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Extreme values and rising tendencies of sea levels along Vietnam coast

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Abstract. A review of the investigations on the sea level changes in South-china sea is presented.

The full set of yearly sea level data at 25 tide gauges along Vietnam coast is used for extreme analysis and trend analysis. Based on the level data collection up to year 2007 the empirical extreme analysis yields new estimates of the design values of sea level with different rare frequencies.

The results of extreme analysis are compared with the theoretical extreme heights of tide obtained by predicting hourly tide heights in a 20-year period. For stations with 11 harmonic constants of main tidal constituents the theoretical astronomical extreme tide levels were calculated by the Peresipkin iteration method. The comparison showed a good agreement between two methods. The analysis also showed that the tidal extremes and design level values of 20-year return period are of the same range. The level values of longer return period are affected mainly by floods and surges at a decreasingly extent.

The rate of yearly changes of sea level due to global warming and other effects is evaluated to be about 1 mm per year.

Keywords: Extreme analysis; Trend analysis; Return period, Design levels, Sea level rise.

1. Introduction

The extreme sea levels are research subject of many purposes. The maximal and minimal values of sea levels and their occurrence probabilities are taken into account in designing hydro-technical installations and in building navigation maps, with minimum sea level being the zero of the navigation maps.

The issues of sea level changeableness are of a common interest, especially in the context of the global warming.

The observation of sea level along Vietnam coast is mainly carried out by a system of tidal gauges of the Vietnam Hydro-meteorological Service. Generally speaking, up to now the number of tidal gauges that belongs to Vietnam waters is not large and the period of observation years is not long enough. So there is no much deal with the behavior of sea level in general and with the empirical calculations of level extremes in particular.

The theory of extreme analysis of statistical mathematics is applied to the hydrometeorology with different distributions of the observed series of climatic and hydrological parameters [6,8]. The main concepts of these methods and their practical realization have been presented in details in [2].

In the case that observed series of sea level is not long enough to apply the procedures of extreme analysis theory, which usually happens

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in the design investigations in the coastal zone and estuaries, one may use theoretical extreme values of soly tidal levels.

In many practical problems the minimal theoretical level is assumed to be the zero depth in tidal seas. This level can be calculated by subtracting maximal low height of tide due to astronomical conditions from the mean sea level. In some countries this value is determined by analyzing a predicted series of 20-year long tidal heights, one choose the lowest height among all low waters in the series as a zero depth. In Russia the minimal theoretical level is determined by known Vladimirsky method. Vladimirsky method gives an analytical solution of the problem with harmonic constants of 8 main tidal constituents. The rest tidal constituents are taken into account approximately. Recently the calculations can be performed rapidly by computers, evaluating extreme heights of tide can be carried out by more detailed schemes and the accuracy is improved by taking a non-restricted number of tide constituents into consideration [7]. A detailed explanation of a scheme to implement this method in practice and the results of its application for 25 tide gauges along Vietnam coast have been presented by Pham Van Huan [2].

A full cumbersome calculation of level extremes has been performed by Nguyen Tai Hoi since 1995 [1]. That report firstly listed series of monthly average, maximal and minimal levels measured at all gauges along Vietnam coast up to middle of the ninetieth. The extreme analysis was then carried out by using an asymptotic Gumbel function of probability distribution of the extremes.

In some rare works there reported the results of analyzing changeableness of sea level and the estimating the trend of sea level rise in the base of analysis of observed series of sea level some years long. The spectrum analysis [3] showed that besides the semiannual and annual periods, in the most of tidal gauges oscillations of period of 6 to 10 years and longer exist.

The trend analysis using monthly mean levels collected up to middle of the ninetieth [2-5] showed that the summary effect by the global warming and oscillations of sea bed in region of Vietnam coast causes a rate of level rise (trend) about 1 to 3 mm per year (Table 1).

