Journal of Coastal Research	18	2	362–371	West Palm Beach, Florida	Spring 2002

Over-Estimation of Sea Level Measurements Arising From Water Density Anomalies Within Tide-Wells—A Case Study at Zuari Estuary, Goa

Antony Joseph, Vijaykumar, Elgar Desa, Ehrlich Desa, and Vani B. Peshwe

National Institute of Oceanography
Dona Paula
Goa – 403 004, India

ABSTRACT

JOSEPH, A.; KUMAR, V.; DESA, E.; DESA, E., and PESHWE, V.B., 2002. Over-estimation of sea level measurements arising from water density anomalies within tide-wells—A case study at Zuari estuary, Goa. *Journal of Coastal Research,* 18(2), 362–371. West Palm Beach (Florida), ISSN 0749-0208.

A 3-year study of water density anomalies within a conventional tide-well indicated that the average water density within the well was consistently lower than that of the external ambient waters. The tide-well at Marmugao, Goa, India is situated at the mouth of the Zuari estuary, and anomalies were reported at all periods except during peak summer and the onset of the summer monsoon. These anomalies lead to an over-estimation of sea level by a tide-well based gauge. We observed that the density difference, $\Delta\rho$, between waters inside and outside of the tide-well had a significant dependence on local rainfall and wind. This trend was noticed throughout the 3 years observation period, with the minimum (0.001g cm^{-3}) difference corresponding to maximum (~6 m s^{-1}) winds and maximum (~350 mm) rainfall. The monthly-mean over-estimation in sea level (Δh), was a minimum (2 mm) during the summer monsoon, rose rapidly to over 22 mm after the monsoon, and remained around this peak value for ~3 months before slowly decreasing to ~4 mm by peak summer. The yearly-mean over-estimation in the mean sea level (MSL) was 11.3 mm. The limitation of the conventional tide-well could be minimized by incorporation of arrays of perforations on its entire submerged portion. Density measurements during different seasons indicated that these perforations gave rise to good mixing between the waters within and outside of the tide-well, thereby improving the accuracy in sea level measurement.

The large number of gauges worldwide that are situated in similar estuarine conditions would have contributed to inaccuracies in the climatology in the sea level records, and this area needs to be addressed. The observed annual repeatability of the density difference pattern indicates that it might be possible to correct the historical sea level records, obtained from tide-well-based gauges, for the observed systematic over-estimation of sea levels, from measurements of density differences inside and outside of tide-wells over a period of one year. This would be a practical way to go back to what is in the archives and recover the absolute sea level. In this paper we have also addressed a feasible solution to the lower density water-trapping problem suffered by the guided-air-acoustic gauges, wherein a long and narrow tube is used to guide the acoustic pulse between the acoustic head and the water surface.

ADDITIONAL INDEX WORDS: *Global climate, MSL, guided air-acoustic gauges, rainfall, wind, monsoon.*

INTRODUCTION

Various techniques are currently available for the measurement of sea level in coastal waters (JOSEPH, 1999). These include probably the oldest and ubiquitous *float-driven gauge,* designed by PALMER (1831), and its more recent version of a *guided air-acoustic gauge,* both these being tide-well based gauges. The tide-well is basically a pressure device wherein an equilibrium is sought between the hydraulic pressures imposed at the orifice by the water heads inside and outside of the tide-well (LENNON, 1970; LENNON, 1971). It also dampens high frequency oscillations to facilitate water level measurements from inside of the well. The recent projections of enhanced global sea level rise demand improvement in the accuracy of sea level measurement. Accurate measurement of sea level is vital to understand the variation in MSL, which is considered to be an indicator of global climate change. Flows, waves, and a combination of flows and waves (JOSEPH *et al.*, 2000), density, and differential heating in the tide-well are all important factors that need to be accounted for, especially when we are trying to measure signals on the order of global sea level variation. A great deal of effort has, therefore, gone into the performance evaluation of these devices in their natural environmental conditions. Some engineering solutions have also been invented in the past few decades to circumvent some of the problems associated with them (*e.g.*, NOYE, 1974; SEELIG, 1977; SHIH and PORTER, 1981; SHIH *et al.*, 1984; SHIH and BAER, 1991; VASSIE *et al.*, 1992; JOSEPH *et al.*, 1995; JOSEPH *et al.*, 1996; PORTER and SHIH, 1996; JOSEPH *et al.*, 1997; JOSEPH *et al.*, 1999; JOSEPH *et al.*, 2000). Permanent tide gauges are generally surveyed into the geodetic network. In situations where large density changes occurred within tide-wells (for example, when kerosene was added to the tide-well to keep it free from freezing), the tide-gauge readings were corrected by comparison to water level measurements from a tide-staff. Such comparisons were made

00019 received 5 February 2000; accepted in revision 10 November 2001.

typically 20 times per month. However, correction based on this methodology is far from adequate when the error is in the order of mm, given the poor resolution of the tide staff and the sea-state-related uncertainties involved in tide-staff readings. In this paper we address the problem of over-estimation of sea level measurement by tide-well based gauges in more detail, based on our analysis of water density profile measurements made inside and outside of a conventional tide-well at the Zuari estuary, (Goa, India), for a period of over 3 years. The maximum tidal range at this site is ~2.5 meter.

WATER DENSITY DIFFERENCE INSIDE AND OUTSIDE OF A CONVENTIONAL TIDE-WELL, AND ITS DEPENDENCE ON RAINFALL AND WIND FORCING

It has been pointed out by LENNON (1970, 1971) and SHIH *et al.*, (1984) that conventional tide-wells have a tendency to trap a water body having a different density structure from that of the open water body outside the well. The resulting drawback of these tide-well devices is the introduction of an error in sea level measurement, usually manifested as an over-estimation. This error has been expected to be significant; especially for tide-wells deployed in estuaries. However, an in-depth study of the trapping mechanism, its relationship with meteorological parameters such as rainfall and wind, and the nature of error associated with the water density anomalies arising from this, have not been found in journal publications for the benefit of the oceanographic community worldwide.

