming or when a reading is being taken. Other instruments may have only the azimuth tangent screw, the horizontal rotation being tight enough not to require a locking screw.

The spirit level has a long sensitive level vial mounted to the telescope tube, with adjusting screws by which the horizontal axis of the vial may be set parallel to the optical axis of the telescope. The departure of the two axes from parallel is called the collimation error. On some spirit levels the telescope and level assembly can be flipped through 180° about its longitudinal axis; this feature is used only in the procedure for removing the collimation error, as described below. On older instruments the bubble was viewed in a tilting mirror, and was centred between graduations etched on the surface of the level vial. On newer instruments the bubble is seen through a viewer with a split optical path, so that half of one end of the bubble is juxtaposed alongside half of the other end of the bubble in the field of view. The telescope is levelled before each reading by turning the telescope tilting screw until the two halves of the bubble ends match up alongside each other in the field of view, as shown in Fig. 53. Illumination of the level vial may be by a built-in battery light, or by natural light directed onto the vial by a movable mirror.

The automatic level has no precise level vial. Instead, it has as part of its optical train an ingenious combination of prisms and/or mirrors, by which every ray of light that enters the system horizontally is deflected until it is parallel to the axis of the telescope. It might be said that with the spirit level the telescope axis is set parallel to the horizontal light rays, whereas with the automatic level the horizontal light rays are set parallel to the

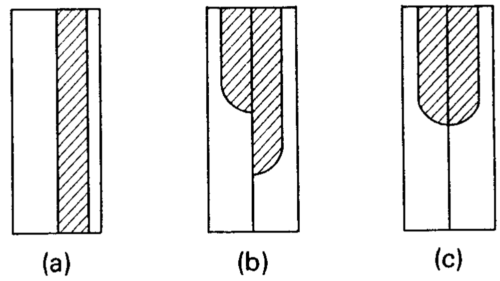

FIG. 53. Level bubble as seen through split optical viewer when instrument is (a) far off level, (b) nearly level and (c) level.

telescope axis. In both systems the horizontal rays are focused at the centre of the reticle. The principle of the optical compensator is illustrated in Fig. 54. All components are shown here as mirrors, but in practice, prisms with one face silvered may be used. The two upper mirrors are fixed to the telescope tube, while the lower mirror is suspended by four filaments from the top of the tube. The geometry of the suspension is such that when the telescope axis is tilted up or down by an angle θ from the horizontal, the suspended mirror will be tilted up or down by exactly the angle 3θ/2. In Fig. 54 the path of a horizontal light ray through the system is shown (a) with the telescope axis horizontal, (b) with the telescope axis tilted up, and (c) with the telescope axis tilted down. The angles of tilt in Fig. 54 b and c are greatly exaggerated for purposes of demonstration, the actual operative range of the compensator being only about plus or minus 10 minutes of arc. This operative range is sufficient as long as the spherical level on the instrument base has been centred by use of the foot-screws. Note, however, that levelling with the foot-screws may not be done between the reading of a backsight and a foresight, because it can change the height of the instrument.