Table 1. The rate of sea level rise along Vietnam coast [2]

Tidal gauge	Co-ordinates	Observation years	Sample size (years)	Trend (*mm/year*)
Hòn Dấu	20°40'N–106°49'E	1957–1994	38	2.1
Cửa Cấm	20°45'N–106°50'E	1961–1992	32	2.7
Sơn Trà	16°06'N–108°13'E	1978–1994	17	1.2
Quy Nhơn	13°45'N–109°13'E	1976–1994	19	0.9
Vũng Tàu	10°20'N–107°04'E	1979–1994	16	3.2

Based on the yearly mean level data collected up to the year 2007 new evaluations of the design values of sea level of different rare frequencies are presented in section 3. The results of extreme analysis are compared with the theoretical extreme heights of tide obtained by predicting hourly tide heights in a 20-year period. For other stations with 11 or 8 harmonic constants of main tidal constituents the theoretical astronomical extreme levels were calculated by the Peresipkin iteration method. The comparison showed a good agreement between two methods. The analysis also showed that the tidal extremes and design level values of 20-year return period are of the same range. The level values of longer return period are affected mainly by floods and surges at a modest extent.

2. Data and methods

2.1. Data

All the analyses are based on sea levels collected at 25 tidal gauges. Three types of data are considered: yearly mean sea levels, yearly maximum and minimum levels. The observation period and the length of data series at points are different and ranges from 27 to 46 years (see Table 2). It is seen that the lengths of the samples are much better than those in the middle of the ninetieth when the design levels had been estimated by us [2] for the first time (see Table 1).

The harmonic constants of a large number of stations are used as the input data for the tide prediction to find the extreme tide levels. For many among these stations the set of harmonic constants are obtained from the observed hourly levels series of one-year or longer. For one-year series the number of harmonic constants equals 30. Stations with a two-year or longer series have the number of harmonic constants up to 114.

Table 2. The characteristics of the data samples

Tide Gauge	Co-ordinates	Observation years	Sample size (years)
Cửa Ông	21.°02'N–107.°22'E	1962-2007	46
Bãi Cháy	20.°58'N–107.°04'E	1962-2007	46
Cô Tô	20.°58'N–107.°46'E	1960-1994	35
Cửa Cấm	20°45'N–106°50'E	1961-2006	46
Hòn Dấu	20°40'N–106°49'E	1960~2007	48
Ba Lạt	20.°19'N–106.°31'E	1960-2006	45
Hoàng Tân	19.°46'N–105.°52'E	1965-2005	41
Hòn Ngư	18.°48'N–105.°46'E	1962-2007	42
Cửa Hội	18.°46'N–105.°45'E	1962-2005	44
Cẩm Nhượng	18.°15'N-106.°06'E	1962-2007	46
Cồn Cỏ	17.°10'N–107.°22'E	1980-2007	27
Cửa Việt	16.°53'N–107.°10'E	1977=2005	29
Sơn Trà	16°06'N–108°13'E	1978-2007	30
Quy Nhơn	13°45'N–109°13'E	1976-2007	32
Tuy Hòa	13.°05'N–109.°17'E	1977-2004	28
Phú An	10.°46'N–106.°42'E	1977-2005	29
Phú Quý	10.°31'N–108.°56'E	1986-2007	22
Chợ Lạch	10.°17'N–106.°07'E	1977-2005	29
Vàm Kênh	10.°16'N–106.°44'E	1978-2005	28
Vũng Tàu	10°20'N–107°04'E	1979-2007	29
Rạch Giá	10.°00'N–105.°05'N	1978-2005	28
Năm Căn	8.°46'N–105.°01'E	1980-2005	24
Cà Mau	8.°39'N–104.°45'E	1978-2005	28
Phú Quốc	10.°13'N–103.°58'E	1980-2007	28
Côn Đảo	8.°41'N–106.°36'E	1980-2007	28

2.2. Extremes analysis with empirical data

A question of principle in the application of extremes analysis theory is the precision of the approximation, i.e. the question on the rate of convergence of precise distribution of extremes to the asymptotic one, in practical aspect, the precision of design values estimated by asymptotic distribution in comparison with its real value (but often unknown).

The methods of estimation of extreme distribution aim at the settlement of the question on the initial series, the relatively short length of initial series. Tibor Farago and Richard W. Kats [6] explained different methods for the estimation of the distribution parameters (k – shape parameter, u_m – local parameter and b_m – scale parameter) and for the determination of design values and their estimate accuracy. Section 3.3 presents the results obtained by applying these methods to series of annually maximal and minimal levels of 25 tidal gauges along Vietnam coast. Because of the short length and the unknown parent distribution of the empirical samples, all nine methods of estimation are applied to each level series to investigate and compare. To avoid a risk of over-estimation or under-estimation the design values of extreme levels of different return periods are obtained as the averages of nine methods (an example of the calculations may be seen in Table 3).