To examine the trapping mechanism, surface water samples were routinely collected since June 1995 (approximately on a weekly basis), from inside and outside of a conventional tide-well (Figure 1) at Marmugao sea level station, Goa, India. Water density measurements were made using a precision density meter (KREMLING, 1972) having an accuracy of $\pm$ 0.001 g cm^{-3}. Figure 2 shows the densities of surface water samples from inside (ρ_1) and outside (ρ_2) of the tide-well from June 1995 to August 1998. The figure reveals a three-year record of the striking yearly repetition of the trend in the changes of the densities of the surface water samples, from inside and outside of the tide-well. It has been observed that, except during the peak summer season (April/May) and the onset of active summer monsoon (June), the density of surface water samples from inside the tide-well remained lower than that of the ambient waters outside. In an attempt to understand the water mixing processes inside the tide-well, and thereby the lower density water trapping mechanism and its relationship with the local wind forcing and precipitation, the time-series of the difference, $\Delta\rho$, [where $\Delta\rho = (\rho_2 - \rho_1)$] were examined. The marked dependence of the density difference ($\Delta\rho$) on the local rainfall and wind forcing, and the repetition of the trend in $\Delta\rho$ starting with every peak summer season, is shown in Figure 3. The figure shows that the value of $\Delta\rho$ approaches zero just before the summer monsoon, and the surface density difference even going slightly negative over a short period at the onset of the summer monsoon season (June). In India June is a month of great variability;

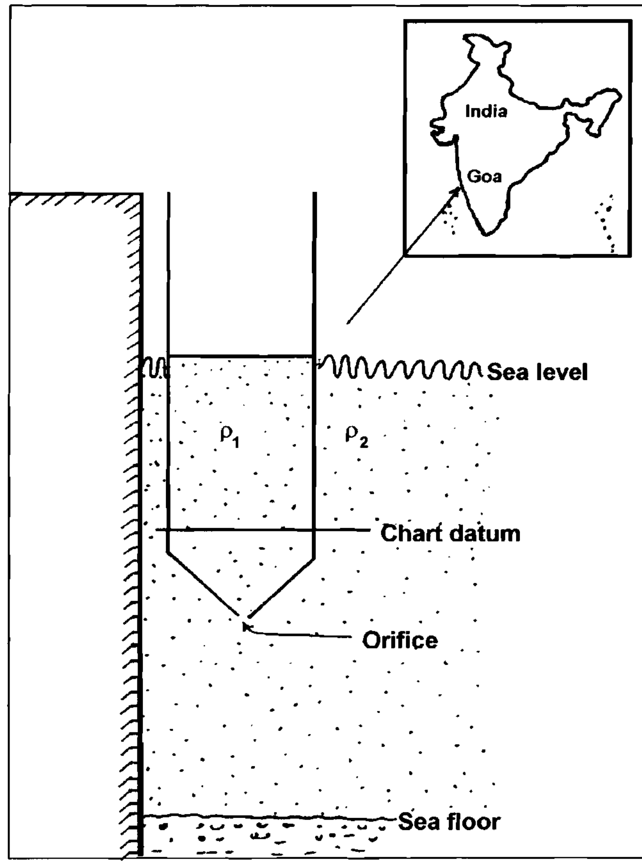

Figure 1. Schematic diagram of a conventional tide-well at Marmugao sea level station, at the Zuari estuary, Goa, India, used for measurements of ρ_1.

late June being very different from early June. The maximum wind speed ($\approx$6m s^{-1}) in the vicinity of the tide station corresponds to late June, during which the values of $\Delta\rho$ were the minimum. This shows that the mixing of water inside the tide-well with that outside of it is related to the local wind forcing. This also provides an indication that the trapping effect may be expected to be more predominant when the wind is weak.

In order to gain a better insight into the nature of the lower density water trapping mechanism, and to estimate the error in sea level measurement arising from this, density profiles from inside and outside the tide-well were obtained using a portable CTD profiler (Seabird) since June 1997. Figure 4 shows some typical profiles during (a) summer monsoon period (*i.e.*, June to September), and (b) non-monsoon period. The profiles show that the depth-mean water densities ρ_1 and ρ_2 are closer to each other during June, the value of $(\bar{\rho}_1/\bar{\rho}_2)$ being equal to or very close to 1.000. Subsequently $(\bar{\rho}_1/\bar{\rho}_2)$ decreases, reaching a minimum value of 0.990 in September. This variability in (ρ_1/ρ_2) may be explained based on the strong rainfall and the wind-driven sea surface wave activity experienced during the early summer monsoon and the flushing activity during the summer mon-

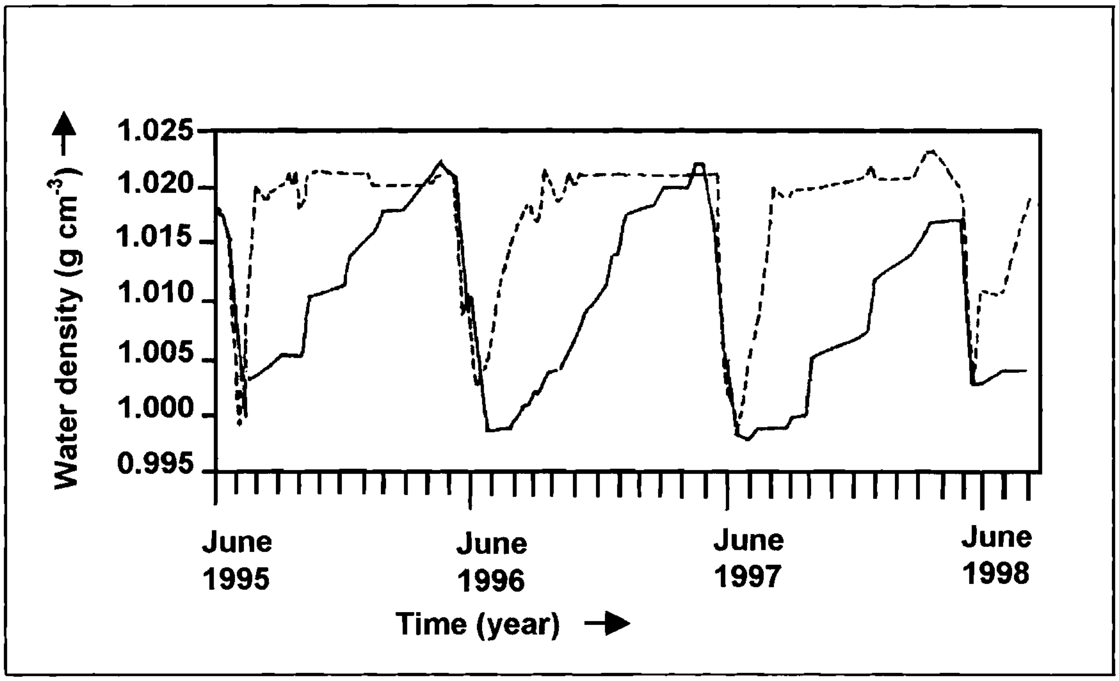

Figure 2. A three-year record of the densities of surface water samples inside (———) and outside (·······) of a tide-well at Marmugao sea level station.

