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Statistical Approach to the Computation of an Influence of the Yangtze Dam on Gravity Fluctuations

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Abstract. Due to the realization of the Three Gorges Dam on the Yangtze River and its content of 40 billion tons of water many geodynamical consequences can still be observed. It is obvious that global geodynamical changes are noticeable at whole basin of the Yangtze river. Such changes can be observed by the GRACE (Gravity Recovery and Climate Experiment) gravimetric satellites (Ilk *et al.* 2005). The GRACE gravity field model data are available in the form of spherical harmonic expansion; by defining a specific filter, one can compute geoid variations at specific locations. As a reference, EGM2008 model was used, on its basis geoid variations were determined.
According to the results, geoid variations at the Yangtze river become more stable after filling the Dam.
In the article a statistical methods were used for the purpose of the evaluation of a differences EGM08-GRACE time series in the area of the Three Gorges Dam. In the article the authors want to present trend analysis and short-term forecasting with ARIMA model usage.

Keywords: ARIMA, geoid, GRACE, the Three Gorges Dam.

Conference topic: Technologies of Geodesy and Cadastre.

Introduction

Each Global and regional changes of gravity are caused by the Earth's mass variations. The mass variations occur due to processes in the interior of the Earth and on its surface, i.e. in a ~100 km thin fluid layer. The different mass variations have various characteristics in time. Considering a monthly resolution of the mass change, seasonal (annual and semi-annual periods) and secular variations can be captured. These are mainly contributed by surface mass variations, particularly due to mass redistribution processes of the atmosphere, oceans, ice and snow cover (cryosphere) and land hydrosphere. Among these processes the largest contribution is provided by the atmosphere, however it is removed by correcting by atmospheric models. The remaining signal is due to different forms of waters. The amplitude of such changes may reach the range of some centimetres per month, which can efficiently be determined with GRACE temporal gravity field models using the following formula:

$$\delta N(\varphi,\lambda,r) = R\sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\bar{C}_{l,m}\cos m\lambda + \bar{S}_{l,m}\sin m\lambda\right)\bar{P}_{l,m}(\sin\varphi). \quad (1)$$

In the formula, δN means geoid change computed with spherical harmonic coefficients ($\bar{C}_{l,m}(t)$ and $\bar{S}_{l,m}(t)$) of l degree and m order, $\bar{P}_{l,m}(t)$ is the Legendre polynomial (Chambers 2006).

Mass variations with the formula above are presented in meters of equivalent water thickness changes (EWT). The use of EWT is convenient for hydrologist and oceanographic users, since it describe the mass variation as the height of a water column over a unit area, so EWT [m] = mass [kg] / unit area [m^2] / density of water [kg/m^3]. Very similar to EWT, a geoid can be computed which is presented in the article.

Note, however, that GRACE has a limitation in spatial resolution, i.e. mass variations within some hundred kilometres cannot be separated, they are averaged. Furthermore, GRACE satellites are sensitive only for large mass redistributions over large distances. Finally, it should also be noted that GRACE cannot distinguish mass variations vertically.

Objections

The Three Gorges Dam (Sanxia Daba) in the upper Yangtze river now completed and filled with water. It is the largest hydropower in the world which helps to unravel many energetic problems of the region (Kite 2011). The disadvantage is that many habitants are lost and more than 1 million people must have left their homes. The decision of building the Three Gorges Dam project has been posed after severe repeated floods at the region in the year of 1949 in order to regulate the river. The constructing of the dam has been started in 1993, filling its reservoir lasted from

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2006 to 2010 (Ponseti, Lopez-Pujol 2006). The Three Gorges Dam type is a concrete gravity designed of 185 m height. Normal storage level of water is 175 m. Width of the dam is. 2,310 m. Projected total capacity is 39.3 billion m, where 22,1 billion m water can be stored. It is planned to further increase the dam's flood control capacity (Wang 2002). Such huge water mass shift is probably changing significantly the local gravity field, but may has less effect on global scales. It is, however, interesting to test whether the filling of the reservoir had a detectable impact as GRACE altitude.

Methodology

For the purpose of the research GRACE data was processed to gain monthly geoid values for the period 2003.08–2016.03. Each data set was computed using spherical harmonic coefficients up to degree and order 120 of the CSR RL05 release note (Forste *et al*. 2008). The data was computed in a grid with a resolution of 0,5 degree x 0,5 degree.