Table 3. The example of extreme value analysis for yearly maximal level at Hòn Dấu
Mean = 378.50; Standard Deviation = 21.70; Maximum = 421.00; Minimum = 332.00 (cm)

Methods	Return period (year)			
	10	20	50	100
2-parameter methods (Gumbel):				
Method of moments (theoretical)	406.80	418.98	434.74	446.56
Method of moments (empirical)	408.53	421.32	437.88	450.28
Method of quantiles	420.76	437.31	458.74	474.80
Linear unbiased estimates (Lieblein)	414.24	429.16	448.46	462.92
Method of probability-weighted moments	413.51	428.57	448.07	462.68
Maximum likelihood method	414.88	430.08	449.74	464.47
3-parameter methods (Jenkinson):				
Method of sextiles	405.24	410.67	415.65	418.29
Method of probability-weighted moments	412.04	420.16	428.25	432.91
Maximum likelihood method	406.01	412.30	418.37	421.75
Average of all methods	411	423	438	448

2.3. Method of computing tidal extremes

Extreme values of tide (so call the theoretical astronomical levels of tide or simply, the tidal extremes) are computed by two methods. First one is to predict the hourly tidal levels for the period of 20-year long. The highest from all high waters will be the maximal value of tide and the lowest from all low waters will be the minimal value of tide. This method has a disadvantage in requirement of large computing time.

The Peresipkin iteration method of estimation of the tidal extremes is tested to examine its efficiency. This method of approximate calculation of tidal extremes and the appropriate computer program for its realization have been explained in detail in [2].

In contrast to the method of predicting level series 20-year long said above, the iteration method has a distinctive advantage in requirement of less computing time.

2.4. Trend analysis

Trend analysis is applied to the series of yearly mean sea levels at 25 tidal gauges listed in Table 2. The rate of sea level rise (mm per year) at each tidal gauge is obtained by regression method of finding an equation of sea levels depending on time (year).

3. The results and discussion

3.1. Tidal extremes for the gauges with full set of harmonic constants

For the hydrographic stations with tidal gauges we used a series of hourly observed levels of one year duration to compute the full set of harmonic constants (30 constituents or more). The hourly levels were predicted for a period of 20 years (1989–2008). The lowest and highest levels chosen for some stations are listed in columns 4 and 5 of Table 4 in the order from the north to the south along Vietnam coast.

3.2. Tidal extremes estimated by Vladimirsky method or Peresipkin iteration method

For the stations with no systematic observations on sea levels we used series of hourly observed levels of duration of some days to compute harmonic constants of main tidal constituents (by Darwin method or by the least squares method). Than, from these restricted sets of the harmonic constants we used the iteration method dealt with in section 2.3 to get the extreme characteristics of the tidal levels. The results of computing are written in Table 4.

Table 4. Tidal extremes along Vietnam coast .estimated by predicting 20-year series and by the iteration method

Station	Co-ordinates	Mean level (cm)	Predicted 20-year period		Iteration method	
			Lowest tide	Highest tide	Lowest tide	Highest tide
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Cửa Ông	21.°02'N–107.°22'E	215	2	469	0	472
Cô Tô	20.°58'N–107.°46'E	204	−7	454	−10	454
Cát Hải	20.°47'20''E–106.°51'18'' E	180	−52	414	−54	416
Cửa Cấm	20°45'N–106°50'E	217	30	406	28	408
Hòn Dấu	20°40'N–106°49'E	194	−18	412	−22	416
Ba Lạt	20.°19'N–106.°31'E	6	−175	185	−177	187
Như Tân	20.°01'N-106.°06'E	83	−6	173	−7	174
Lạch Sùng	19.°57'N–105.°58'E	−16	−182	128	−185	130
Hoàng Tân	19.°46'N–105.°52'E	3	−188	161	−190	163
Hòn Ngư	18.°48'N–105.°46'E	182	28	317	27	318
Cửa Hội	18.°46'N–105.°45'E	171	20	291	19	291
Cửa Gianh	17°42'N–106°28'E	−34	−157	61	−160	37
Nhật Lệ	17.°30'N–106.°36'E	0	−77	54	−78	54
Cồn Cỏ	17.°10'N–107.°22'E	80	36	120	36	120
Cửa Tùng	17.°01'N–107.°06'E	80	36	113	36	113
Thuận An	16.°34'N–107.°38'E	50	25	77	25	77