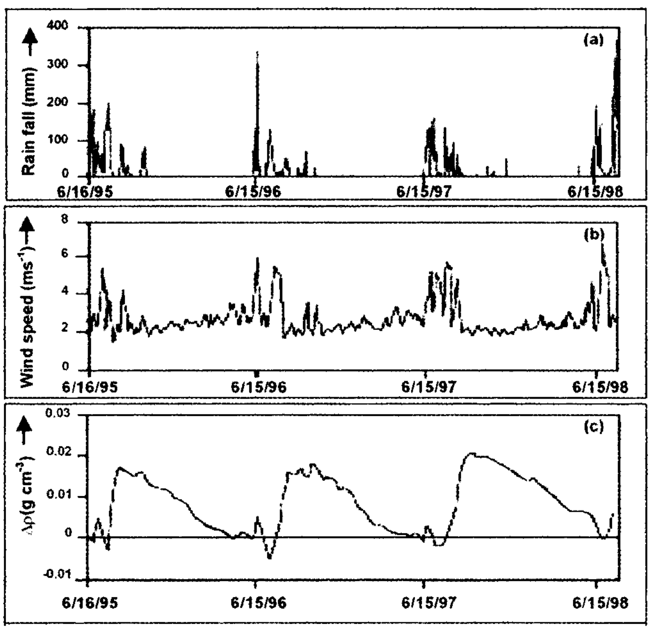

Figure 3. A three-year record of (a) daily-mean rainfall, (b) daily-mean wind speed, and (c) density difference, $\Delta\rho$, inside and outside of a tide-well at Marmugao sea level station.

soon. With the onset of the summer monsoon in June, the estuary receives a large, seasonal influx of lower density water due to rainfall, which flushes out the relatively higher density saline water from the estuary. The characteristically strong wind-waves associated with the onset of the summer monsoon in June gives rise to strong mixing of the entire estuarine water body, including the water body inside the tide-well, as revealed from the density profiles of these two water bodies during June. The influx of lower-density river water in the estuary, together with strong wind-wave-induced mixing during the monsoon period, results in a rapid decrease in the densities of the waters both inside and outside of the tide-well. As a result of the subsequent weakening of the mixing process, arising from the weakened wind-waves, the 'lower-density water' that entered inside the well is not flushed out immediately, giving rise to 'trapping' of lower-density water inside the well. For example, the 'low density water' of the monsoon season is retained inside the well for a long time until February. This is also evident from Figure 2.

With the weakening of the summer monsoon rains, the estuary is dominated by the higher salinity water intrusion from the adjoining open sea. However, the weakened wind-waves significantly reduce mixing between the water bodies inside and external to the tide-well. This could be inferred from visual observations of significantly dampened high-frequency vertical oscillations of a float in the tide-well as against its severe vertical oscillations in late June, during which the sea was turbulent most of the time. The absence of free exchange of water inside the tide-well with that outside [as a result of a single, small (~5 cm diameter) orifice

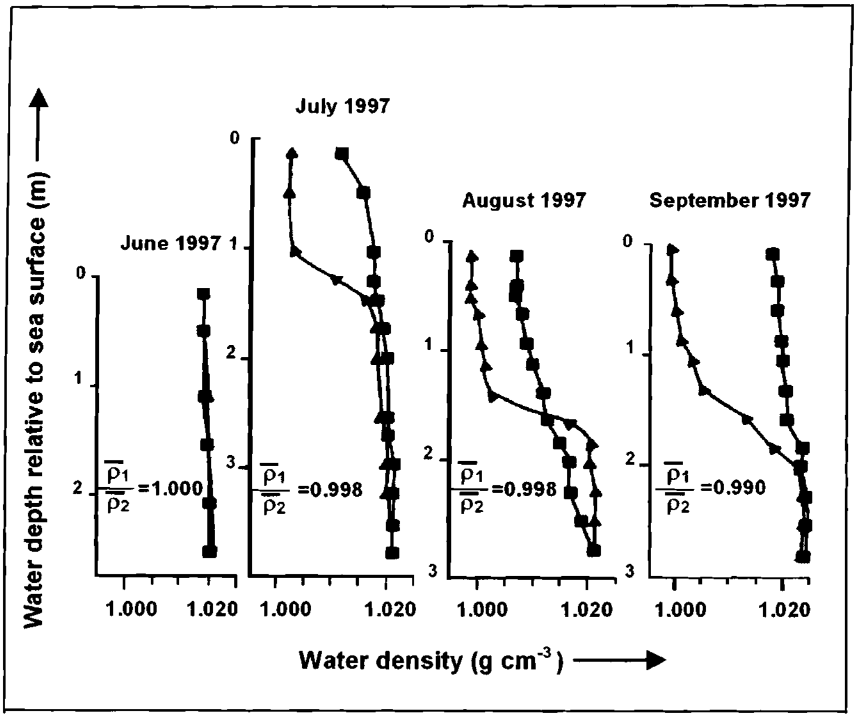

Figure 4(a). Typical depth-profiles of water densities inside (△) and outside (□) of a tide-well at Marmugao sea level station during summer monsoon (*i.e.*, June to September) period, 1997.