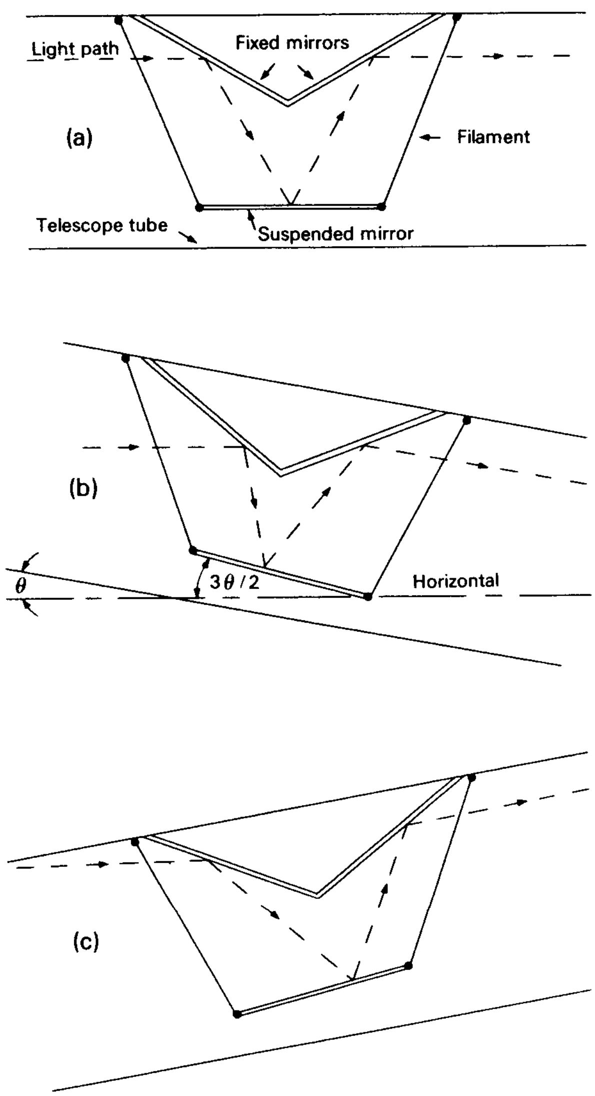

FIG. 54. Illustration of optical compensation in self-levelling instruments for (a) telescope level, (b) telescope tilted up by an angle θ and (c) telescope tilted down by an angle θ.

6.20 Levelling — instrument adjustments

The adjustment of the spherical level on the instrument base should be checked first. To accomplish this, the telescope is positioned over one of the foot-screws, and the bubble is centred in the spherical level by means of the foot-screws. The telescope is then rotated 180° in azimuth, and, if the bubble has not remained in the centre of the scribed circle, it is brought half way back to the centre by means of the foot-screws. The instrument should now be level, and the spherical level can be adjusted by centering the bubble the rest of the way by means of the spherical level adjusting screws. The adjustment may be checked by returning the telescope to its original azimuth; the bubble should remain centred. The reasons for positioning the telescope over a foot-screw at the start are to provide a reference for its reversal in azimuth, and to facilitate the centering of the bubble with the foot-screws.

The collimation of the instrument should next be tested, and adjusted if necessary. For a spirit level this involves setting the axis of the main level vial parallel to the optical axis of the telescope; for an automatic level it involves matching the cross-hairs to the axis of the optical compensator. The first step is to establish a truly horizontal line of sight. Some spirit levels are designed so the telescope can be rotated 180° about its longitudinal axis, permitting rod readings to be taken in both the upright and the inverted position. Since the collimation error appears with the opposite sign in the two readings, their average is the true instrument height above the reference point on which the rod is resting. With the telescope back in the upright position, it is moved with the tilting screw to read the average of the two previous readings on the rod. The telescope should now have its optical axis horizontal, and it remains only to adjust the axis of the precise level vial by moving its adjusting screw until the bubble is centred. The distance from the instrument to the reference point should be about 40 m. Since only one point is required, and since a peg driven into the ground is frequently used as the reference point, this procedure is often called the "one-peg test."

Instruments that do not have the reversing feature for the telescope require what is called a "two-peg test" for adjustment of the collimation; some spirit levels and all automatic levels fall into this class. The true difference in elevation between two reference points (pegs) is first established by setting the instrument up exactly equidistant from the two points and reading the rod on each of them. Since the collimation error will appear in both readings with the same sign and magnitude, the difference between the readings should give the true difference in elevation of the points. The instrument is then set up as close to one point as is possible while still retaining the ability to focus on the rod, and a reading is taken on the rod at that point. Applying the known difference in elevation of the two points to this reading gives the reading that should be obtained on the rod at the distant point if there is no error. The instrument is pointed at the distant rod and, if it is an automatic level, the reticle is adjusted in position until the centre horizontal cross-hair is at the required rod reading. If the instrument is a spirit level, the telescope is moved with the tilting screw to the required rod reading, and the precise level vial is adjusted until the bubble is centred. The distance between the two points in the test should be about 50 m. When taking the reading very close to the rod, only a few divisions on the rod may be visible, and it is wise to have the rodman verify the approximate reading by pointing to it with a pencil when the observer calls it out.

An instrument should receive a collimation test at the start of a season, after it has been transported, and whenever it is suspected that it may have received a jolt or been exposed to rough handling. The effect of any collimation error that may not have been detected can be greatly reduced by keeping the total distance of the foresights as close as possible to that of the backsights in each line of levelling. Detailed descriptions of the locations and methods of manipulation of the various parts of a particular instrument will be found in the instruction manual accompanying the instrument.

