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1. Maps of the topography of water surface levels in the Danube Delta, between the main branches

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Abstract: Within the project "Hydrological Monitoring of Wetland Areas Using SAR Techniques (Hydro-SAR)", concluded by the TERRASIGNA (Romania) with the European Space Agency (ESA), the task of GeoEcoMar was to track and check the correlation of data provided by InSAR techniques with ground observations and measurements in the Danube Delta. Activities in the field and laboratory enabled elaboration of maps of vector fields for the water flow directions on the Danube Delta territory, based on the relief of the water surface levels at 450, 400, 350, 300, 250, 200, 150, 100, 50 and 0 cm, measured at Tulcea hydrologic station. In order to elaborate the maps of water surface levels, the altimetric stability of hydrometric gauges from the Danube Delta territorry was checked by establishing the Earth crust subsidence in each gauge location. Interpretation of recorded data shows a relative low subsidence rate for the location of the hydrometric gauge in Tulcea (observations recorded for the period 1858-2013) selected as hydrometric reference point, with the origin of the zero of the gauge situated at 0.57 m altitude relative to the Black Sea – Sulina reference system. The paper presents isoline maps of the water surface levels on the surface of the Danube Delta between the main distributaries (Chilia – Sulina – Sf. Gheorghe), for the above mentioned water surface levels.

Key words: InSAR techniques, water surface level, hydrometric gauge, empirical function

1. Assessing the stability of altimetry of the Earths's crust for locations of the level gauges in the Danube Delta

Geological and geophysical studies revealed that the Danube Delta is a continuously subsiding area (Panin, 1998; Polonic et al, 1999; Giosan et al., 2006), with subsidence values of 1,5 – 5 mm/year. InSAR technologies revealed that the subsidence is not uniform, the Danube Delta showing subsiding, stable or uplifting areas (Oaie et al., 2010). In the Danube Delta area, another method used for asessing the process of subsidence of the Earth's crust considers the water levels of hydrometric level gauges (Fig. 1), using measurements of the Danube level on the Delta territorry. The measurements have been compared and correlated to the levels measured at the Tulcea hydrometric gauge.

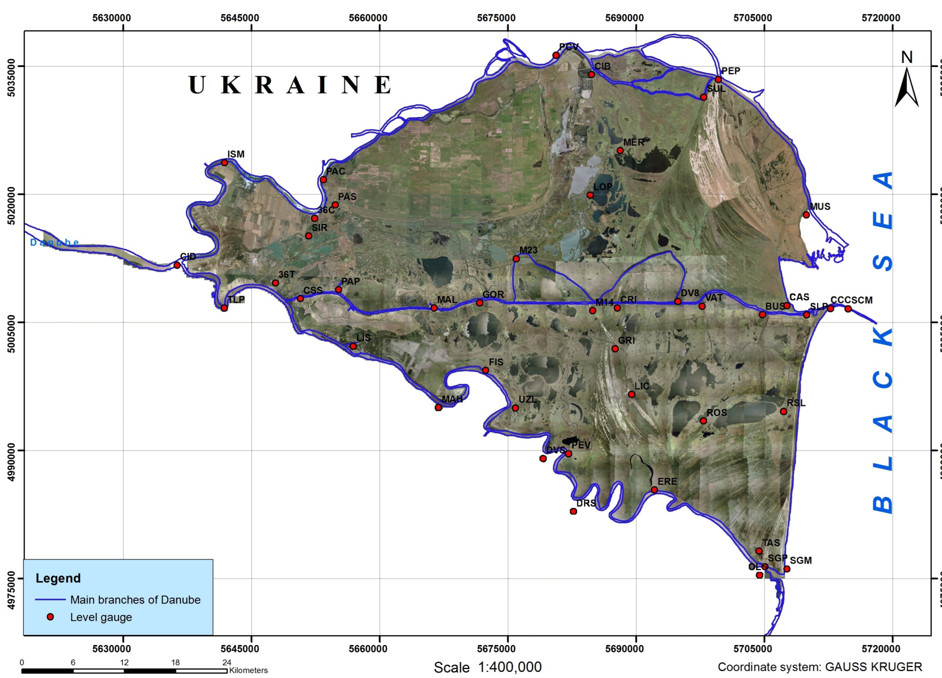

Fig.1. Location of level gauges on the Danube Delta territory

If compared with the measurements from 1858, when the level measurements in the Danube Delta were initiated, the subsidence movements of the Earth's crust have impacted the levels of the origin of hydrometric level gauges.

Subsidence calculations, performed for 7 locations of hydrometric gauges, located along the Tulcea and Sulina distributaries, have shown negative values of around 2 cm at Gorgova locality and of about 42 cm at Sulina – Black Sea location (Fig. 1).