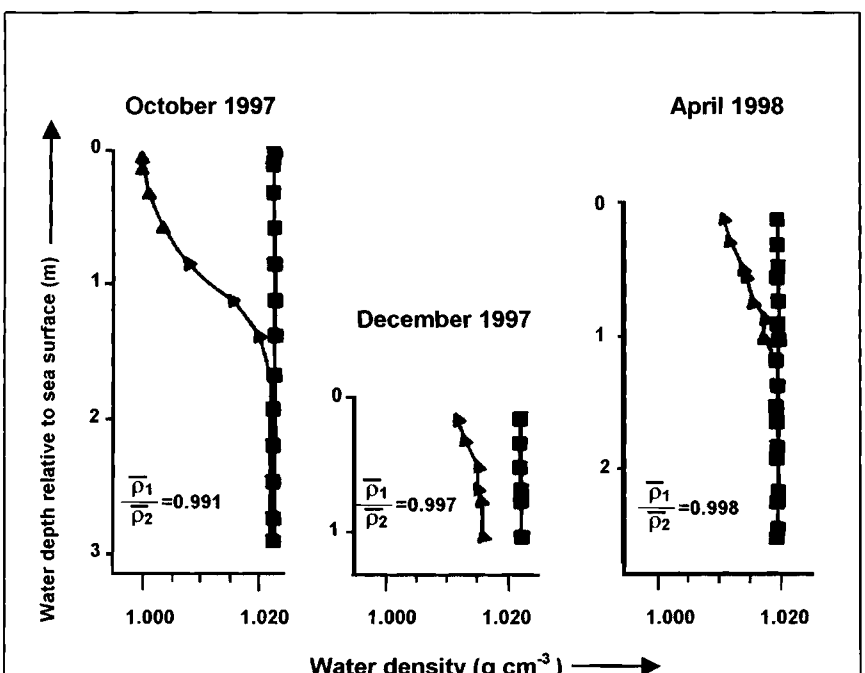

Figure 4(b). Typical depth-profiles of water densities inside (△) and outside (□) of a tide-well at Marmugao sea level station during non-monsoon period.

at the base of the tide-well] appears to have prevented the mixing of the higher salinity water in the estuary with the trapped lower density water in the tide-well. This has contributed primarily to the observed density differences during the relatively calm periods, these densities having attained equilibrium only by May (*i.e.*, just preceding the summer-monsoon season). This trapping mechanism appears to have helped in maintaining an appreciably lower density-profile inside the tide-well compared to that external to it for approximately 10 months in a year (from July through April).

HIGHER WATER LEVEL WITHIN CONVENTIONAL TIDE-WELL

The consequence of lower-density water trapping is a systematic increase of water level inside the tide-well compared to that external to it (which is the true sea level). This is because the pressure balance at the orifice depends both upon the water heads inside (h_1) and outside (h_2) of the tide-well above its orifice level and the depth-mean densities $\bar{\rho}_1$ (of water column h_1) and $\bar{\rho}_2$ (of water column h_2). Thus, during a given sampling period,

$$h_1 \bar{\rho}_1 g = h_2 \bar{\rho}_2 g \quad (1)$$

so that

$$h_2 = h_1(\bar{\rho}_1/\bar{\rho}_2) \quad (2)$$

Thus, the generally reduced value of $\bar{\rho}_1$ (relative to $\bar{\rho}_2$), resulting from the trapping of a lower-density water body, gives rise to a systematic seasonal over-estimation of the water level inside the tide-well relative to the true open-sea level outside. The over-estimation, (Δh), in sea level measurement is given by ($h_1 - h_2$). Thus, the value of Δh inherent in the measurement of sea level, by a sea level gauge deployed in a tide-well, is given by:

$$(\Delta h) = (h_1 - h_2) = h_1 [1 - (\bar{\rho}_1/\bar{\rho}_2)] \quad (3)$$

Sea level measurement is conventionally referenced to a datum, known as chart datum (CD). Thus, h_1 is the measured sea level plus the depth of the orifice below the CD. In the present study, the values of h_1 during each sampling were obtained from a guided air-acoustic gauge. In this gauge a vertical narrow cylindrical tube (known as *sounding tube*), which guided the acoustic pulses generated by a piezoelectric transducer located in air, was mounted along the axis of a protective-well having an internal diameter of ~14 cm. The bottom portion of this tide-well (Figure 5) is attached to a double-cone and a parallel-plate assembly to minimize the flow- and wave-induced Bernoulli draw-down effects (SHIH and BAER, 1991). The stilling-well-to-orifice diameter ratio for the acoustic system's protective-well was 3:1. However, this ratio in the case of the conventional tide-well (Figure 1) was 12:1. It might be true that the above 3:1 ratio for the acoustic system's protective-well would allow enhanced mixing in the protective well. However, the important consideration is the degree of mixing within the sounding tube rather than the mixing within the protective well. This is because the acoustic system measures the height of the water column within the sounding tube. The narrow sounding tube tends to obscure the advantage of the 3:1 ratio for the acoustic system's protective well, thereby preventing enhanced mixing of the water body within the sounding-tube with the open-waters. Thus, the *conventional tide-well,* which was used by us for the measurement of ρ_1, and the *protective-well* of the air-acoustic gauge, from which the values of h_1 were obtained during each sampling, can be expected to have suffered from similar lower-density water trapping problems. It may be noted that water density measurement from the protective-well was not practical because of the presence of the acoustic head and its attachments, including the sounding tube and its locator.

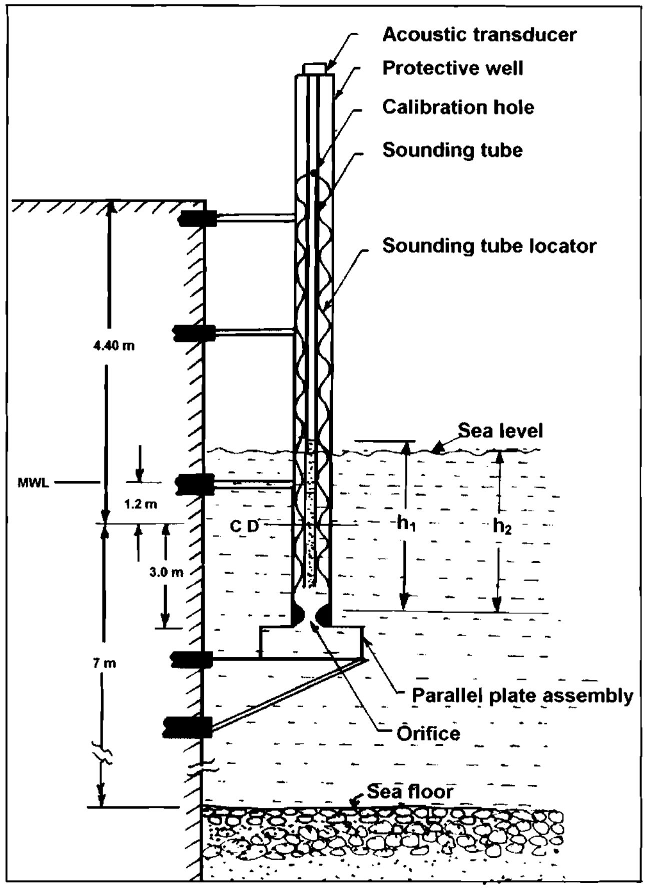

Figure 5. Schematic diagram of a guided air-acoustic gauge at Marmugao sea level station used for sea level measurement in the present study.

