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Professional paper

Long-term measurements at Bakar tide-gauge station (east Adriatic)

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We present hourly sea levels at Bakar tide-gauge station, located on the east coast of the Adriatic Sea. The station was established in 1929. The recorded data represent the longest time series of an oceanographic parameter measured in Croatia. They have been used in various scientific studies and practical applications. Sea levels were collected using float-type chart-recording tide gauge to which two digital instruments have been added recently. We describe station's location, its operational history, maintenance, principle of measurements, recorder zero checks and practice, and leveling history. Details on data sampling, quality checks and processing are included. Also, a brief summary of the most important results derived from these data is given and some practical applications are mentioned. The data are available through SEANOE (Međugorac et al., 2021; https://doi.org/10.17882/85171).

Keywords: tide gauge, Bakar, hourly sea level, benchmarks

1. Introduction

Sea level has been measured in Bakar for more than 90 years, since December 1929. The data recorded represent the longest time series of an oceanographic parameter measured in Croatia. The Bakar tide-gauge station began its operational history with deployment of a float-type chart-recording instrument over a stilling well. In the early 2000s it was upgraded with digital sensors, one float-type and one radar, installed aside the mechanical instrument (Pasarić and Orlić, 2008). Analog sea levels have been digitized at hourly resolution and are of good quality (buddy checked with station Rovinj; PSMSL, 2021), enabling studies of phenomena on a wide range of temporal scales – from mean sea level to seiches (*e.g.*, Kasumović, 1952; Orlić et al., 1994; Cerovečki et al., 1997; Pasarić and Orlić, 2001; Orlić et al., 2018). Hourly data provide support for advancement of simulation techniques of oceanographic processes (*e.g.*, Janeković et al., 2005; Bajo et al., 2019), and serve for evaluation of climate/nowcast numerical models (*e.g.*, Međugorac et al., 2020). Bakar sea levels have been often used for practical purposes. They were essential for determination of altitudes and definition of national chart datum (Kasumović, 1950; Jovanović, 1989; Rožić, 2009), and were used for traffic regulation (Orlić and Pasarić, 1997). Also, high frequency data, hourly and subhourly, are important for coastal engineering: Bakar data were used in construction planning (ports and hydro-power plants), flood risk management, protection of spring-water intakes from salinization etc.

Bakar tide gauge is a typical coastal station (IOC, 2006) established in December 1929 by the Geophysical Institute in Zagreb (Orlić and Pasarić, 1997; Orlić, 2001). It is located near the head of the Bakar Bay in the Adriatic Sea (Fig. 1a). Bakar Bay is an elongated basin with depths up to 38 m, 4.5 km long, connected with the Adriatic by a narrow strait (~400 m). The station was placed on the premises of the Port Authority, now the Customs Office (latitude 45° 18.3' N,

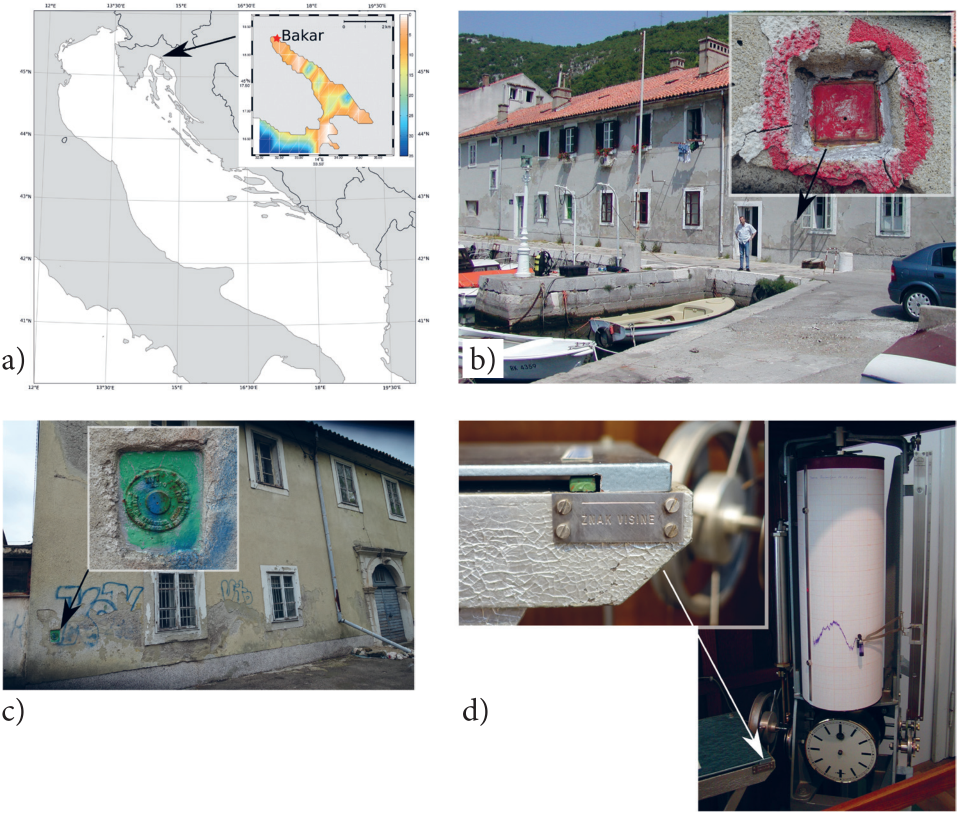


Figure 1. (*a*) The Adriatic Sea. Smaller inset shows bathymetry of the Bakar Bay and exact location of the tide-gauge station (red star). (*b*) Front side of the Bakar station and bench mark BV15663. (*c*) Back side of the station and bench mark A510. (*d*) Mechanical instrument and contact point.