Using the methodology proposed by Berendeim (1959) and benefiting from the numerous level data measured on the Danube Delta distributaries, at Tulcea and Sulina, it was possible to calculate the subsidence based on the correlation between variations of the mean annual discharges of the Danube from one year to another (∆Qmea), measured at the entry point in the Danube Delta, and variations of the mean annual levels (∆Hmea) at the level gauges Ceatal Ismail, Tulcea harbour, Ceatal Sf. Gheorghe, Gorgova, Crişan, Sulina harbour and Sulina – Black Sea, for the period 1858-2012.

Using a wide hydrologic database (Bondar, Iordache, 2012), from mean annual discharges to mean annual levels, two empyrical functions were determined in each location endowed with a level gauge:

- The trend function

$$Qmea(t) = a * t + b \quad (1)$$

- The correlation function between annual mean variations (∆Qmea) of the discharges and variations of annual mean levels (∆Hmea)

$$\Delta Hmea = m * \Delta Qmea + n \quad (2)$$

where Qmea represents the mean annual discharge, t – time (in years), ∆Qmea – variation of the mean annual water discharge and ∆Hmea – the variation of the mean annual level.

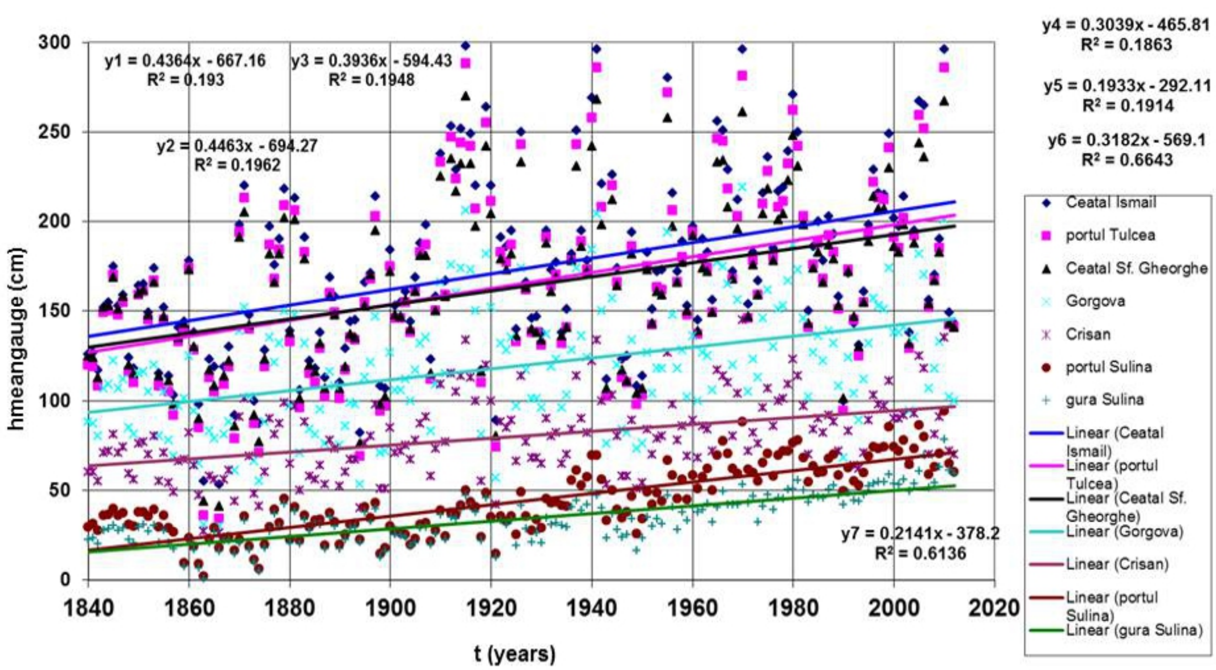

Fig. 2. Trends of the variation in time of annual mean levels of the Dube at Ceatal Ismail (1), Tulcea harbour (2), Ceatal Sfântu Gheorghe (3), Gorgova (4), Crişan (5), Sulina harbour (6) and Sulina – Black Sea (7).

Figures 2 and 3 show the graphs of the two empirical functions with the numerical values of parameters a, b, m, n for the 7 mentioned level gauges.