There is a known systematic error of the GRACE gravity field models, that they are strongly disturbed along the satellite's orbit (called stripes), so during the processing a destriping should be applied by using a special filter. Conceptually, by filtering the signal content should be untouched, and only the systematic errors should be get rid of (Tapley 2008).

To perform destriping process of spherical harmonic coefficients (normalized, up to degree and order 120), a filter should be applied on the GRACE gravity models. We decided to use very simple DDK5 filter (Klees *et al.* 2008).

Using EGM2008 model spherical harmonics, values of the geoid height were computed exactly at the same locations as from GRACE gravity field models. The idea of the paper was to evaluate differences between GRACE and EGM models using many statistical processes.

For the purpose of the statistical analysis of a gravity fluctuations, differences EGM08-GRACE observations were computed for the period 2002.08–2016.03. Differences between reference EGM08 model and observations from GRACE gravitational observations are close to zero. In the exact locations of the Three Gorges Dam mean differences are above 8 milimeters. Taking into account the adjacent areas of the Three Gorges Dam, mean differences between EGM08 and GRACE observations are about 2 milimeters, while the maximum differences are about 6 milimeters. Differences EGM08 and GRACE in August 2008 and December 2015 are presented in the Figure 1.

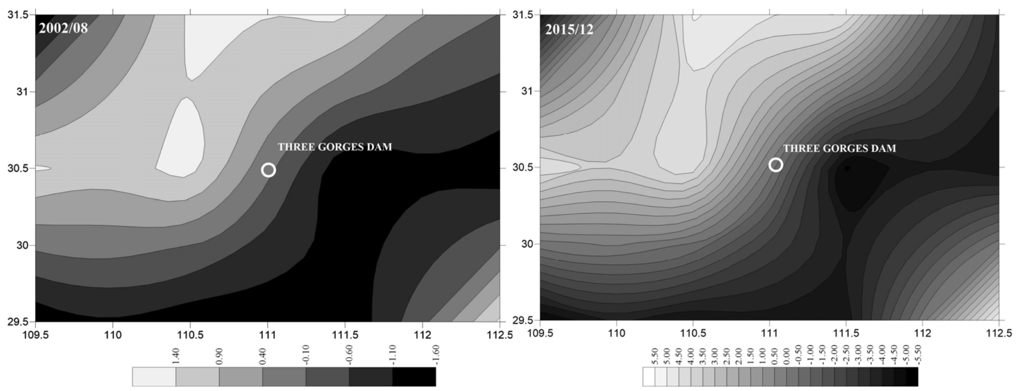

Fig. 1. Differences between EGM08 and GRACE observations.
In the figure adjacent areas presented; the exact location
of the Three Gorges Dam is distinguished

Statistical Approach

The statistical analysis of various mass phenomena need to be based on time series assessment. In such approach, time is the independent variable, thus, direct variable are the numerical values of the examined phenomenon. The aim of the described analysis is making phenomenon prognosis possible; moreover, it can bring an answer what is the reason of the phenomenon development. On the other hand, statistical analysis can let us make a simulation based on a phenomenon (Rzepecka *et al.* 2015).

Time series are the realization of some stochastic processes. Time series analysis let us understand the mechanism that initiate the phenomenon, so stochastic process. Time unit of the process impose time series analysis method.

The typical elements of the process generating a time series are:

– trend,
– periodical fluctuations,
– random fluctuations,
– interventions into a process (sudden changes caused by external influences).

Most of the statistical analysis takes into account that random fluctuations are generated by a normal distribution where an expected value is equal zero and with a stable variation. Prognosis is a following course of events concluding. It need to be based on a time data, or on a basis of a values describing random variables. Which prognosis method will be chosen, is defendant on time series components. If a time series included only systematical component (like equal level and random fluctuations-random noise), variable coefficient should be computed. If variable coefficient was no more than 0.05, than we should smooth the time series with a weighted moving average (WMA) or a naive method should be used. When only a trend is distinguished and is used for time series structures identification, many different methods are used, like Holt or Winters models. Moreover, time series with a trend can be approximated with a linear function. When time series are characterized with a seasonal fluctuations, indicators method can be used, or Fourier harmonics analysis and autocorrelation method. If all systematic elements are present in the time series, analysis is based on distinguishing mentioned elements from a time series. This is called a time series decomposition. The most effective forecasting method is the ARIMA model, which was tested in the paper.