longitude 14° 32.4’ E), and has not been moved during its entire lifetime. The location was chosen after considering several sites in the area. Stjepan Škreb, head of the Geophysical Institute at the time, visited Senj, Sušak, Kraljevica and Bakar in March 1928 with intention to establish a tide-gauge station. Most of the visited sites had flaws like great distance from the sea, possible interference with harbor traffic, impossibility of parallel meteorological measurements, etc. Bakar met the required conditions, but also the tide gauge could be placed in the Harbor Master’s Office and the officers were engaged as observers (all observers at the station were the harbor masters). This allowed them an easier access to the instrument and regular monitoring of recordings. It is worth mentioning that the station is over 100 km away from the home institution and therefore the proper functioning of instruments depends heavily on the conscientious work of observers.

Tide-gauge station Bakar is the stilling-well type of a station (Fig. 2). The instrument is installed over the well 2.7 m deep and 0.5 m wide. The well communicates with the sea through a narrow pipe 10.8 m long and 0.1 m wide. This design filters out short-wave oscillations with periods less than ~1 min and allows measurements of the entire range of long-wave oscillations (the well does not dry out). The station is connected to the national geodetic network via bench marks BV15663 in front of the building and A510 at its back (Figs. 1b and 1c).

Measured hourly data at Bakar are available since December 1929 with a 10-year gap around World War II and several smaller gaps due to diverse reasons (*e.g.*, the pipe was clogged, ink was missing, problems with the cable, clock was

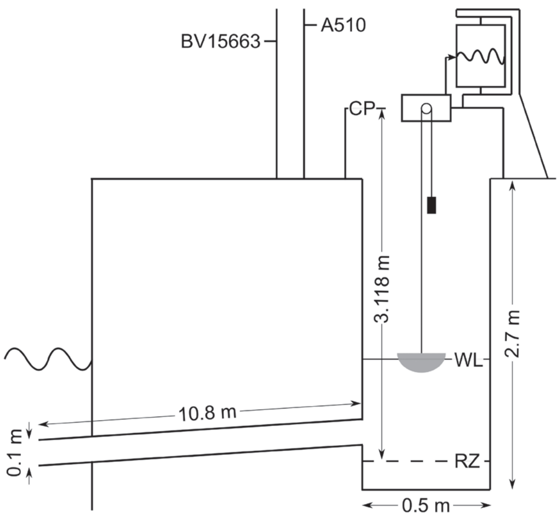


Figure 2. Schematic presentation of the tide-gauge station Bakar: CP – contact point, RZ – recorder zero, WL – water level, BV15663 – the bench mark at the front of the building (Fig. 1b), A510 – the bench mark at the back of the building (Fig. 1c).

not wound). It should be pointed out that the pre-war data and the post-war data are comparable, because the instrument has been always adjusted in the same way and therefore all data are referred to the same recorder zero.

2. Station and its maintenance

2.1. Types of instruments

Mechanical tide gauge (Otto A. Ganser, Wien, Nr. 228) was installed in December 1929. The original instrument was replaced in November 1979 by another mechanical tide gauge (A. Ott, Kempten, Nr. 20.030) having a larger recording drum and therefore being able to record extreme minima and maxima. Previously, extremes were observed using a tide pole mounted in front of the station in 1951. After 1979 the instrument has been recording the entire range of sea levels. Recordings are analog – the pen writes on the millimeter paper placed on a cylindrical drum which is rotated by clockwork (Fig. 1d).

In addition to the chart recorder, a digital float-type sensor (OTT Thalimedes) was installed in October 2003 on the same stilling well. The two instruments are completely independent (two floats) and were set to measure with respect to the same reference level. Sea level is measured by the digital floater with resolution of 1 minute. The data are sent to the home institution with 15 min latency. The mechanical tide gauge is considered the main instrument because it is more stable, while the digital one has been used for studies of high-frequency processes and for near real-time demands and also as a backup.

A radar tide gauge (OTT Kalesto) was installed in September 2004 in open air in the framework of ESEAS-RI project (Vilibić et al., 2004). The sensor OTT Kalesto was replaced by a newer version (OTT RLS) in March 2022. The radar tide gauge is located at the coast about 330 m southeast from the main instrument. Radar sensor is also set to measure with respect to the same reference level as the other two, and was used as redundant instrument for measurements of high-frequency processes or as a backup (in situations when stilling-well is being cleaned which can take several hours). The radar sensor provides 1-min data as averages of (i) 40 measurements done in 17 seconds (OTT Kalesto) or (ii) 16 Hz measurements in a 20-second window (OTT RLS). Ancillary air pressure is measured: 10-min averages until April 2021 and 1-min averages after that. The data are sent to home institution with 15-min latency.