Despite a self-calibrating technique used in the air-acoustic gauge, it is known to exhibit errors in the measurement of sea level (VASSIE *et al.*, 1992). These errors arise from temperature-gradient-induced anomalies of sound velocity along the sounding-tube of the acoustic gauge. Our inter-comparison measurements of sea level against a temperature-compensated pressure gauge, and air temperature profile measurements within the protective-well using a chain of temperature probes also indicat-

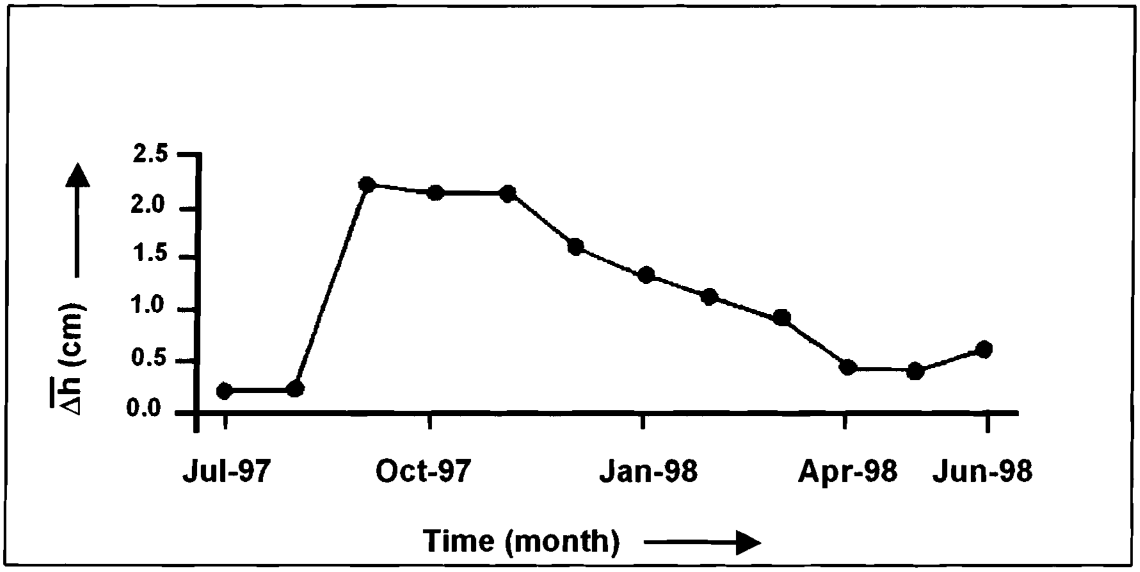

Figure 6. Monthly-mean over-estimation, ($\Delta\bar{h}$), in the measurement of sea level from the Marmugao sea level station over a one-year period from July 1997 to June 1998.

ed a strong temperature-gradient-induced noise in the sea level data measured by the air-acoustic gauge (JOSEPH *et al.*, 1997). However, our studies have indicated that this noise (up to a maximum of 6 cm for a short duration in the morning), though serious while considering individual measurement, is periodic in nature and, therefore, might largely be averaged out while estimating mean sea level on a monthly or yearly basis. Performance evaluation by PORTER and SHIH (1996) also revealed that the error in the yearly-mean sea level, arising from the temperature gradient within the sounding-tube of an air-acoustic gauge, is not of a serious nature. Thus, our evaluation of the *systematic* over-estimation of the monthly-mean and yearly-mean sea level measurement, arising from trapping of a lower density water body within the tide-well, is unlikely to have been contaminated by the temperature-gradient within the sounding tube of the air-acoustic gauge.

Table 1. *Monthly-mean values of* $\Delta\rho$ *and* Δh *for a 1-year cycle, beginning the peak summer-monsoon month of July 1997.*

Month	$\Delta\rho$ (g cm^{-3})	Δh (mm)
July	0.001	2.2
August	0.001	2.2
September	0.010	22.2
October	0.009	21.5
November	0.009	21.5
December	0.007	16.2
January	0.006	13.5
February	0.005	11.5
March	0.004	9.4
April	0.002	4.6
May	0.002	4.5
June	0.003	6.7

OVER-ESTIMATION OF MEAN SEA-LEVEL

The monthly-mean over-estimation, Δh, in the measurement of sea level, arising from lower density water trapping effect, for a typical one-year period from July 1997 to June 1998 in the Zuari estuary is shown in Figure 6. It is observed that the over-estimation during the summer monsoon months of July and August was 2.2 mm.

However, with the weakening of the summer monsoon the over-estimation shot up to 22.2 mm, and remained close to this peak value for a period of 3 months in the post-monsoon period, from September through November. Subsequently, the value of Δh began falling gradually, reaching a value of 4.5 mm in the month of May. The value of Δh remained at 6.7 mm in June, which experienced both the peak summer period and the beginning of summer monsoon season. The observed yearly repetition in the trend of $\Delta\rho$ (Figure 3) suggests a similar yearly repetition for Δh as well.

The monthly-mean values of $\Delta\rho$ and Δh for a 1-year cycle, beginning the truly summer monsoon month of July is shown in Table 1. From this, the annual over-estimation in mean sea level (MSL) during July 1997–June 1998 was found to have been 11.3 mm. The percentage of the monthly-mean values of Δh over the tidal elevation (*i.e.*, sea level relative to CD) is shown in Figure 7 (in the present case, the orifice of the tide-well was 1m below CD).