Results

In the paper, we present a process of observing forecasting model, while using only past events models. The observed process was a differences between EGM08 and GRACE models, for a case study the Three Gorges Dam exactly, and for adjacent areas. The aim was to create a time series model which would describe in a detailed way past events. A well-built model can let us create accurate prognosis model. All tested data is real, measured month-by-month, for the period 2002.08–2016.03. The geoid heights from GRACE CSR RL05 DDK5 are presented in the Figure 2. An increasing trend can be observed, computed value is 0,19 millimeter per year.

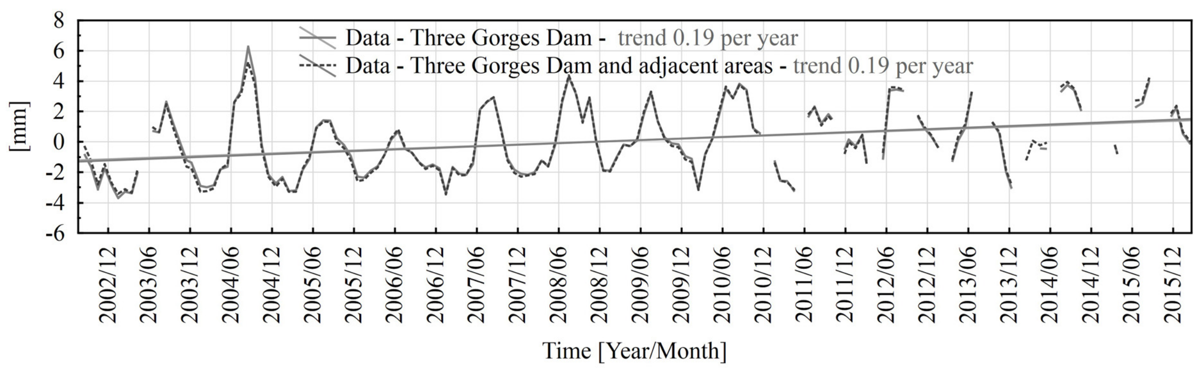

Fig. 2. Time series of a GRACE for the Three Gorges Dam and adjacent areas

A prognosis with the ARIMA method (p,d,q) were performed. ARIMA (Auto Regressive Integrated Moving Average) model consists of three elements: autoregressive process AR, moving average process MA, and integration level (Nau 2017). Parameters numerical values determination, connected with autocorrelation function p and moving average q, were essential for ARIMA model selection process. In addition, we introduced both, seasonal autoregressive elements of a P degree and seasonal moving average of a Q degree. Autoregressive process, consisting of linear combination of the past processes and its degree, is essential for defining how many past values has an influence on the current value. So, it can be said that a time series value is a sum of a random element and a linear combination of all past observations. It can be described by a formula (StatSoft):

$$x_t = \xi + \varphi_1 x_{(t-1)} + \varphi_2 x_{(t-2)} + \varphi_3 x_{(t-3)} + \ldots + \varepsilon \, , \qquad (2)$$

where: ξ – is an equal (free element); φ_1, φ_2, φ_3 – are the parameters of an autoregressive model.

Every observation consists of a random element and a linear combination of all past observations. Indirectly to the autoregressive process, each element of the time series can be influenced by a realization of a random element in the past. This influence can be described by a autoregressive element, see formula below:

$$x_t = \mu + \varepsilon_t - \theta_1 \varepsilon_{(t-1)} - \theta_2 \varepsilon_{(t-2)} - \theta_3 \varepsilon_{(t-3)} - \cdots , \qquad (3)$$

where: μ – is an equal; Θ_1, Θ_2, Θ_3 – are parameters of the moving average (StatSoft).

In the research, based on a time series evaluation we were able to conclude that the time series is heterogeneous, moreover, autocorrelation function let us assume that it is not stationary. The next step was to delete heterogeneity and achieving stationary state. For this purpose a differentiation was established, i.e. Value-by-value a seasonal delay value was subtracted. Stationary of the series was evaluated with autocorrelation and partial autocorrelation methods. This is presented in the Figure 3 and Figure 4.