2.2. Maintenance of the station

Measuring program includes periodic checks of recorder zero, cleaning of the stilling-well and connecting pipe, and checks of the contact-point level against tide-gauge bench mark (Pugh and Woodworth, 2014). Recorder-zero checks of float tide gauges are carried out twice a year, in spring and autumn. They are

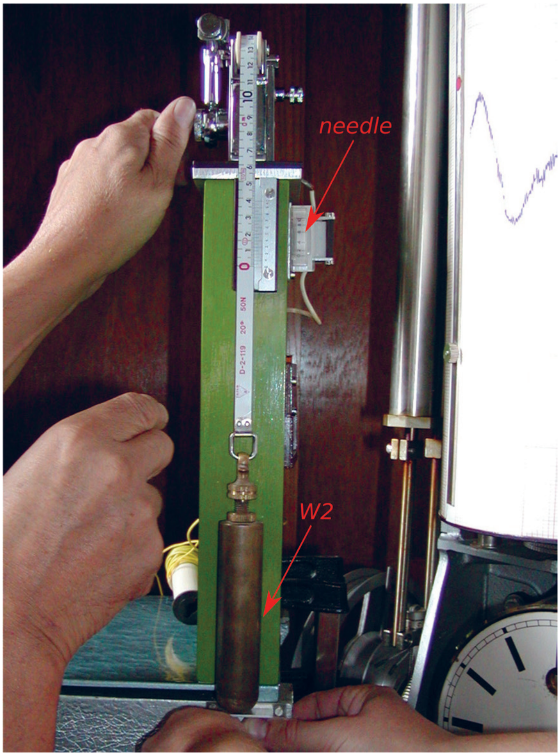
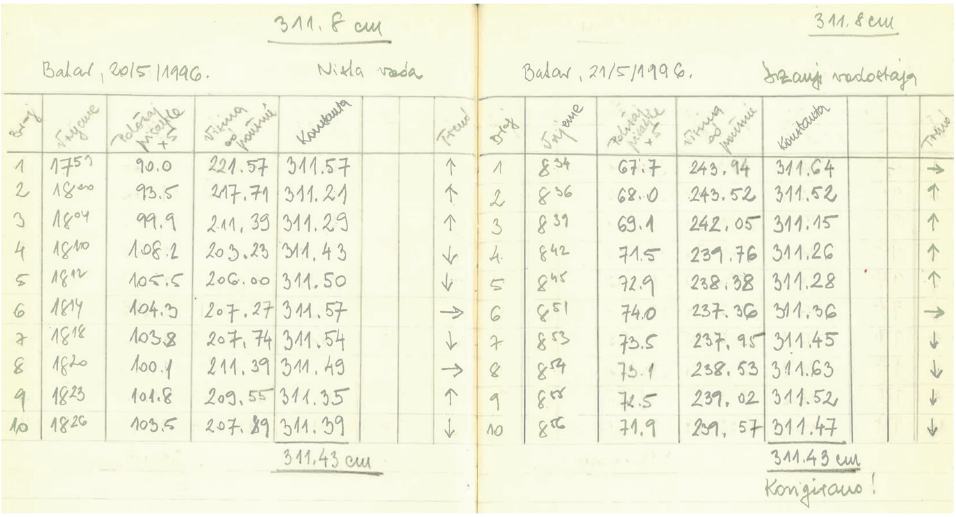


Figure 3. An instrument used to measure distance from the contact point level to the water surface. The smaller weight *W1* (not shown) is placed in the water and connected to an electrical circuit with the instrument. The moment the bigger weight (*W2*) touches the water, the electrical circuit closes which is signalized by a sound and needle movement. In the figure, check is made whether the tip of the weight *W2* is at the level of the contact point when zero is read on the meter.

performed using steel-tape instrument shown in Fig. 3. The device is used to measure distance from the contact point to the water surface (Fig. 2: CP-WL). It is designed so as to connect steel tape (thermally inert meter) and sea water into an electrical circuit when tape touches the water surface. Checks are performed by calculating tide-gauge constant (Fig. 2: CP-RZ, *i.e.*, distance from sea level to contact point plus the actual water level indicated by the tide gauge). Tide-gauge constant at Bakar equals 311.8 cm. During a standard check, several series of ten measurements are performed during different phases of the tidal cycle (Fig. 4). In this way, friction and all other factors affecting float-to-recorder transmission are taken into account. If the calculated average tide-gauge constant deviates from 311.8 cm, then water level given by the instrument is corrected by adjusting position of the recording pen.

History of recorder-zero checks is shown in Fig. 5. Until 1980s these were performed less frequently, but for the last 40 years they have been carried out



311.8 cm

Bakar, 20/5/1996. Niska voda

Broj	Vrijeme	Položaj pisaljke +5	Visina od površine	Konstanta	Trend
1	17^{57}	90.0	221.57	311.57	↑
2	18^{00}	93.5	217.71	311.21	↑
3	18^{04}	99.9	211.39	311.29	↑
4	18^{10}	108.2	203.23	311.43	↓
5	18^{12}	105.5	206.00	311.50	↓
6	18^{14}	104.3	207.27	311.57	→
7	18^{18}	103.8	207.74	311.54	↓
8	18^{20}	100.1	211.39	311.49	→
9	18^{23}	101.8	209.55	311.35	↑
10	18^{26}	103.5	207.89	311.39	↓

311.43 cm

311.8 cm

Bakar, 21/5/1996. Dizanje vodostaja

Broj	Vrijeme	Položaj pisaljke +5	Visina od površine	Konstanta	Trend
1	8^{34}	67.7	243.94	311.64	→
2	8^{36}	68.0	243.52	311.52	↑
3	8^{39}	69.1	242.05	311.15	↑
4	8^{42}	71.5	239.76	311.26	↑
5	8^{45}	72.9	238.38	311.28	↑
6	8^{51}	74.0	237.36	311.36	→
7	8^{53}	73.5	237.95	311.45	↓
8	8^{54}	73.1	238.53	311.63	↓
9	8^{55}	72.5	239.02	311.52	↓
10	8^{56}	71.9	239.57	311.47	↓

311.43 cm

Korigirano!