Chơn Mây	16.°19'N–107.°59'E	80	34	115	33	115
Sơn Trà	16°06'N–108°13'E	93	10	175	10	142
Cù Lao Chàm	15.°57'N–108.°32'E	–23	–99	49	–95	50
Sa Huỳnh	14.°40'N–109.°04'E	–6	–99	88	–99	90
Quy Nhơn	13°45'N–109°13'E	160	75	247	70	232
Nha Trang	12°15'05N–109°11'05E	121	8	227	8	225
Cam Ranh	11.°53'N–109.°12'E	124	30	206	29	207
Phan Thiết	10.°55'N–108.°06'E	0	–130	79	–131	79
Vũng Tàu	10°20'N–107°04'E	259	–27	413	–15	402
Cà Mau	8.°39'N–104.°45'E	76	–7	146	–7	146
Hà Tiên	10.°22'N–104.°28'E	70	32	121	32	121
Rạch Giá	10°00'N–105°05'E	5	–48	90	–34	84
Mỏ Bạch Hổ	10.°00'N–107.°00'E	372	190	488	192	469
Mỏ Đại Hùng	8.°29'N–108.°38'E	189	73	273	72	273
Phú Quốc	10.°13'N–103.°58'E	58	5	96	5	96
Trường Sa	8.°38'N–111.°55'E	0	–98	87	–99	87
Hoàng Sa	16.°33'N–111.°37'E	118	45	189	45	189

It is seen from Table 4 that the results of two methods of computations are in good agreement. The mean absolute declination between two estimates equals 2.1 cm for the lowest tides and 3.9 cm for the highest tides. The mean square declination equals 3.7 cm for the lowest tides and 8.5 cm for the highest ones. The rare maximal differences (10 cm or more) between two methods of estimation occur only for stations which have a considerably high value of amplitude harmonic constants of tidal constituents Sa and Ssa . Thus, harmonic constants Sa and Ssa for station Cửa Gianh equal 21 and 8 cm respectively; for Sơn Trà – 18 and 12 cm; for Quy Nhơn – 10 and 7; for Vũng Tàu – 20 and 6; for Rạch Giá – 12 and 2 and for Bạch Hổ – 17 and 3 cm. It is known that constituents Sa and Ssa have not only purely tidal nature but also meteorological one. These two constituents are affected by seasonal oscillations of the meteorological processes and especially by floods in estuaries. In this case the tidal extremes chosen from a 20-year series of predicted levels are more exact.

From these experiments followed a rule of thumb that for a station which has high harmonic constants of annual and semi-annual periods the extreme tides must be determined by both two methods - procedure of predicting 20-year series and Vladimirsky method, the lesser among two estreme values will be the lowest tide and the bigger among two extreme values - highest tide.

3.3. Results of computing design values from observed yearly maximum and minimum sea levels

In this section we use series of the yearly minimal and maximal levels at stations listed in Table 2 to evaluate the design levels with different return periods by extreme analysis. In each year one lowest level (or one highest level) was chosen to establish the sample series.

Table 5. Design levels (cm) at 25 tidal gauges along Vietnam coast

Tidal gauge	Return period (year)								Trend of MSL (mm/year)
	10	20	50	100	10	20	50	100	
	Minimum				Maximum				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Cửa Ông	12	1	−12	−21	477	489	504	515	1.1
Bãi Cháy	1	−10	−23	−32	440	451	464	474	1.0
Cô Tô	−1	−11	−23	−33	450	462	477	489	1.0
Cửa Cấm	−184	−193	−205	−215	216	225	237	245	0.0
Hòn Dấu	−7	−13	−22	−28	411	423	438	448	1.0
Ba Lạt	−126	−133	−143	−149	314	374	467	555	0.1
Hoàng Tân	−157	−162	−169	−173	256	283	320	351	0.1
Hòn Ngư	−7	−18	−33	−43	374	387	402	414	0.9
Cửa Hội	−173	−178	−185	−190	213	230	253	271	0.2
Cẩm Nhượng	−130	−135	−142	−146	218	235	258	275	0.4
Cồn Cỏ	−2	−5	−8	−11	180	188	199	207	0.0
Cửa Việt	−89	−92	−95	−98	160	177	199	216	0.5
Sơn Trà	13	9	3	−2	226	238	253	264	0.5
Quy Nhơn	21	13	2	−5	277	283	291	297	0.8
Tuy Hòa	−78	−85	−94	−100	467	512	567	607	0.1
Phú An	−247	−256	−267	−275	147	150	155	158	0.1
Phú Quý	77	70	61	55	318	325	334	340	1.1
Chợ Lạch	−180	−186	−194	−200	180	185	192	197	0.2
Vàm Kênh	−248	−252	−258	−262	61	65	70	74	0.0
Vũng Tàu	−35	−43	−53	−60	434	439	446	451	-0.1
Rạch Giá	−62	−64	−67	−69	110	119	130	139	0.0
Năm Căn	−327	−360	−403	−435	143	148	154	159	0.1
Cà Mau	−59	−63	−69	−73	120	129	140	148	0.2
Phú Quốc	4	−1	−7	−12	169	175	184	191	0.5
Côn Đảo	16	8	−1	−8	415	423	434	441	1.2