A TECHNIQUE TO REDUCE LOWER-DENSITY WATER TRAPPING

Tide-Well

Hitherto known tide-wells used since 1831 (PALMER, 1831) in numerous float-driven sea level gauges in several parts of the world had the objectives of creating a wave-

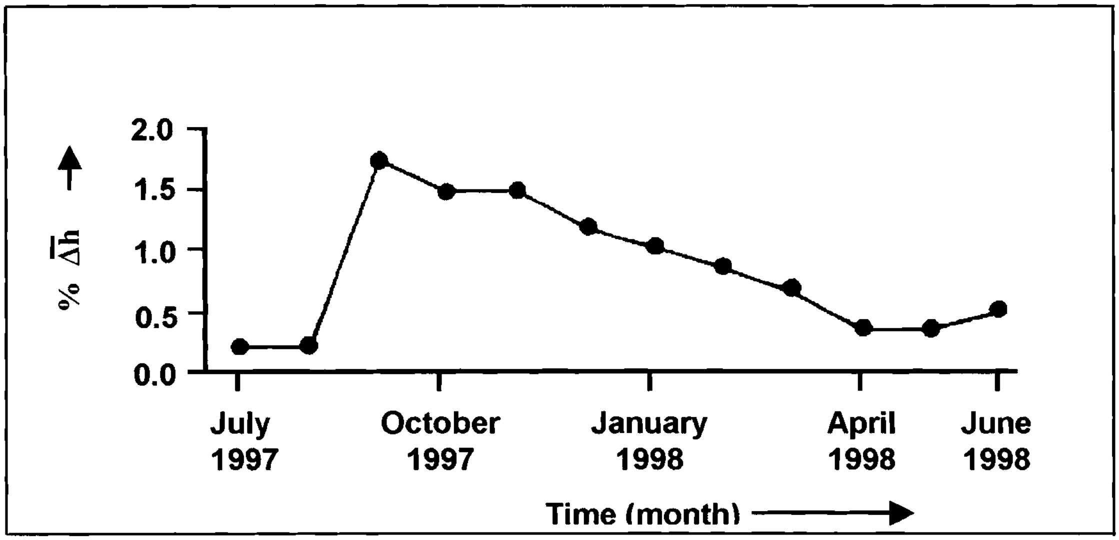

Figure 7. Monthly-mean of the percentage over-estimation of sea level relative to the tidal elevation over a one-year period from July 1997 to June 1998.

dampened water surface within the well, and to provide adequate protection to the float and its tether. The protective-wells as used with the modern guided air-acoustic gauges are primarily meant to protect the sounding tube, and to provide a secluded water level within the sounding tube, having minimum draw-down effects, arising from the dynamic pressure induced by the water flows and the sea surface gravity waves that are usually present in the vicinity of the gauge. Previous short-term measurements (LENNON and MITCHELL, 1992) have indicated the possibility of water level anomalies as large as 80 mm, and an overall bias of more than 20 mm to mean sea level estimates, arising from the lower density water trapping effect observed in the Mersey estuary, UK. Long-term measurements by us in the Zuari estuary, India, have also revealed similar over-estimation in the monthly-mean sea level, and a yearly-mean bias of 11.3 mm. These observed errors are of a sufficiently serious nature to merit attention and correction for a realistic estimation of the contributory role of global climate changes on mean sea level variations.

Our improved tide-well is provided with arrays of perforations on its entire submerged portion. In our experiment, in connection with minimizing the trapping of lower-density water, the diameter of the perforations was 1 cm, and the distance between the centers of adjacent perforations was 10 cm. These perforations serve the dual purposes of (1) good mixing between well- and external-waters, and (2) minimizing the Bernoulli dynamic pressure effects, as reported by LEBRETON *et al.*, (1991) and JOSEPH *et al.*, (1995, 2000). As copper is known to behave as a repellent for marine growth (HUGUENIN and ANSUINI, 1975), all the perforations were passed through copper strips to avoid their possible closure from marine growth during long-term deployments. It may be noted that the effectiveness of the perforations depends on their size and the separation between adjacent perforations, as well as the diameter of the tide-well. Results of density profiling of the waters inside and outside of the conventional and the modified tide-wells are presented in Figure 8. The figure shows that these perforations have a profound influence in allowing free exchange of water in the tide-well with the ambient waters ($\bar{\rho}_1 = \bar{\rho}_2$), thereby avoiding the lower-density water trapping effect, which is a major drawback in hitherto known tide-well based sea level gauges. However, we must caution that the perforations of our choice, with regard to their diameter and pitch, may not necessarily be the best to simultaneously handle the trapping problem and Bernoulli dynamic pressure effects. JOSEPH *et al.*, (2000) have discussed the effectiveness of a particular type of perforations, the reduction in Bernoulli dynamic pressure effects in this case being as good as that in the case of a parallel-plate front-end.

Acoustic Gauge's Sounding Tube

We have noted that providing arrays of perforations on the submerged portion enables good mixing between the water bodies within and external to the tide-well. Whilst this solution is useful in float-driven gauges and any sea level gauge deployed in the tide-well, the existing guided air-acoustic gauges having a long and narrow sounding tube may not be able to take the full advantage of the said improvement to the conventional tide-well. This is because the air-acoustic gauge's sounding tube, in the present form, is devoid of any lateral perforations on its submerged portion, and therefore can still trap a lower-density water body.

Is there a method to correct the present acoustic system from lower density water trapping effect? It may be argued that pouring ambient water into the sounding tube once per day may solve the problem. However, the top end of the