Figure 4. An example of two series of measurements performed to check recorder zero in May 1996. Columns denote following: 1 – ordinal number of a measurement, 2 – exact time of a measurement, 3 – recorded water level, 4 – distance between contact point and water level, 5 – calculated tide-gauge constant, 6 – sea-level trends at the moment. In the upper right corners tidal cycle phases (left: low water; right: rising tide) and Bakar's tide-gauge constant (311.8 cm) are indicated. Calculated averages of the tide-gauge constant are written in the bottom right corners as is a note that position of the pen of the mechanical instrument was corrected (*Korigirano!*).

regularly two times a year. Corrections were mostly less than 1 cm: 93.68% of all cases lie in the range of ±1 cm. However, there was an occasion when major adjustment was made. In March 1953 the cable broke and the observer tied the two dials so that the instrument could work until the cable was replaced. This shortened the cable by 11.5 cm which is visible as the red triangle in Fig. 5.

Cleaning of the stilling well and of the connecting pipe has been done every two years to control biological fouling and to ensure good flow through the pipe (marked with black *C*s in Fig. 5). This includes scraping of walls with cable and rinsing with compressor. Also, floats are cleaned to prevent inclination or weight change due to fouling.

Checks of the contact-point level against the tide-gauge bench marks have been done in intervals of 20–30 years, four times in the station history (marked with blue *B*s in Fig. 5). Levelings were performed in 1938 and 1963 by the Military Geographical Institute, Belgrade (Vojnogeografski institut Kraljevine Jugoslavije, 1938; Vojnogeografski institut, 1965), in 1986 by the Faculty of Geodesy, Zagreb (Geodetski fakultet Sveučilišta u Zagrebu, 1986), and in 2015 by the Hydrographic Institute of the Republic of Croatia, Split (Glavurdić, 2015). Original reports are available, except for the 1963 measurement for which there is only correspondence between Geophysical Institute in Zagreb and Military Geo-

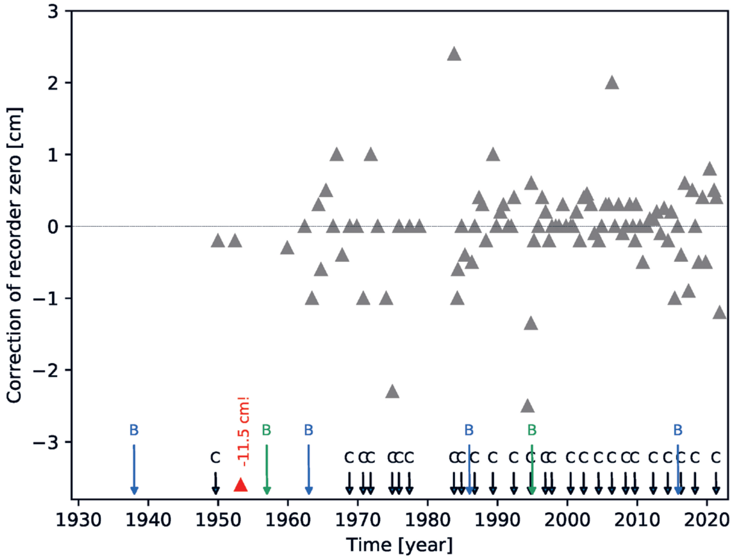


Figure 5. History of station maintenance over the 1929–2021 interval. Gray triangles indicate recorder-zero corrections. Red triangle marks correction of -11.5 cm, moved upward to fit the figure. Black arrows indicate cleaning of stilling well and of connecting pipe. Blue arrows indicate levelings of bench marks BV15663 and A510 (Fig. 2); green arrows indicate levelings of bench mark BV15663 and MCXVI.

graphical Institute in Belgrade (Vojnogeografski institut, 1965) in which the leveling is specified. In addition, checks of vertical distance between tide-gauge bench mark BV15663 (and in some cases of bench mark A510) and remote bench mark MCXVI were performed (marked with green Bs in Fig. 5) in 1957 by the Main Geodetic Administration (Glavna geodetska uprava, 1957) and in 1995 by the State Geodetic Administration and Faculty of Geodesy in Zagreb (Državna geodetska uprava i Geodetski fakultet u Zagrebu, 1995). The remote bench mark MCXVI (in older sources marked as MCXVI/306) is placed on a living rock above the city Bakar on the road Rijeka–Senj (before the turn-off to Meja, km 228+000). Here we emphasize importance of the remote bench mark being on stable ground and at a certain distance from the tide gauge, because it will allow us to make conclusions about vertical movements of the station building or local area around it. The two sets of levelings are summarized in Tab. 1.