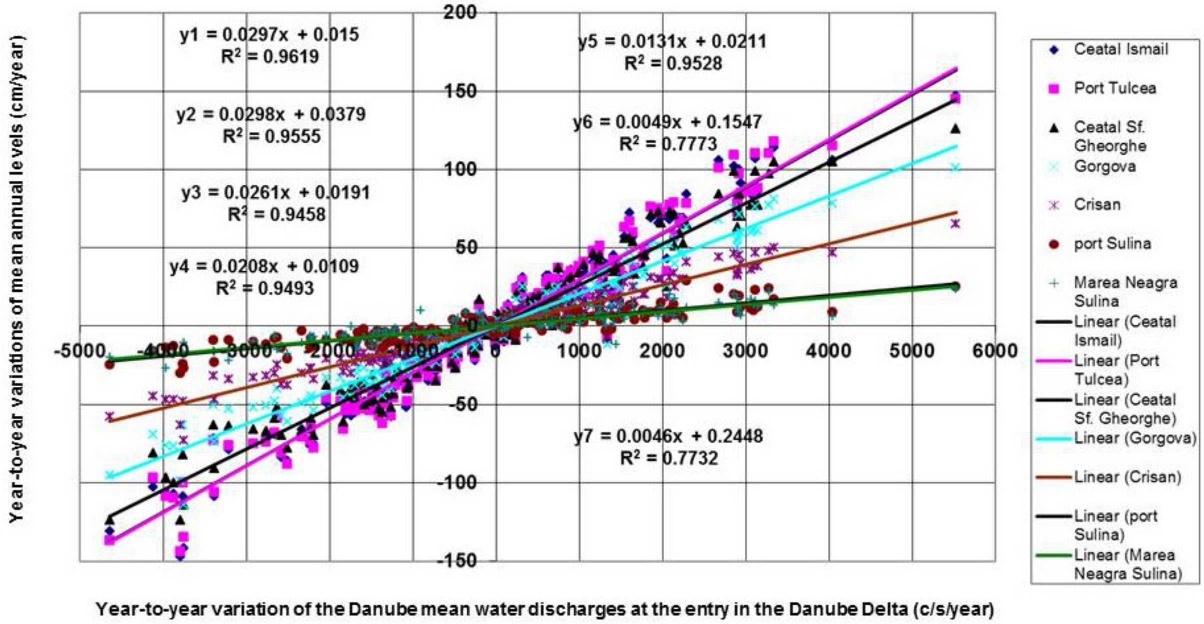

Fig. 3. Corelations between variations of mean annual discharges of the Danube at the entry in the Danube Delta and variations of mean annual levels at level gauges located along the Tulcea and Sulina distributaries.

Table 1 shows numeric values of the parameters (a), (b) and of the correlation coefficients from the empiric function (1), for 7 level gauges.

Tabel 1. Variation of the empirical function parameters (1)

Level gauge	Parameters of the empirical function		
	(a)	(b)	Correlation coefficients
Ceatal Ismail	0.436	- 667.2	0.193
Tulcea harbour	0.446	- 694.3	0.196
Ceatal Sf. Gheorghe	0.394	- 594.4	0.195
Gorgova	0.304	- 465.8	0.186
Crişan	0.193	- 292.1	0.191
Sulina harbour	0.297	- 526.7	0.660
Sulina – Black Sea	0.235	- 419.1	0.680

The following conclusions can be drawn from the correlation of Fig. 2, the values (a) and (b) and the empirical function (1):

- At hydrometric posts along the Tulcea and Sulina distributaries, the mean annual level of the Danube shows increasing variation trends in time;
- Rates of variation in time of the level trends decrease in downstream direction, from 0.446 cm/year to 0.235 cm/year;
- Graphs overlap in case of close level gauges (ex.Ceatal Ismail – Tulcea, Sulina harbour – Sulina – Black Sea).

Table 2 presents the numeric values of parameters (m), (n) and of the correlation coefficients of the empirical function (2), for the seven hydrometric stations mentioned in Table 1.

Table 2. Numerical values of parameters (m), (n) and of the correlation coefficients of the empirical function (2)

Level gauge	Parameters of empirical function (2)		
	(m)	(n)	Correlation coefficients
Ceatal Ismail	0.0297	0.015	0.962
Tulcea harbour	0.0298	0.0379	0.955
Ceatal Sf. Gheorghe	0.0261	0.0191	0.946
Gorgova	0.0208	0.0109	0.949
Crişan	0.0131	0.0211	0.953
Sulina harbour	0.0049	0.1547	0.777
Sulina – Black Sea	0.0046	0.2448	0.773

Table 2 shows that the empirical function (2) is characterized by correlation coefficients larger than 0.77.

Specifications:

- Parameter (a), indicates the rate of annual global increase of the mean level influenced by both Danube water discharges and subsidence;
- Parameter (b), indicates the year when the mean annual water level becomes zero;
- Parameter (m) is a scale coefficient, indicating the variation of the mean water level reported to unit variation of the mean annual water discharge;
- Parameter (n), indicates the annual increase of the mean level, when the variation of the mean annual water level is zero.

Examining figures (2) and (3), as well as the parameters in Table 2, the following conclusions can be drawn:

- Parameter (n) shows that the mean annual level can vary when the variation of the mean annual discharge is zero. In case of positive values of the mean annual level, the level increase (growth) can occur under the influence of subsidence;

- Calculations have demonstrated that the values of parameter (n) are positive in all locations of the level gauges, which indicates an active subsidence of the crust exists along the Tulcea and Sulina distributaries. The phenomenon can be extrapolated to the entire Danube Delta territory, depending on the variation of the mean annual levels.