Table 3 is an example of calculations performed for estimating distribution parameters and determining the design values discussed in [6]. The analogous analyzing procedure was carried out for all the stations with the observation period 27 to 46 years long (Table 2). For each station the design levels were computed by 9 estimating methods. Further, nine values were averaged and summarized in Table 5.

Now we compare the design levels of return period 20 years (columns 3 and 7 in Table 5) with tidal extremes (columns 4 and 5 in Table 4).

Keep in mind that the reference level of each tidal gauge in Table 4 differs from that in Table 5. With station Cửa Cấm, for example, if we substitute a zero of this station (217 cm) from the tide minimum 30 cm in Table 4, then the value of the tide minimum referenced to mean sea level will be −193 cm. Substitution 217 cm from the tide maximum 406 cm yields a tide maximum 189 cm. If we do the same with station Cửa Hội, the tide extremes referenced to mean sea level of this station will be -151 and 120 cm respectively.

From the comparison between the minimum design levels of 20-year return period and the tide minima for some stations follows that these design levels differ from tide minima lesser than about 60 cm. This difference is caused by the surge oscillations in the coastal zone and the analysis errors as when.

Surges also affect the maximum design levels in the same way. However, for the maximum design levels, their differences to the tide maxima are much larger at those stations which located in river mouths, such as Ba Lạt (189 cm), Hoàng Tân (122 cm) and Cửa Hội (110 cm). This is the work of floods.

This remark has an important methodological significance in the practice of calculations of lowest sea levels for the regions which lack of long observations. In this case the lowest sea level can be the tide minimum substituted by a surge correction, and the highest sea level - the tide maximum added by a surge correction and a maximal height of flood.

3.4. Results of trend analysis with yearly mean sea levels

The regression equation of mean sea level relative to time (years) is determined for each station in Table 2. From these equations follows the estimates of the rate of sea level rise (column 10 in Table 5). Obviously, the obtained here sea level trends have the different reliability, depending on the sample length and the precision of data collected.

As seen from Table 5, the rate of level rise is different from station to station, even by sign. The average for all stations is 0.6 mm/year (~1 mm/year).

4. Concluding remarks

Evaluating theoretical extreme heights of tide by the method of predicting 20-year series of hourly height and by the iteration method gives close to each other results.

Predicting tide in 20-year period takes great computer time, while the iteration method allows more rapid calculation. Therefore in practical investigation at the region where no gauges set up we should fulfill the measurement of hourly levels in some days to derive the harmonic constants of main tide constituents. Than with the Vladimirsky method or the Peresipkin iteration method applied, we can compute the tide theoretical extremes, which have a certain practical usefulness.

The differences between extreme levels in 20-year duration and the design levels of 20-year return period are not larger then the analysis errors in the case of restricted length of used samples.

The theoretical extremes of tide have the sense of extreme levels. If the surge correction is known, one should substitute this value from the minimum tide height to obtain a more reliable lowest sea level and add it to the maximum tide height to have a highest sea level. For estuary stations, the highest sea level must be corrected by the flood height.

The obtained design levels have the different reliability. However, for the stations with observation more than 30 years the design levels in Table 5 can be considered as satisfactory.

The rate of yearly changes of sea level along Vietnam coast due to global warming and other effects is evaluated to be about 1 mm per year.

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