The first set of height measurements (Tab. 1, first row), contact point to tide-gauge bench marks, showed that the instrument's contact point (Fig. 1d) is below the bench mark BV15663 (Fig. 1b) at a distance of: 25.44 cm (1938), 27.96 cm (1963), 28.01 cm (1986), and 28.29 cm (2015). The 1938 leveling differs significantly from the last three and we consider it unreliable. At the time the contact point was not marked with a plate (Fig. 1d), but there was an incised line on the pedestal of the tide gauge. We suspect that under these circumstances the contact

Table 1. Leveling of bench marks. Vertical distances in cm between tide-gauge contact point (CP) and/ or bench marks BV15663, A510, MCXVI.

	BV15663	MCXVI	Year, Institution
Contact point	25.44		1938, Military Geographical Institute, Belgrade
	27.96		1963, Military Geographical Institute, Belgrade
	28.01		1986, Faculty of Geodesy, Zagreb
	28.29		2015, Hydrographic Institute of the Republic of Croatia, Split
BV15663		5894.28	1957, Main Geodetic Administration, Zagreb
		5894.32	1995, State Geodetic Administration, Zagreb and Faculty of Geodesy, Zagreb
A510	17.27		1986, Faculty of Geodesy, Zagreb
	17.19		2015, Hydrographic Institute of the Republic of Croatia, Split
		5877.08	1995, State Geodetic Administration, Zagreb and Faculty of Geodesy, Zagreb

point was not targeted correctly which resulted in significantly lower vertical height between the two points. This is mentioned in a correspondence between Geophysical Institute in Zagreb and Military Geographical Institute in Belgrade (Vojnogeografski institut, 1965) in which they discussed whether the stated height was measured with respect to the incised line or to the edge of the sign. In this document, two additional measurements were mentioned, carried out in 1932 and 1947, but no reports can be found. Therefore, it is obvious that height measurement from 1938 should be omitted from further discussion. The last three levelings show that the floor around the well in the building was sinking at a rate up to 0.1 mm/y. This is derived from the fact that the distance between the two points increased slightly (3.3 mm) over the 52 years, while the walls of the building were sinking at an extremely low rate of 0.01 mm/y. The latter was estimated from measurements carried out between tide-gauge bench mark BV15663 and the remote bench mark MCXVI (Tab. 1, second row); the relative heights were 58.9428 m in 1957 and 58.9432 m in 1995, showing that in the 38 years the vertical distance increased by 0.39 mm. Since these vertical movements are of one or two orders of magnitude smaller than the speed at which mean sea- level rises (Orlić and Pasarić, 2000), datum corrections were not applied to the reported sea levels. It is recommended that leveling should be performed once a year (Pugh and Woodworth, 2014). However, tide-gauge station Bakar is on stable ground and the available data indicate that rather irregular geodetic measurements in the past did not reduce the quality of the dataset.

In Tab. 1 (third row) are also indicated two vertical distances between BV15663 and A510 bench mark, located at the front and the back side of the building (Fig. 1). They show almost no change in height distance (less than 1 mm in 29 years) and confirm the conclusion stated above – walls of the building are stable. Also available is one measurement of a height between remote benchmark MCXVI and A510 (Tab. 1, third row). However, no conclusions can be made from only one measurement, but it is reported here for the record and archive.

3. Data description

Hourly sea levels are obtained by digitizing weekly charts which are kept in the archive of the Department of Geophysics. The historical dataset, from the first recorded sea level to 1983, was digitized and fully processed within ESEAS-RI project (Vilibić et al., 2004). Subsequent digitizations have been performed once a year. Prior to digitizing, records are smoothed to avoid aliasing. Smoothing excludes all oscillations with periods shorter than 2 hours. This is important because the Bakar tide-gauge station is positioned in the bay with strong local seiche activity, with amplitudes usually higher than 20 cm and which in extreme cases exceed 50 cm. Period of the first mode of the Bakar Bay seiches is ~20 min (Šepić et al., 2008). Hence, hourly sea levels are not affected by local seiches and may deviate significantly from instantaneous values. Digitized hourly data are checked for outliers by applying Tukey 53H filter (Otnes and Enochson, 1978) and by visual inspection. Tidal analysis is performed for each year. Checks for timing errors are carried out by inspection of the current-year tidal constants against their history and also by inspection of the de-tided sea levels – shifts are recognized as leakage of the tidal signal into residual series which is visible in time and in frequency domains.

The whole dataset has been meticulously quality checked and flags provide quality for each value. The data are indicated as: (1) measured, good value, (2) interpolated, probably good value (linear regression of short gaps, up to 24 hours, done within the de-tided time series), (3) corrected, probably good value (offset, mostly due to bad positioning of chart), (4) doubtful value (corrections, using predicted tidal signal or regression on nearby station, applied due to malfunctioning of instrument or clogged connecting pipe), or (9) no value (the instrument not