Unfortunately, the mean annual levels for the rest of the level gauges within the Danube Delta could not be processed yet, in order to quantify the trends and year-to-year variations, depending on the variations of the mean annual water discharges of the Danube. In order to have a general view upon the subsidence phenomenon, additional data recorded in the past are required.

Situation of the levels of origin of the level gauges in the Danube Delta area

Considering the relative low subsidence affecting the location of Tulcea level gauge, this was chosen as "hydrometric reference point" (information recorded for a period of 173 years). Therefore, in order to assess the origin of level gauges on the Danube Deta territory, this level gauge with the origin level of + 56 cm was used.

Assessment of the water surface levels required correlation of the monthly mean levels of the Danube at Tulcea with the monthly mean levels at hydrometric sites in the Danube Delta. The correlation was represented as second-degree empirical functions (3).

$$Z = a. H^2 + b. H + c \qquad (3)$$

where Z represents the absolute level (Black Sea – Sulina) at the hydrometric sites in the Danube Delta, H the relative Danube level at Tulcea and a, b, c, the parameters of the empirical function (3).

Table 3 shows the numerical values of the parameters of the empirical function (3).

Table 3. Numerical values of the parameters of the empirical function (3)

No.	Observation point	Code	Gauss-Kruger coordinates		Parameters		
			x (km)	y (km)	a	b	c
			Chilia Distributary				
1	Ceatal Ismail, Mile 43	cid	5637	5012	-0.0002	1.081	60
2	Ismail Harbour, Chilia Distributary, km 95	Ism	5643	5024	0.0004	0.718	52
3	Pardina, Chilia Distributary, km 78	Pac	5654	5022	0.0001	0.695	44
4	Chilia Veche bridge, km 47	Pcv	5679	5033	0.0003	0.378	33
5	Periprava, Chilia Distributary, km 22	Pep	5702	5034	-0.00007	0.268	24
6	Black Sea – Sulina	Scm	5716	5007	-0.000079	0.11	31.6
			Area between Distributaries Chilia, Tucea and Sulina				
7	Magearu Canal, Letea	mag	5699	5019	0.00007	0.014	52
8	Matiţa hydrographic area	Lop	5685	5020	0.0003	0.341	46
9	Mila 23, Dunarea Veche	m23	5677	5013	0.0005	0.31	52
10	Black Sea – Sulina	Scm	5716	5007	-0.000079	0.11	31.6
			Tulcea and Sulina Distributaries				
11	Ceatal Ismail, Mile 43	cid	5637	5012	-0.0002	1.081	60
12	Tulcea, Tulcea Distributary, Mile 38.6	Tlp	5642	5007	0	1	56
13	Ceatal Sf. Gheorghe, Sulina Distributary, Mile 33.6	Css	5650	5008	-0.00003	0.934	55
14	Gorgova, Sulina Distributary, Mile 22	Gor	5672	5008	0.00007	0.668	38
15	Crişan, Sulina Distrbutary, Mile 12.3	Cri	5678	5007	0.00003	0.429	26
16	Sulina, Mile 0	Slp	5711	5006	0.000069	0.149	36.6
17	Black Sea –Sulina	Scm	5716	5007	-0.000079	0.11	31.6
			Area between Sulina and Sf. Gheorghe Distributaries				
18	Caraorman beach-ridge, at junction with Litcov canal	Gri	5688	5002	0.00002	0.431	24
19	Roşuleţ Fishery, lake Roşuleţ	Rsl	5708	4996	0.0003	0.069	19
20	Roşu holiday village, Litcov canal	Ros	5697	4994	0.0002	0.195	20
21	Caraorman Fishery, Litcov canal	lic	5698	4994	0.0001	0.325	23
22	Black Sea – Sulina	Scm	571	5007	-0.000079	0.11	31.6
			Sf. Gheorghe Distributary				
23	Ceatal Sf. Gheorghe, Sulina Distributary, Mile 33.6	Css	5650	5008	-0.00003	0.934	55
24	Mahmudia, Sf. Gheorghe Distributary, km 87	mah	5666	4996	0.00007	0.72	49
25	Uzlina Canal, Sf. Gheorghe Distributary, km 68	uzl	5675	4995	0.00009	0.629	46
26	Dunavăţ Canal, Sf. Gheorghe Distributary, km 54	dvs	5680	4990	0.000044	0.514	42
27	Dranov Canal, Sf. Gheorghe Distributary, km 44	drs	5683	4984	-0.0003	0.597	33
28	Sf. Gheorghe, km 2	sgp	5706	4977	-0.0001	0.147	26.5
29	Black Sea –Sulina	Scm	5716	5007	-0.000079	0.11	31.6

Processing and interpreting the information served to elaborate 10 maps of the vector fields for water flow directions on the Danube Delta territory, based on the water level surface at levels 450, 400, 350, 300, 250, 200, 150, 100, 50 and 0 cm, measured at the Tulcea hydrologic station (Figs. 4 – 13).