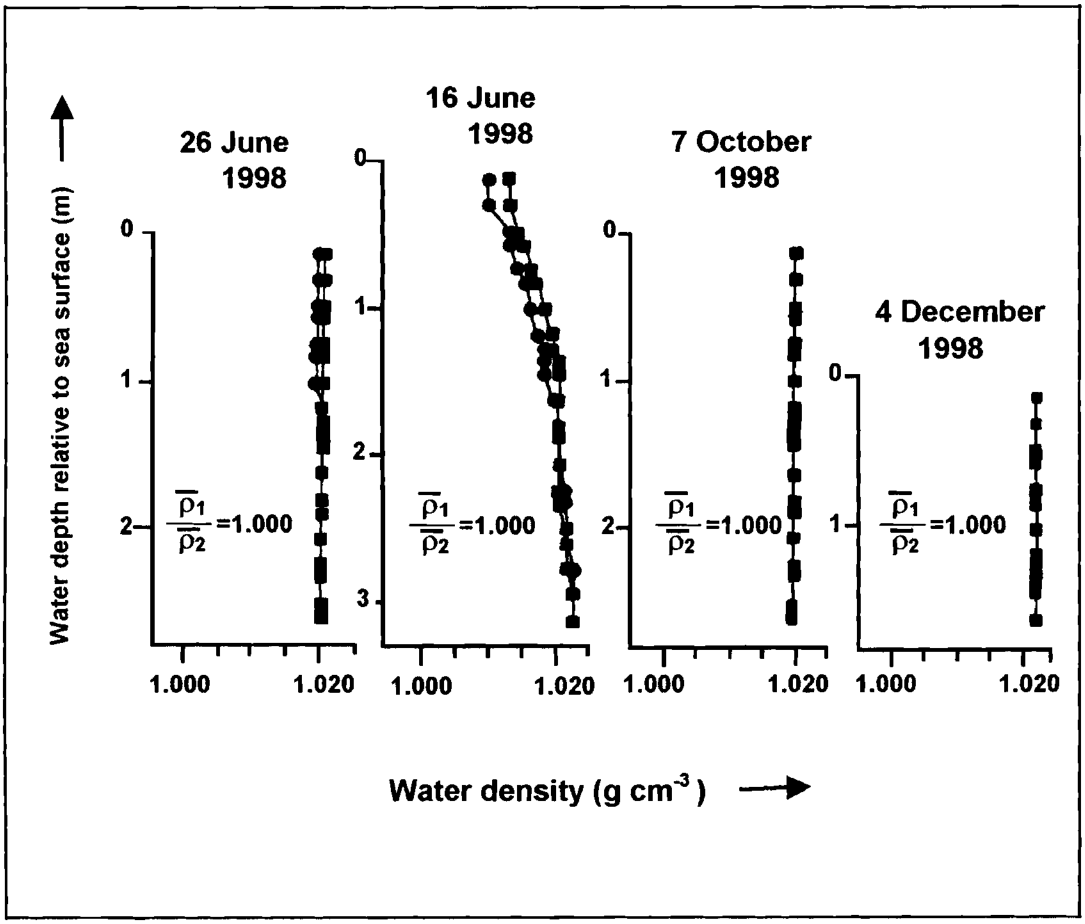

Figure 8. Density profiles of the water bodies inside (●) and outside (□) of the perforated tide-well at the Marmugao sea level station.

sounding tube is mated with the acoustic head and, therefore, no inlet exists for pouring ambient water into the sounding tube except the minute calibration hole, which is not to be disturbed. Further, daily human intervention of this nature is not feasible in a long-term recorder such as a sea level gauge.

A feasible solution appears to be based on making a simple alteration on a modified sounding tube described by PATHAK and RAMADASS (1997), specifically intended to correct for temperature-gradient-induced error in sea level measurement. In this, several spatially separated resonating side-tubes are fixed orthogonal to the sidewall of the sounding tube at different depths. The resonant characteristics of these side-tubes with the center-frequency of the interrogation pulse can be used to estimate the effective velocity of sound for different portions of the sounding tube, thereby minimizing the temperature-gradient-induced error in sea level measurement. In operation, the reflections of the sound pulse at the junction of the side-branch and the tube go through a series of alternating maxima and minima as the center-frequency of the sound pulse is varied. The reflection maxima occur when the effective length of the side-branch (physical length plus the Raleigh correction) is an odd multiple of the quarter of the wavelength for a given frequency of sound. The length of the side-branch tube for which this happens is given by (PATHAK and RAMADASS, 1997):

$$L = (2n - 1)\,\lambda/4; \quad n = 1, 2, 3, \ldots; \qquad (4)$$

Where:

L—length of the side-branch tube including the Raleigh end-correction [m]
λ—wavelength of sound [m]; (λ = C/F),
C—velocity of sound in air [m/s]
F—frequency of transmitted sound [Hz]

It is possible to have more branches connected to the sounding tube of the acoustic gauge at different distances from the acoustic head. Using the formula given above, each branch is designed to respond to a specific sound frequency such that the sound pulse with appropriate center-frequency is predominantly reflected by the branch without loss of energy of the acoustic pulse to the surrounding, with an improved signal-to-noise ratio. Thus, the effective velocity of sound in air can be estimated for different portions of the sounding tube. By the use of properly tuned resonating side-branches and signals of different frequencies for calibration and for measurement of the tidal level, it is possible to overcome some of the limitations of the existing *in-situ* calibration methods.

This modified sounding tube can also allow good mixing of the water body within the sounding tube with that external to it if the closed-ended, resonating side-tubes described by PATHAK and RAMADASS (1997) be converted to open-ended side-tubes. Because resonance is equally possible with both closed-ended and open-ended tubes, this simple modification should provide an easy solution to the lower-density water-trapping problem suffered by the air-acoustic sea level gauges, if arrays of perforations are provided on their protective-well as well.

CONCLUSIONS

This paper has addressed a systematic error in the measurement of sea level by any gauge deployed within a tide-well, such as float-driven gauge, guided air-acoustic gauge, and so forth, arising from trapping of a lower-density water body by the well. Measurements were made of water density differences inside and outside of a tide-well at the Marmugao sea level station in the Zuari estuary, Goa, for a period of over 3 years. These measurements have indicated that except during the peak summer season and active summer-monsoon season, the depth-mean density of the water body inside the tide-well remained to be consistently lower than that outside of it. Our analysis has indicated that the density difference ($\Delta\rho$) of these two water bodies is primarily related to

(1) flushing of the estuarine waters, in the vicinity of the gauge, by lower-density river water during the summer monsoon rainfall season.
(2) subsequent thorough mixing of this low-density water with that in the tide-well as a result of strong wind forcing during the onset of the summer monsoon rainfall.
(3) trapping of this low density water in the well as a result of poor mixing between the water bodies inside and outside of the well, arising from a significantly reduced wind forcing.

The consequence of lower-density water trapping is a systematic increase of water level inside the tide-well compared to that outside of it (which is the true sea level). The resulting monthly-mean over-estimation (Δh), in the measurement of sea level was 22.2 mm, during the 3 months from September through November. Subsequently, the value of Δh gradually fell to 2.2 mm in July. The yearly-mean over-estimation in MSL during July 1997–June 1998 was 11.3 mm. When the aim of sea level measurement is to capture the climate signal from an analysis of the annual mean sea level variations of the order of 1 mm, the observed systematic error in the measurement of sea level cannot be ignored.

As part of the present work, the limitation of conventional tide-wells was sought to be minimized by a modified tide-well, which permitted free exchange of the waters within the well with the ambient waters external to it (Indian patent pending No. 2378/DEL/98). The improved tide-well is provided with arrays of perforations on its entire submerged portion. These perforations serve the dual purpose of:

(1) good mixing between well- and external-waters.
(2) minimizing the Bernoulli dynamic pressure effects.