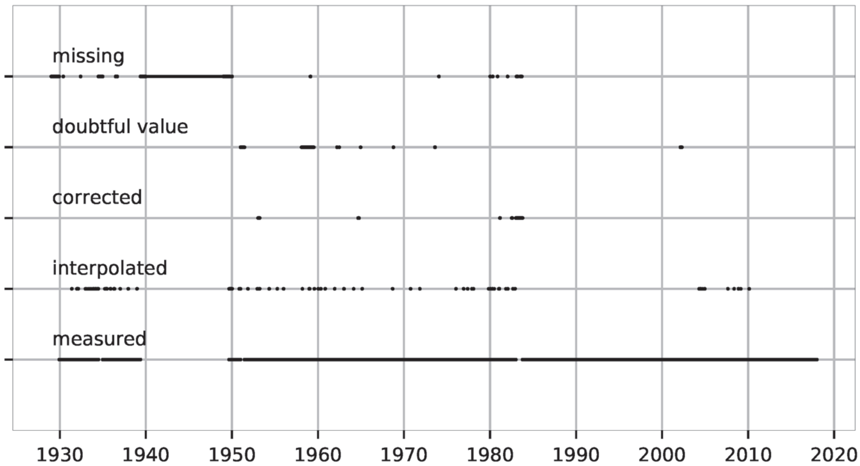


Figure 6. Data availability for the interval 1929–2017.

operating or longer intervals of malfunctioning). As discussed above, datum corrections were not applied to the data.

The time series of quality checked hourly values starts from 5 December 1929. Larger data gaps (>1 month) occurred in 1934, 1936, and during 1939–1949 due to World War II (Fig. 6). From 1950 till 1983 several data gaps occurred lasting several consecutive days (max 17 days). After 09/1983 all hourly data are available, although some of them are obtained by interpolation or regression on nearby station.

Sea level is expressed in centimeters, relative to the mean sea level ($Z0$ = 73.8045 cm) calculated over 18.6 year interval (1962–1980; national geodetic system HVRS71). If values are to be expressed relative to the chart datum (national system HRSDM71) then 32.30 cm should be added to the reported sea levels. Accuracy of the data is 1 cm and precision 0.1 cm. Time is in UTC+1.

From the hourly time series, daily mean sea levels and monthly means are calculated. These time series have been publicly available for several decades: the former were being published in the Annual Reports (Hydrographic Institute of the Republic of Croatia, 1954–2020) and the latter were being distributed through the Permanent Service for Mean Sea Level (PSMSL, 2021).

4. Data availability

The time series of hourly sea-level data from the Bakar tide-gauge station is publicly available and can be reached through the SEANOE website (Međugorac et al., 2021; https://doi.org/10.17882/85171). Format of the data is CSV including description of the measurements. The data are available for scientific purposes with no restrictions (Creative Commons license *CC-BY-NC*). The time series spans from December 1929 until three years ago. Data for each ending year will be regularly added at the beginning of current year. We would be grateful to be notified of any papers that resulted from the Bakar sea levels. This would give us information on the impact of our data but also it would be helpful in securing funding for future work of the station. Additional information, news and activities at the station Bakar can be found on the official website: https://www.pmf.unizg.hr/geof/en/research/oceanography/tide-gauge_station_bakar.

5. Data use and scientific results

Bakar data have been used in a large number of scientific studies. A complete list of scientific papers that used Bakar measurements is available at Bakar tide-gauge website (https://www.pmf.unizg.hr/geof/en/research/oceanography/tide-gauge_station_bakar/data), but we will highlight some of them. In an early paper, Goldberg and Kempni (1938) used the data to investigate the Bakar Bay seiches, having thus documented the triple fundamental mode (at the periods of 26.9, 22.3 and 19.7 min) as well as the higher modes (at the periods of 7.8 and

4.3 min). Later, Cerovečki et al. (1997) explored seiches of the whole Adriatic and have found that their decay time is very long (3.2 ± 0.5 days). Kasumović (1952) was the first to perform harmonic analysis for the Bakar station and has thus confirmed that the tides in the area could be adequately approximated by seven harmonic constituents. Tsimplis et al. (1995) have used the Bakar data, along with the data originating from a number of other tide-gauge stations, to check the quality of their numerical model of tides of the Mediterranean Sea. Measurements at Bakar were also extensively used while exploring response of the Adriatic Sea to the atmospheric forcing. Orlić et al. (1994) have shown that bora – an important wind in the area – brings about rising of sea level along the Italian coast and its lowering along the Croatian coast and that the lowering is highly variable in space due to the bora-wind curl. The Adriatic Sea responds not only to the synoptic-scale forcing but also to the planetary-scale forcing, as confirmed by Pasarić et al. (2000) who performed cross-spectral analysis of long time series of sea level, atmospheric pressure and wind. The Bakar data also proved useful while analyzing seasonal (Pattullo et al., 1955) and year-to-year variability (Orlić, 2001). It has been shown that the range of the former variability is about 10 cm whereas the range of the latter variability reaches 50 cm. Finally, the Bakar data were also utilized while analyzing sea-level rise, both linear (*e.g.*, Emery and Aubrey, 1991) and non-linear (Orlić et al., 2018). Whereas the overall Adriatic trends were found to be similar to the global trends, the more detailed study has revealed that the Adriatic sea level was rising before 1950s, that it was stable from 1950s to 1990s, and that it is rising again from 1990s onward. It has thus become obvious that the processes governing sea-level rise in the Mediterranean and Adriatic Seas differ from the global processes.