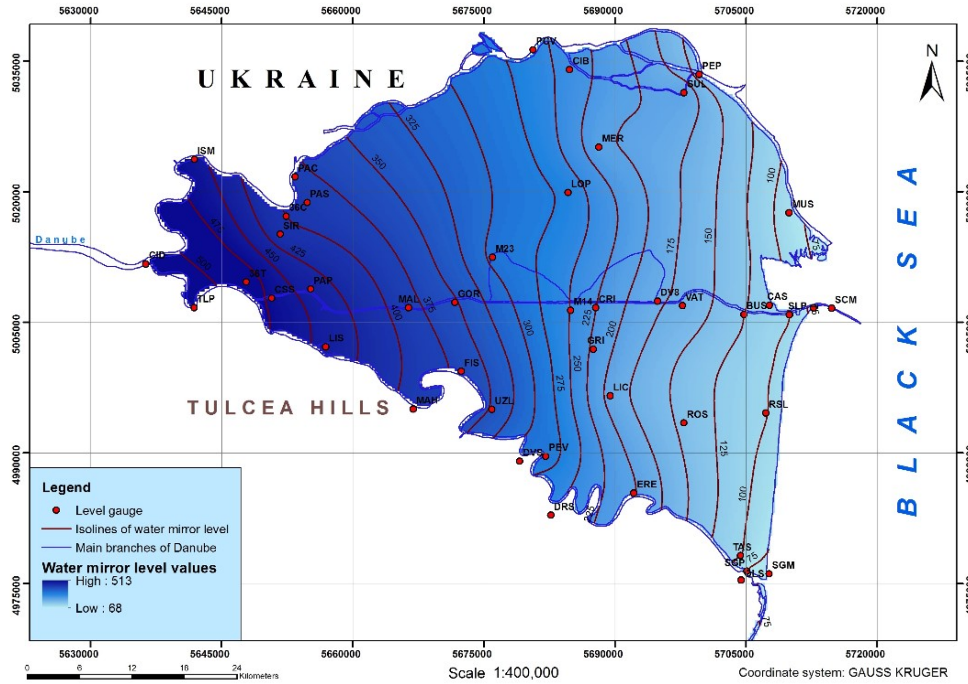

Fig. 4. The relief of water surface levels in the Danube Delta in relation to the reference system Black Sea – Sulina, for a level of Danube at Tulcea of 450 cm.

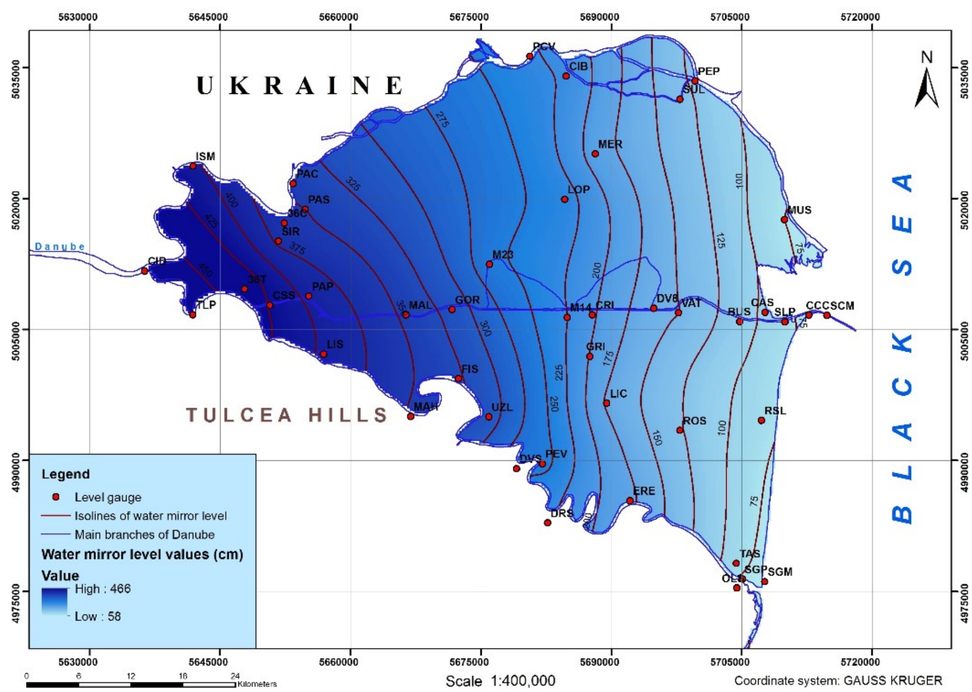

Fig. 5. The relief of water surface levels in the Danube Delta in relation to the reference system Black Sea - Sulina for a level of Danube at Tulcea of 400 cm.