The perforations were found to have a profound influence in preventing the lower-density water trapping effect, which is a major drawback in hitherto known tide-well based sea-level gauges (especially so in estuarine sites with much larger tidal ranges). In this paper we have also addressed a feasible solution to the lower-density water-trapping problem suffered by guided air-acoustic gauges.

ACKNOWLEDGMENTS

The authors are thankful to the Department of Ocean Development (DOD), New Delhi for providing funds to carry out the work reported here. They are also thankful to the Officers of the India Meteorological Department, Goa, for providing the wind data and rainfall data, and to Mr. G. Namboothiri for providing the Seabird CTD to carry out the density profile measurements.

LITERATURE CITED

HUGUENIN, J. E. and ANSUINI, F. J., 1975. The advantages and limitations of using copper material in marine aquaculture. *IEEE Oceans'75*, 444–453.

JOSEPH, A.; FODEN, P., and TAYLOR, K., 1995. An experimental evaluation of flow-induced errors in a pressure transducer and some design solutions to improve its performance in a flow field, *Internal Document No. 82*, Proudman Oceanographic Laboratory, p.52 [Available from Librarian, Proudman Oceanographic Laboratory, Birkenhead, Merseyside L43 7RA, U.K].

JOSEPH, A.; DESA, J.A.E.; DESA. E.; MCKEOWN, J., and PESHWE, V.B., 1996, Wave effects on a pressure sensor, *Proceedings of the International Conference in Ocean Engineering (ICOE-96)*, 568–572.

JOSEPH, A.; PESHWE, V.B.; KUMAR, V.; DESA. E.S., and DESA, E., 1997. Effects of fresh water trapping and temperature gradient in the sounding tube of an NGWLMS gauge deployed in the Zuari estuary, Goa, *Proceedings of the Symposium on Ocean Electronics (SYMPOL'97)*, Cochin University of Science and Technology, Cochin, Kerala State, India, 73–82.

JOSEPH, A., 1999. Modern techniques of sea level measurement, *Encyclopedia of Microcomputers, Marcel Dekker, Inc.*, 23, 319–344.

JOSEPH, A.; DESA, E.; DESA, E.S.; SMITH, D.; PESHWE, V. B.; KUMAR, V., and DESA, J.A.E., 1999. Evaluation of pressure transducers under turbid natural waters. *Journal of Atmospheric and Oceanic Technology*, 16, 1150–1155.

JOSEPH, A.; KUMAR, V.; DESA, E.S.; DESA. E., and PESHWE, V. B., 1999. A technique to circumvent lower density water trapping by tide-wells, *Proceedings of the Symposium on Ocean Electronics (SYMPOL'99)*, Cochin University of Science and Technology, Cochin, Kerala State, India, 55–63.

JOSEPH, A.; DESA, J.A.E.; FODEN, P.; TAYLOR, K., MCKEOWN, J., and DESA, E., 2000. Evaluation and performance enhancement of a pressure transducer under flows, waves, and a combination of flows and waves, *Journal of Atmospheric and Oceanic Technology*, 17(3), 357–365.

KREMLING, K., 1972. Comparison of specific gravity in natural sea-water from hydrographical tables and measurements by a new density instrument, *Deep Sea Research*, 19 (5), 377–384.

LEBRETON, B.; DOLOU. H.; BATANY. C., and KERINEC. J.C., 1991. Evaluation des maregraphes Suber en presence de courants forts.

Suite: Evaluation d'un attenuateur de depression, *Ann. Hydrogr,* 17, 37–43.

LENNON, G.W., 1970. Sea level instrumentation, its limitations and the optimisation of the performance of conventional gauges in Great Britain, *Symposium on Coastal Geodesy,* Munich.

LENNON, G.W., 1971. Sea level instrumentation, its limitations and the optimisation of the performance of conventional gauges in Great Britain, *The International Hydrographic Review,* XLVIII (2), 129–147.

LENNON, G.W. and MITCHELL, W. MCL., 1992. The stilling well—A help or a hindrance?, *Joint IAPSO-IOC Workshop on Sea Level Measurements and Quality Control, IOC Workshop Report No.81,* 52–64.

NOYE, B.J., 1974. Tide well systems I: Some non-linear effects of the conventional tide well, *Journal of Marine Research,* 32 (2), 129–153.

NOYE, B.J., 1974. Tide well systems II: The frequency response of a linear tide-well system, *Journal of Marine Research,* 32 (2), 155–181.

PALMER, H. R., 1831. Description of graphical register of tides and winds, *Philosophical Transactions of the Royal Society of London,* 121, 209–213.

PATHAK, A.G. and RAMADASS, G.A., 1997. An acoustic tide gauge with provision for in situ calibration, Indian Patent Pending No. 1443/MAS/97. (also patent pending in US).

PORTER, D.L. and SHIH, H.H., 1996. Investigations of temperature effects on NOAA's next generation water level measurement system, *Journal of Atmospheric and Oceanic Technology,* 13, 714–725.

SEELING, W.N., 1977. Stilling well design for accurate water level measurement. *Technical Paper No.* 77-2, U.S. Army Corps of Engineers Coastal Engineering Research Center, Kingman Building, Fort Belvoir, Virginia 22060.

SHIH, H.H. and PORTER, D.L, 1981. Error models for stilling well—Float type tide gauges. *Proceedings of IEEE Oceans'81,* 1118–1123.

SHIH, H.H.; DEITEMYER, D.H., and ALLEN, M.W., 1984. Field evaluation of a new tide gauge stilling well design. *Proceedings of 3rd International Offshore Mechanics and Arctic Engineering Symposium,* New Orleans, 98–105

SHIH, H.H. and BAER, L., 1991. Some error in tide measurement caused by dynamic environment, *In:* PARKER, B.B. (Ed.) *Tidal Hydrodynamics*, John Wiley and Sons Inc., 641–671.

VASSIE, J.M.; WOODWORTH, P.L.; SMITH, D.E., and SPENCER, R., 1992. Comparison of NGWLMS, bubbler and float gauge at Holyhead, *Workshop Report No. 81, Joint IAPSO-IOC workshop on sea level measurements and quality control,* 40–51.