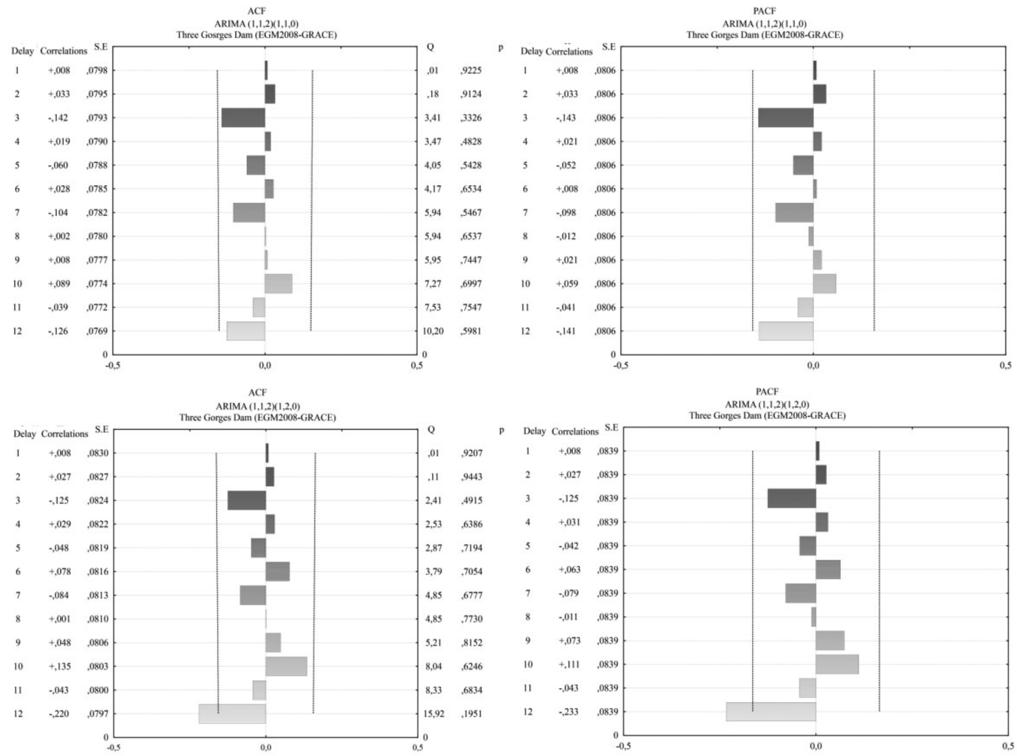

Fig. 3. Autocorrelation function and partial autocorrelation function
for the Three Gorges Dam

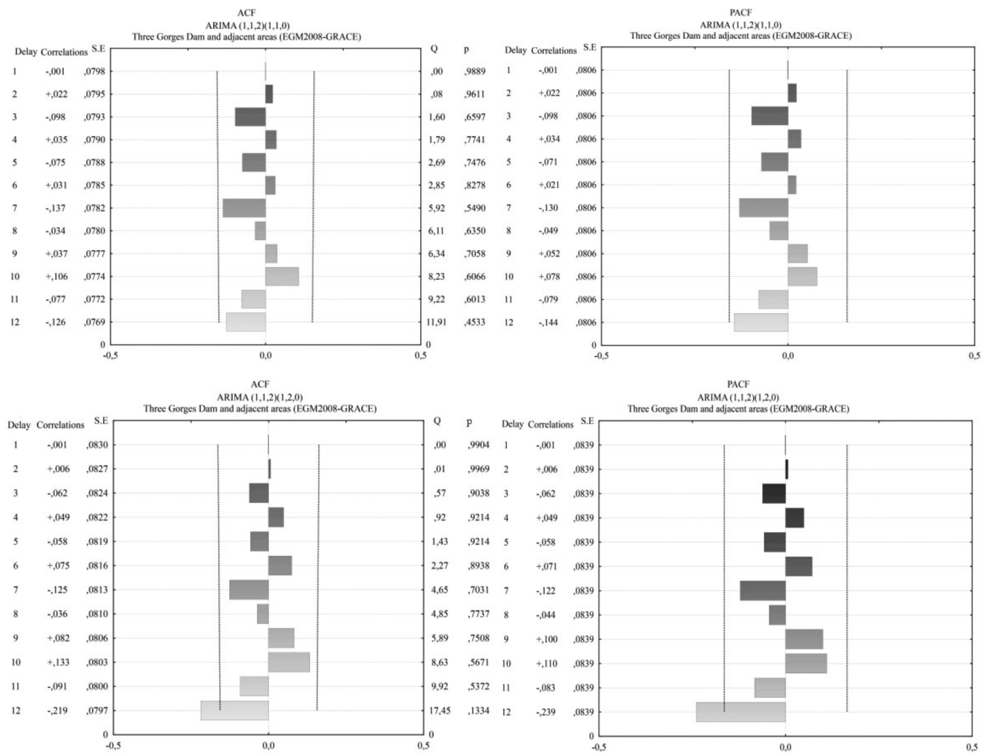

Fig. 4. Autocorrelation function and partial autocorrelation function
for the Three Gorges Dam and adjacent areas

After determining model's parameters, a forecasting was performed with the ARIMA model (1,1,2)(1,1,0) and ARIMA model(1,1,2)(1,2,0). Calculated standard errors and estimated parameters for the models are presented in the Table 1.