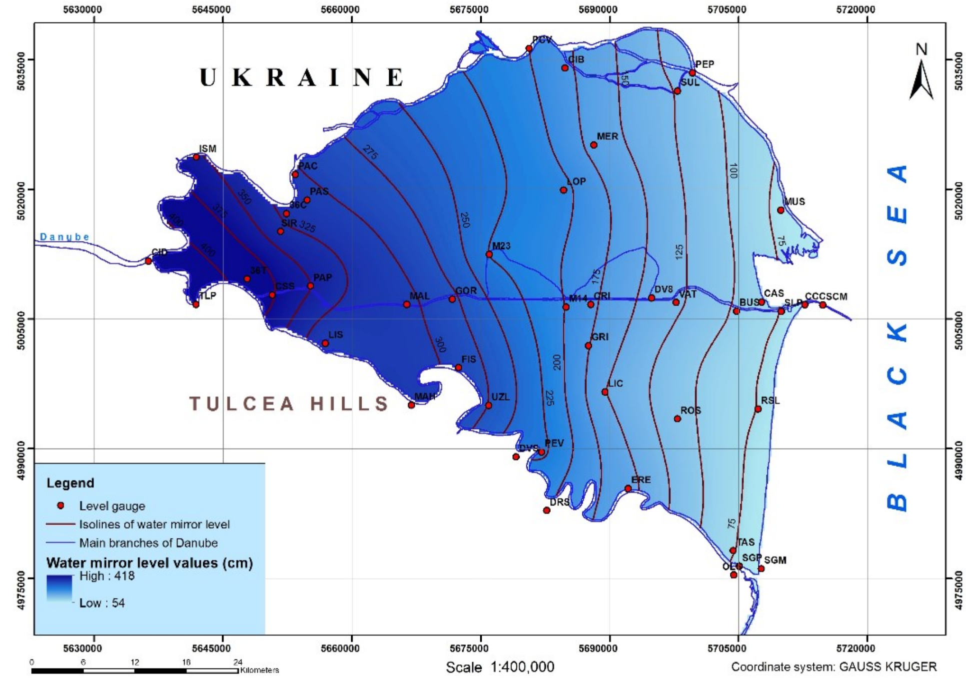

Fig. 6. The relief of water surface levels in the Danube Delta in relation to the reference system Black Sea - Sulina for Danube level at Tulcea of 350 cm

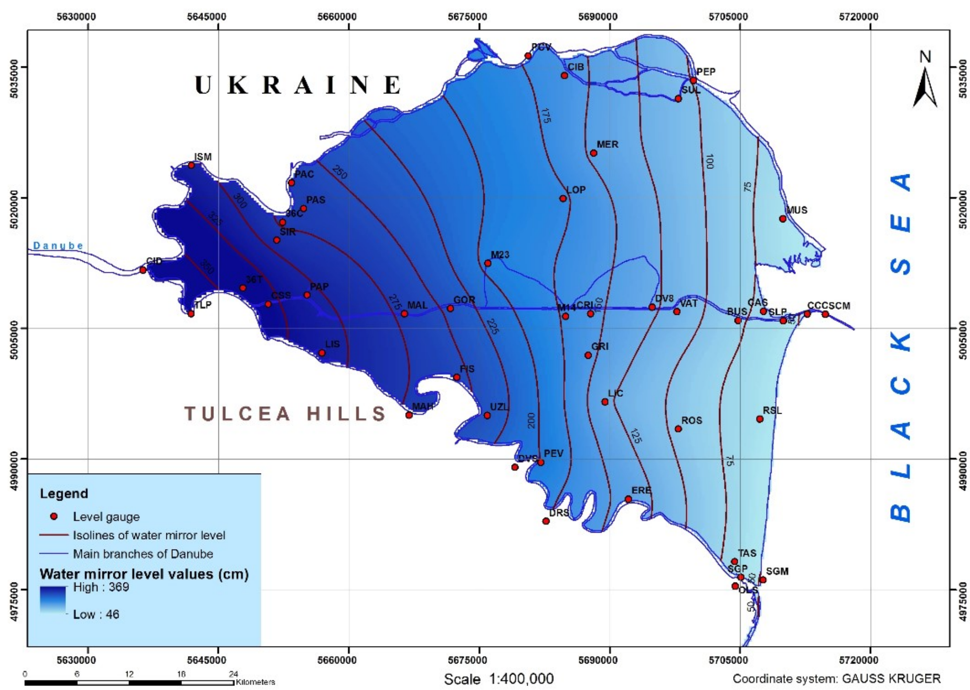

Fig. 7. The relief of water surface levels in the Danube Delta in relation to the reference system Black Sea - Sulina for Danube level at Tulcea of 300 cm