6.21 Levelling — observation and recording procedures

Suppose levelling is to be run from BM 1 to BM 2. The instrument is set up on its tripod at a point not more than about 30 m from BM 1, and in the general direction of BM 2. The eyepiece is focused to give a sharp image of the cross-hairs, if possible against a blank field of view such as the sky. The rod is then held to rest vertically on BM 1, and the telescope is directed at and focused on the rod by means of the objective lens focusing screw. The test for proper focus of the objective lens is that there should be no parallax between the cross-hairs and the image of the rod; i.e. when the observer moves the viewing position of his eye up and down slightly, there should be no relative motion of the image and the cross-hairs. When this is achieved, no further adjustment of the objective lens should be made during the reading, but the image and the cross-hairs may be sharpened up by further adjusting the eyepiece if necessary. Readings are made on the rod at the positions of the three horizontal cross-hairs (upper, middle, and lower) and are recorded as the A, B, and C entries in the "Backsights" column of the standard levelling form, a sample of which is shown in Fig. 55. If a spirit level is being used, the bubble must be centered at the time of each reading, using the telescope tilting screw to do so. If the image of the rod as viewed through the eyepiece is inverted, the "upper" cross-hair is the one that gives the highest rod reading, even though it appears in the lower part of the field of view.

As soon as the recorder determines that the differences in the pairs of readings, *A–B* and *B–C*, agree to within 2 mm, the rodman is directed to a suitable turning point, TP 1, in the general direction of BM 2, and no more than about 30 m from the instrument. Readings are taken on the rod at TP 1, in the same manner as before, and recorded in the "Foresights" column of the levelling form, to complete the readings for set-up #1. It is essential that the height of the instrument not be changed between reading of backsight and foresight, which means that neither the tripod nor the foot-screws may be adjusted during this interval. After assuring that *A–B* and *B–C* agree, the instrument is moved to a new position in the general direction of BM 2, up to 30 m from TP 1. The process of leapfrogging the rod and instrument along is continued until the final foresight readings are taken on BM 2. The series of

LOCATION ____________________ YEAR ____________

LEVELLING

METRIC

LINE		DIFFERENCE OF ELEVATION		
FROM	TO	FORWARD	BACKWARD	MEAN

	FORWARD	BACKWARD
SUM OF BACKSIGHTS	+	+
SUM OF FORESIGHTS	−	−
DIFFERENCE OF ELEVATION	+	

REMARKS

Date	LEVELLING AT	Page	of
Inst. No.		Observer	
Weather		Recorder	
Visibility		Rodman	
Line	Forward/Backward		

METRIC

Backsights			Station	Elevations	Set-up	Foresights		
A	D	F	B.S. +			A	D	F
B	E	G	H.I.			B	E	G
C	L	J	F.S. −			C	L	J
H						H		
K						K		
A	D	F	B.S. +			A	D	F
B	E	G	H.I.			B	E	G
C	L	J	F.S. −			C	L	J
H						H		
K						K		
A	D	F	H.I. +			A	D	F
B	E	G	B.S.			B	E	G
C	L	J	F.S. −			C	L	J
H						H		
K						K		
Sums						Sums		

A – Rod reading upper hair

B – Rod reading middle hair

C – Rod reading lower hair

Sums – Sums of L and Sums of J

$D = A - B$ $\quad F = \frac{D-E}{3}$ $\quad H = A+B+C$ $\quad K = A - C$

$E = B - C$ $\quad G = B + F$ $\quad J = \frac{H}{3}$ $\quad L = D + E$

Checks: $K = L$; $G = J$; $D = E \pm \cdot 002$ m. (max.)

Form L1

FIG. 55. Standard Canadian Hydrographic Service levelling form.

set-ups is illustrated in Fig. 56. Calculation of the remaining quantities (*F* to *L*) on the levelling form, and completion of the summary on the opposite side of the form finishes the forward running of the line. The line must, however, be run again in the opposite direction (i.e. from BM 2 to BM 1). If satisfactory agreement is obtained between the forward and backward running, the mean value is accepted as the difference in elevation between BM 1 and BM 2.