Table 1. Parameters of ARIMA, standard errors and trust values or the computation

	ARIMA (1,1,2)(1,1,0) [mm]				ARIMA (1,1,2)(1,2,0) [mm]			
	Para-meters	Evaluation parameters	Standard error	Trust value	Para-meters	Evaluation parameters	Standard error	Trust value
Three Gorges Dam (EGM2008-GRACE)	P(1)	0.56	0.09	0.000	P(1)	0.57	0.12	0.000
	q(1)	0.73	0.10	0.000	q(1)	0.68	0.12	0.000
	q(2)	0.22	0.09	0.016	q(2)	0.21	0.09	0.022
	Ps(1)	–0.36	0.08	0.001	Ps(1)	–0.56	0.07	0.000
Three Gorges Dam and adja-cent areas (EGM2008-GRACE)	P(1)	0.57	0.10	0.000	P(1)	0.55	0.13	0.001
	q(1)	0.76	0.11	0.000	q(1)	0.71	0.14	0.000
	q(2)	0.17	0.09	0.007	q(2)	0.17	0.10	0.084
	Ps(1)	–0.39	0.08	0.000	Ps(1)	–0.58	0.07	0.000

In the Table 1 moving average parameters estimation are presented. These is standard errors delay. Mentioned parameters are statistically important, as the significance value was <0.05 in the both cases. The forecast created on a base of the two mentioned models, which is presented in a Figure 5 and Figure 6. Prognosis is presented in the dashed lines.

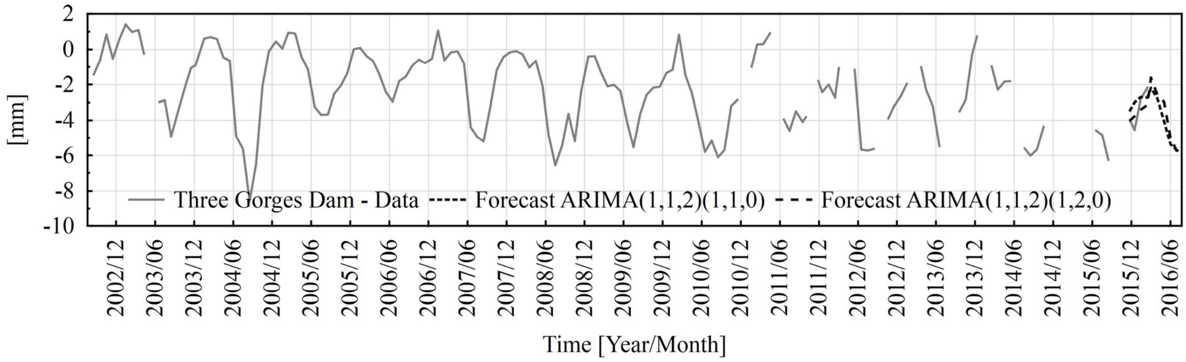

Fig. 5. Time series with the ARIMA model (1,1,2)(1,1,0) and ARIMA model (1,1,2)(1,2,0) with a prediction for a following four months in the exact Three Gorges Dam location

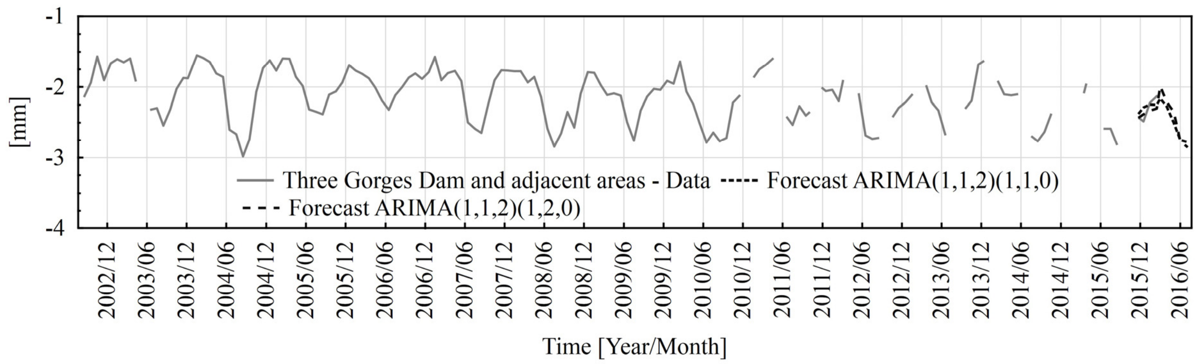

Fig. 6. Time series with the ARIMA model (1,1,2)(1,1,0) and ARIMA model (1,1,2)(1,2,0) with a prediction for a following four months in the adjacent areas of the Three Gorges Dam

When starting a research, four newest months were left for the purpose of further possibility of self-check. The self-control is presented in a Table 2 and Table 3.