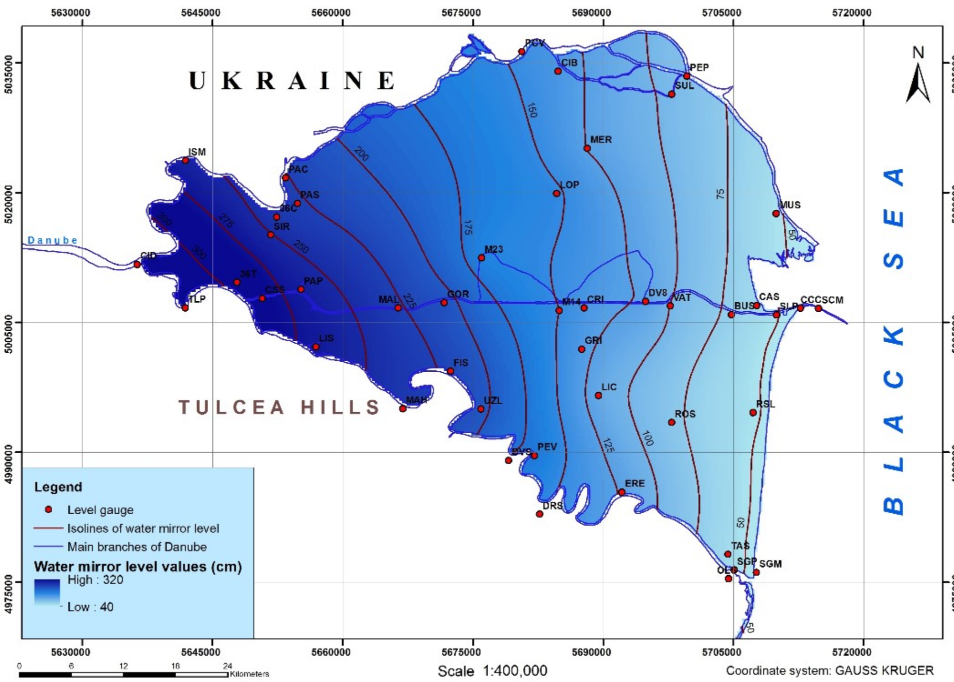

Fig. 8. The relief of the water surface levels in Danube Delta in relation to the reference system Black Sea - Sulina for Danube level at Tulcea of 250 cm.

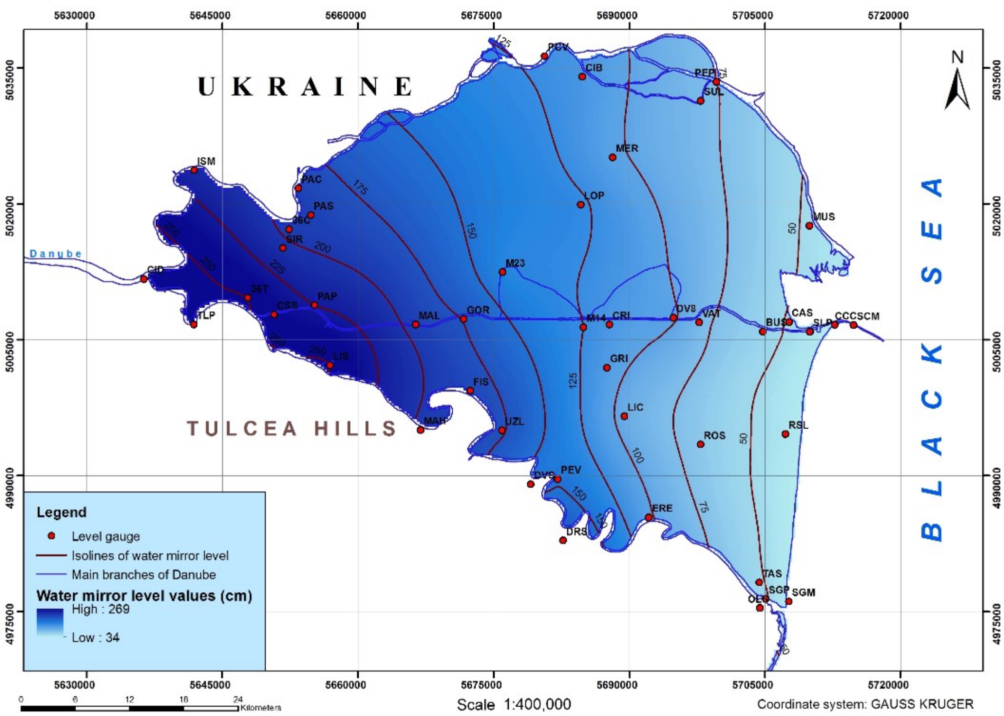

Fig. 9. The relief of the surface of water in Danube Delta in relation to the reference system Black Sea - Sulina for Danube level at Tulcea of 200 cm.