Practical applications of the data, unlike scientific results, are less well documented. Bakar sea levels were essential, along with data from the other four long-term east Adriatic tide gauges (Koper, Rovinj, Split and Dubrovnik), for definition of the national system of altitudes (HVRS71) and chart datums (HRSDM71). For this purposes mean sea levels were calculated for the period of 18.6 years centered around 1 July 1971 (epoch 1971.5) (Rožić, 2009). Also, over the years, many national or private organizations required sea-level data for their hydro technical tasks (*e.g.*, hydro-power plant Senj, construction of the Rijeka Port), for consideration of micro location for new tide gauges in the Kvarner area (*e.g.*, tide gauge in Rijeka), for flood risk management (*e.g.*, project VEPAR), for protection of spring water intakes (*e.g.*, Perilo, Dobrica) and for various official reports on coastal/river floods that have endangered the Northern Adriatic coastline.

6. Summary

We have presented time series of hourly sea levels measured at the tide-gauge station Bakar in the period December 1929 – December 2017. The dataset consists of a single series measured with chart-recording float-type instrument mounted over a stilling well. Over the years, there have been difficulties in operation of the station, hence gaps in the data emerged of which the longest occurred during WWII. In the last several decades station and instruments were regularly maintained which secured high quality of the data. Due to its length and quality, the dataset presents a valuable tool to study sea-level variability on timescales ranging from subsynoptic to decadal.

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References

Aarup, T., Merrifield, M., Perez, B., Vassie, I. and Woodworth, P., Eds. (2006): I*OC: Manual on Sea-Level Measurement and Interpretation. Volume 4: An Update to 2006 Intergovernmental Oceanographic Commission Manuals and Guides No. 14*, UNESCO/Intergovernmental Oceanographic Commission, Paris.

Bajo, M., Međugorac, I., Umgiesser, G. and Orlić, M. (2019): Storm surge and seiche modelling in the Adriatic Sea and the impact of data assimilation, *Q. J. Roy. Meteorol. Soc.,* **145**, 2070–2084, https://doi.org/10.1002/qj.3544.

Bakar tide gauge: https://www.pmf.unizg.hr/geof/en/research/oceanography/tide-gauge_station_bakar, last accessed on November 24, 2021.

Cerovečki, I., Orlić, M. and Hendershott, M.C. (1997): Adriatic seiche decay and energy loss to the Mediterranean, *Deep-Sea Res. I*, **44**, 2007–2029, https://doi.org/10.1016/S0967-0637(97)00056-3.

Državna geodetska uprava i Geodetski fakultet u Zagrebu (1995): Izjednačenje nivelmanskih mreža svih redova u I nivelmanskom poligonu IINVT (document is in archive of State Geodetic Administration), Zagreb, Croatia (in Croatian).

Emery, K. O. and Aubrey, D. G. Eds. (1991): *Sea levels, land levels and tide gauges*. Springer Verlag, New York, 237 pp.

Geodetski fakultet Sveučilišta u Zagrebu (1986): Visinski odnosi kod mareografa u Bakru, Zagreb, https://urn.nsk.hr/urn:nbn:hr:217:256667 (in Croatian).

Glavna geodetska uprava (1957): Mareografi (document is in archive of State Geodetic Administration), Zagreb (in Croatian).

Glavurdić, A. (2015): Određivanje visinskih odnosa između dva repera i dvije oznake na mareografu u Bakru, Hrvatski hidrografski institut, Split, https://urn.nsk.hr/urn:nbn:hr:217:955422 (in Croatian).

Goldberg, J. and Kempni, K. (1938): O oscilacijama Bakarskog zaljeva i općem problemu zaljevskih seša, *Prirodoslovna istraživanja Kraljevine Jugoslavije*, **21**, 129–234 (in Croatian).

Hydrographic Institute of the Republic of Croatia (1954–2020): Reports on Tide Gauge Measurements (Adriatic Sea – East Coast), Split, https://www.hhi.hr/en/products-and-services/official-navigational-publications.

Janeković, I. and Kuzmić, M. (2005): Numerical simulation of the Adriatic Sea principal tidal constituents, *Ann. Geophys.*, **23**, 3207–3218, https://doi.org/10.5194/angeo-23-3207-2005.

Jovanović, B. (1989): Istraživanja geodetske i hidrografske nule, njihova primena i važnost, *Hidrografski godišnjak*, **87**, 115–134 (in Serbian).

Kasumović, M. (1950): Srednja razina Jadranskog mora i geodetska normalna nula Trst, *Radovi Geofizičkog zavoda u Zagrebu*, **2(3)**, 1–22 (in Croatian).

Kasumović, M. (1952): Harmonička analiza plime i oseke luke Bakar, *Radovi Geofizičkog zavoda u Zagrebu*, **3(1)**, 1–9 (in Croatian).

Međugorac, I., Pasarić, M. and Güttler, I. (2020): Will the wind associated with the Adriatic storm surges change in future climate?, *Theor. Appl. Climatol.*, **143**, 1–18, https://doi.org/10.1007/s00704-020-03379-x.

Međugorac, I., Pasarić, M. and Orlić, M. (2021): Historical sea-level measurements at Bakar (east Adriatic), *SEANOE*, https://doi.org/10.17882/85171.

Orlić, M. (2001): Anatomy of sea level variability – An example from the Adriatic, in: *The Ocean Engineering Handbook*, edited by El-Hawary, F., CRC Press, Boca Raton, 1–14.