Table 2. Comparison between real data (EGM08-GRACE) and computed with the ARIMA method in the location of the Three Gorges Dam

Three Gorges Dam (EGM2008-GRACE) [mm]							
Epoch	Data	ARIMA (1,1,2)(1,1,0)	differences	Epoch	Data	ARIMA (1,1,2)(1,2,0)	differences
12-2015	–3.93	–3.50	–0.43	12-2015	–3.93	–4.04	0.11
01-2016	–4.54	–2.98	–1.55	01-2016	–4.54	–3.76	–0.78
02-2016	–2.81	–2.70	–0.11	02-2016	–2.81	–3.40	0.59
03-2016	–2.17	–2.74	0.57	03-2016	–2.17	–3.12	0.95

Table 3. Comparison between real data (EGM08-GRACE) and computed with the ARIMA method in the location of the adjacent areas of the Three Gorges Dam

Three Gorges Dam and adjacent areas(EGM2008-GRACE) [mm]							
Epoch	Data	ARIMA (1,1,2)(1,1,0)	differences	Epoch	Data	ARIMA (1,1,2)(1,2,0)	differences
12-2015	–2.43	–2.38	–0.05	12-2015	–2.43	–2.43	0.00
01-2016	–2.48	–2.29	–0.19	01-2016	–2.48	–2.38	–0.10
02-2016	–2.22	–2.25	0.03	02-2016	–2.22	–2.33	0.11
03-2016	–2.13	–2.25	0.12	03-2016	–2.13	–2.30	0.17

Conclusions

In the research a gravity fluctuations in a form of a differences between reference EGM08 model and observations from GRACE gravitational observations are presented. It was computed that mentioned differences arenn close to zero. In the location of the Three Gorges Dam the mean values are about 2 millimeters, the maximum values are 8 millimeters. In the adjacent areas of the Three Gorges Dam the mean values are about 2 millimeters, the maximum values are 6 millimeters.

A practical use of the ARIMA model was presented in the research. In the first step, identification of a number and type of the parameters was performed. Used tools were: time series graphs, autocorrelation correlograms (ACF), and partial autocorrelation (PACF). ARIMA models with a one autoregressive parameter (p) were used: ACF – falls exponentially; PACF – maximum gained at a delay 1, no correlation for the rest delays, and with two moving average parameters (q): ACF – huge values at 1 and 2 delays, no correlation for the rest delays, PACF – sine curve or a combination of exponential signs. Besides of a non-seasonal parameters, seasonal parameters need to be estimated for the calculated delay; so seasonal autoregressive (ps), seasonal differential (ds), and seasonal moving average (qs). We were able to construct ARIMA model (1,1,2)(1,1,0) of one autoregressive parameter, two non-seasonal moving average parameters and one seasonal autoregressive parameter. All the parameters were estimated for the time series after one differentiation with a delay equal 1 and one seasonal differentiation. By the second ARIMA model (1,1,2)(1,2,0) we could describe one autoregressive model, two non-seasonal moving average parameters, and one seasonal autoregressive parameter. All the parameters were estimated for the time series after one differentiation with a delay equal 1 and one seasonal differentiation.

The models were analysed, for all parameters assessment a standard error (e. g. see Table 1) were estimated, based on a matrix consisting of a derivatives and partial derivatives of a seasonal order. The matrix is approximated with a finished differentiation. Also, the second method of an accuracy and reliability evaluation – the forecasting was compared with the real values (e. g. see Table 2 and Table 3). When comparing real values and those computed with the ARIMA models, differences were less than 1 millimeter in the location of the Three Gorges Dam, and 0,19 millimeters in the adjacent areas of the Three Gorges Dam.

Based on a rest values autocorrelation, we could conclude that the rest values are not correlated and have a normal distribution.

On a basis of all described analyses, a time series forecasting in the area of the Three Gorges Dam was performed. The final result was presented in a Figure 5 and Figure 6.

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