The levelling form shown in Fig. 55 may appear at first glance to be unnecessarily complicated, but the safeguards against error that are provided by three-wire levelling and the check calculations in the levelling form more than pay for themselves by reducing the need for re-levelling. Although the form is laid out so it can be completed mechanically step-by-step, a little time spent in understanding the logic of the steps can make the task more satisfying, and perhaps more efficient. The check on the mean of three readings ($G=J$) comes from the simple algebraic identity

$$(A+B+C)/3 = B+((A-B)-(B-C))/3.$$

The difference between the upper and lower reading ($A-C$) is the "stadia interval," and is proportional to the distance of the rod from the instrument. Multiplication of this interval by the "stadia factor" for the instrument would give the actual distance, but since our interest is simply to equalize the total distance of the foresights to that of the backsights, the stadia interval serves just as well. The length of the backsight and foresight at each set-up should as nearly as practicable equal each other, but the recorder should keep an eye on the running sums of the stadia intervals and advise the observer, so that any imbalance can be corrected by the end of the line. The check on the stadia interval ($K=L$) is simply the identity

$$A-C = (A-B) + (B-C).$$

Use of a pocket-size electronic calculator can be of great assistance in completing the levelling form. There are available programmable pocket calculators which, once the three readings (*A*, *B*, and *C*) are entered, will carry out the remaining calculations successively at the press of a button. All values must, of course, still be entered on the form. Levelling form sheets without the summary section on the reverse are also provided, to supplement that shown in Fig. 55 when more than three instrument set-ups are required between primary points (BMs, gauge gnomon, staff gauge zero). One summary page must, however, be completed for each section of levelling between primary points. These summaries provide the input for the benchmark and datum information that must also be shown on the Temporary Gauge Data form.

6.22 Levelling — Accuracy

The accuracy demanded of hydrographic levelling exceeds that necessary strictly for sounding reduction because the information may be used as

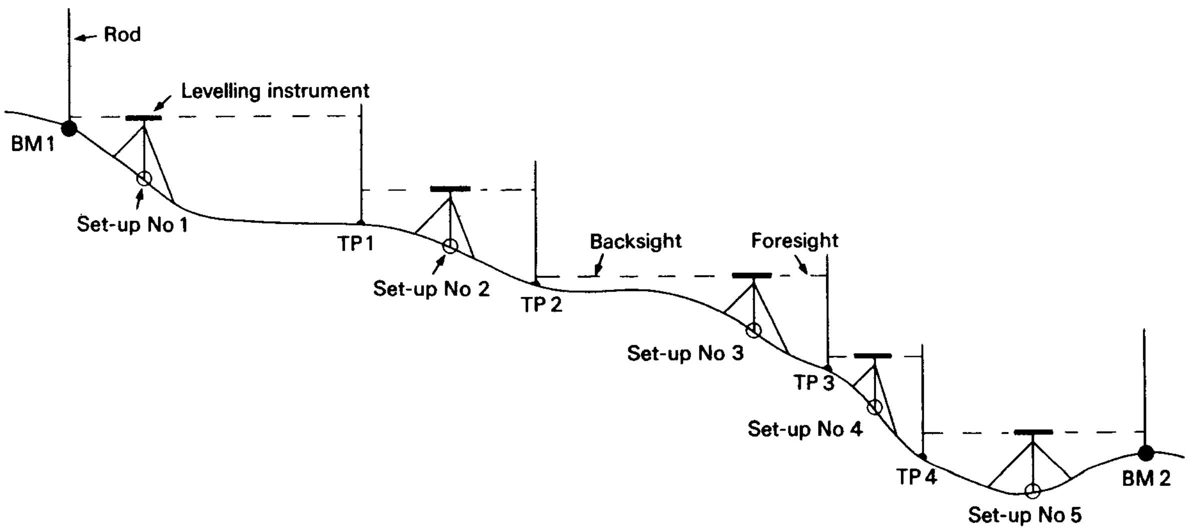

FIG. 56. Illustration of differential levelling procedure.

well for other purposes, because the increased accuracy may help to identify an unstable mark more quickly, and because the small extra investment in time and effort required does not add significantly to that expended at lower standards.

The collimation error may never be completely removed from an instrument. If the error is found to be no more than 20 seconds of arc, which corresponds to a reading error of 3 mm over a distance of 30 m, no further adjustment need be made to the collimation, provided that care is taken to balance the sums of foresight and backsight distances to within 10 m over each segment of line between primary points.

The precision of the rod readings is judged by the agreement between the two halves of the stadia interval, i.e. the upper stadia reading minus the middle wire reading, and the middle wire reading minus the lower stadia reading. If the difference is greater than 2 mm, the readings should be repeated.