Orlić, M. and Pasarić, M. (1997): Sedam desetljeća mareografskih mjerenja u Bakru, *Prirodoslovna istraživanja riječkog područja*, Prirodoslovna biblioteka, Rijeka, **1**, 201–211 (in Croatian).

Orlić, M., Kuzmić, M. and Pasarić, Z. (1994): Response of the Adriatic Sea to the bora and sirocco forcing, *Cont. Shelf Res.*, **14**, 91–116, https://doi.org/10.1016/0278-4343(94)90007-8.

Orlić, M. and Pasarić, M. (2000): Sea-level changes and crustal movements recorded along the east Adriatic coast, *Nuovo Cimento C*, **23**, 351–364.

Orlić, M., Pasarić, M. and Pasarić, Z. (2018): Mediterranean sea-level variability in the second half of the twentieth century: A Bayesian approach to closing the budget, *Pure Appl. Geophys.*, **175**, 3973–3988, https://doi.org/10.1007/s00024-018-1974-y.

Otnes, R. K. and Enochson, L. (1978): *Applied time series analysis.* Vol 1, 2nd Ed., Wiley, New York.

Pasarić, M. and Orlić, M. (2001): Long-term meteorological preconditioning of the North Adriatic coastal floods, *Cont. Shelf Res.*, **21**, 263–278, https://doi.org/10.1016/S0278-4343(00)00078-9.

Pasarić, M. and Orlić, M. (2000): Mareografska postaja Bakar: mehanički ili radarski instrument?, in: *Znanstveno savjetovanje – Hidrološka mjerenja i obrada podataka (zbornik radova)*, edited by Ožanić, N., Građevinski fakultet Sveučilišta u Rijeci, Rijeka, 319–328 (in Croatian).

Pasarić, M., Pasarić, Z. and Orlić, M. (2000): Response of the Adriatic Sea to the air pressure and wind forcing at low frequencies (0.01–0.1 cpd), *J. Geophys. Res.*, **105/C5**, 11423–11439, https://doi.org/10.1029/2000JC900023.

Pattullo, J., Munk, W., Revelle, R. and Strong, E. (1955): The seasonal oscillation in sea level, *J. Mar. Res.*, **14**, 88–155.

PSMSL: https://www.psmsl.org/data/obtaining/stations/353.php, last accessed on 24 November 2021.

Pugh, D. and Woodworth, P. (2014): *Sea-level science: Understanding tides, surges, tsunamis and mean sea-level changes.* Cambridge University Press, Cambridge, 395 pp.

Rožić, N. (2009): Hrvatski transformacijski model visina, Geodetski fakultet, Sveučilište u Zagrebu (in Croatian).

Šepić, J., Orlić, M. and Vilibić, I. (2008): The Bakar Bay seiches and their relationship with atmospheric processes, *Acta Adriat.*, **49**, 107–123.

Tsimplis, M. N., Proctor, R. and Flather, R. A. (1995): A two-dimensional tidal model for the Mediterranean Sea, *J. Geophys. Res.*, **100/C8**, 16223–16239, https://doi.org/10.1029/95JC01671.

VEPAR: https://meteo.hr/istrazivanje_e.php?section=projekti&param=projekti_all&el=VEPAR_e, last accessed on November 24, 2021.

Vilibić, I., Domijan, N., Leder, N., Strinić, G., Orlić, M. and Pasarić, M. (2004): ESEAS-RI in Croatia: A step towards sea level service, in: *Proceedings of the Workshop on Observing and Understanding Sea Level Variations*, St. Julians, Malta, 1–11 November 2004, 17–18.

Vojnogeografski institut (1965): Visina biljega visine u Bakru – Korespondencija, Beograd, https://urn.nsk.hr/urn:nbn:hr:217:851069 (in Serbian).

Vojnogeografski institut Kraljevine Jugoslavije (1938): Precizni nivelman – Veza mareografa u Bakru, Beograd, https://urn.nsk.hr/urn:nbn:hr:217:160535 (in Serbian).

SAŽETAK

Dugogodišnja mjerenja na mareografskoj postaji Bakar (istočni Jadran)

Iva Međugorac, Miroslava Pasarić i Mirko Orlić

U radu su detaljno prikazana mjerenja satnih visina razine mora na mareografskoj postaji Bakar, smještenoj na istočnoj obali Jadrana. Mareografska je postaja utemeljena 1929. godine, a prikupljeni podaci predstavljaju najdulji vremenski niz nekog oceanografskog parametra izmjerenog u Republici Hrvatskoj. Podaci su do sada korišteni u mnogobrojnim znanstvenim studijama a imali su i praktičnu primjenu. Vodostaji su izmjereni analognim plovčanim mareografom uz koji su nedavno postavljena i dva digitalna instrumenta. U radu je opisana lokacija bakarske postaje, njena operativna povijest, održavanje, princip mjerenja, provjera lokalne mareografske nule te povijest geodetskih niveliranja. Uključeni su i detalji o uzorkovanju, provjeri kvalitete i obradi podataka. Također, dan je kratak pregled najvažnijih znanstvenih rezultata proizašlih iz ovih mjerenja, a spomenute su i neke praktične primjene. Podaci su dostupni u bazi SEANOE (Međugorac i sur., 2021; https://doi.org/10.17882/85171).

Ključne riječi: mareograf, Bakar, satni vodostaji, geodetski reperi

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