The most revealing test of levelling precision is the closing error, the disagreement between the elevation differences determined on the forward and backward running of the line. When BMs are so close together that only one instrument set-up is required, the backward running of the segment may amount simply to moving the instrument to a different location and repeating the measurements. Some errors are constant or systematic, and may be made to cancel out of the calculations; examples are the zero error on a levelling rod, which cancels out in subtracting foresight from backsight, and a small collimation error, which can be made to cancel out by equalizing foresights and backsights. There are also systematic errors that may not cancel out, such as might be caused by a rod with an expanded or contracted scale. Fortunately, most systematic errors would not accumulate a large error in the short distances and small elevation differences usually involved in hydrographic levelling. The criterion on which the agreement between forward and backward runnings is judged assumes that the errors involved are random errors, so that their effect would be expected to accumulate as the square root of the distance covered in the levelling. It is, of course, reasonable to hope that if the random errors have been kept small, so also have the systematic ones. The criterion is that the difference between forward and backward values must not exceed the greater of

$$3 \text{ mm or } 8(K)^{1/2} \text{ mm},$$

where K is the length of the levelling line (one way) in kilometres.

Following are the values of $8(K)^{1/2}$ mm for distances up to about 1 km:

190 m (or less)	3 mm
191 m to 316 m	4 mm
317 m to 472 m	5 mm
473 m to 660 m	6 mm
661 m to 878 m	7 mm
879 m to 1129 m	8 mm.

6.23 Setting gauge zeros

There are usually two gauge zeros to set, that of the staff gauge and that of the automatic gauge. The zero of the staff gauge is normally set first, and the zero of the automatic gauge then set to agree with it. If, however, it is felt that the staff gauge zero has been set too high, the zero of the automatic gauge may be set lower to avoid negative readings; if this is done, the difference in zeros should be some simple amount such as 20 or 30 cm. The gauge zeros ought not to be changed once they have been referenced to the BMs and water level recording commenced.

If the gauge site has been previously occupied, it should be possible to recover the old BMs, whose elevations above chart datum are known. By standard levelling from one of the BMs, the height of the levelling instrument above datum is found for a set-up from which the staff gauge is visible. The staff gauge is then juggled and secured in position when the instrument reading on the staff equals the instrument height above datum. Since this operation cannot be performed perfectly, the actual zero of the staff must still be referenced to the BMs by repeat levelling, and the information recorded on the Temporary Gauge Data form as well as on the levelling sheets. If an electric sight gauge is installed in conjunction with an automatic gauge and stilling well, the elevation of the gnomon on the floor of the gauge shelter is found by standard levelling from the BMs. (*Note*: a short length of level rod or metre stick is required to fit in the door of the shelter for the reading on the gnomon, and the zero of its scale must be matched to that of the main level rod.) The elevation of the gnomon above datum should then be marked on a card and prominently displayed inside the gauge shelter. The length of tape required to reach from the top of the gnomon to the water surface in the well is substracted from the gnomon elevation to give the height of the water above chart datum at that instant. The automatic gauge is then made to read that water level, thus setting its zero to chart datum. Setting the water level on a float gauge is done by holding the float wire and slipping the pulley past it until the desired reading is obtained. Pressure recorders usually have an adjusting screw with which to make the setting, but the appropriate instrument manual should be consulted for particulars. Use of a sight gauge wherever a stilling well is available is encouraged, but is not mandatory. If there is no sight gauge, the setting of the automatic gauge must be done against readings taken on the staff gauge. In either case, the setting should be done in two stages, a coarse setting against the first water level reading, followed by a fine setting against a second water level reading. It should then be checked against a third reading.

In some regions the relation between chart datum and Geodetic Datum or IGLD may be well enough established that BMs in one of those nets can be used to set gauge zeros, even when there has been no gauge at the site before.

When it is not possible to set the gauge zeros from known BM elevations, the zero of the staff gauge may be set rather arbitrarily, provided only that it be safely (about half a metre) below the lowest water level anticipated. A few observations on a temporary staff may be compared with observed or predicted water levels at nearby locations to help in making this judgement. The staff gauge zero must then be related to the BMs by standard levelling. If a sight gauge is being used, the elevation of its gnomon above the zero of the staff gauge is determined by levelling, and this value is displayed in the gauge shelter. The zero of the automatic gauge may be set to agree with that of the staff gauge, and may be checked from time to time, by using the sight gauge as described above. If there is no sight gauge, the setting of the automatic gauge must be done against readings taken on the staff gauge.

In all of the above cases, the elevations of the gauge zeros with respect to each other and with respect to the BMs must be entered onto the Temporary Gauge Data form in the appropriate slots.