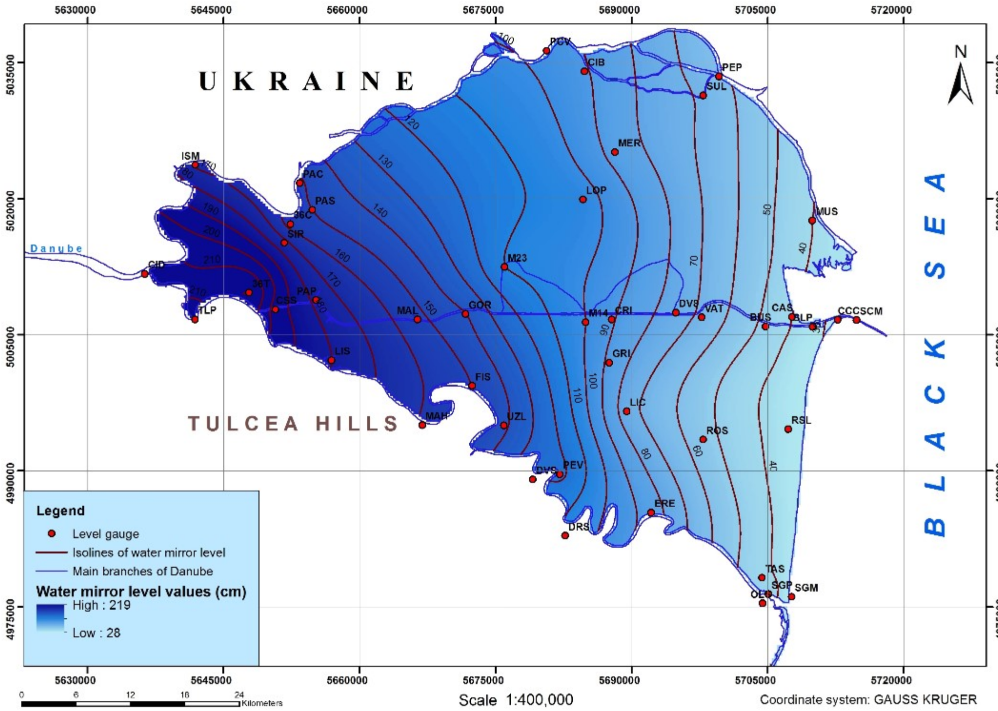

Fig. 10. The relief of the surface of water in Danube Delta in relation to the reference system Black Sea - Sulina for Danube level at Tulcea of 150 cm

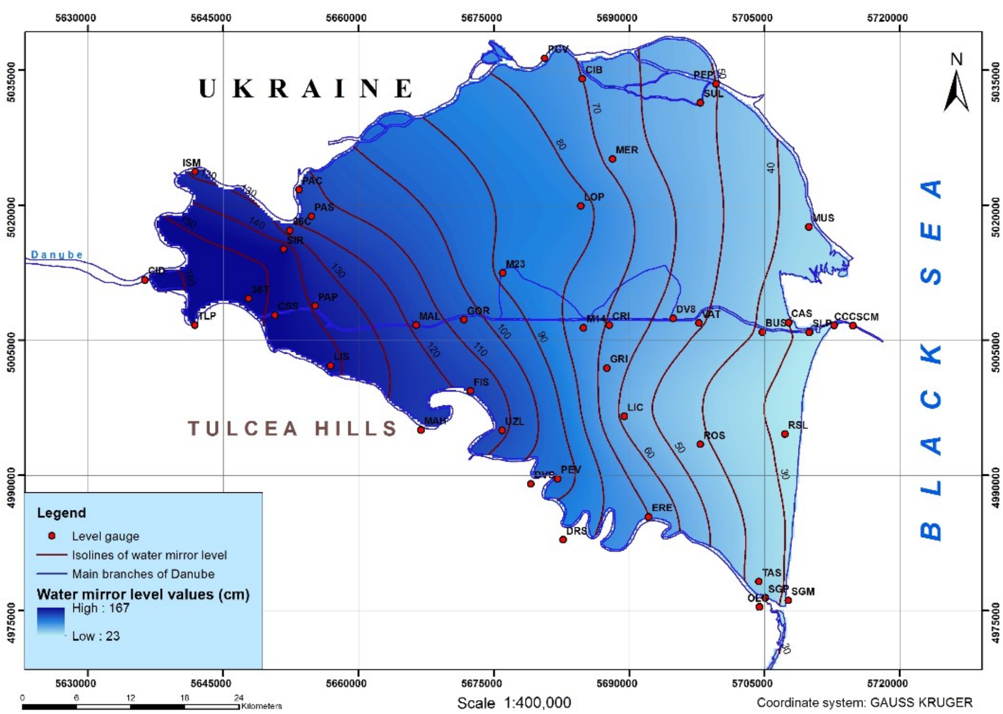

Fig. 11. The relief of the surface of water in Danube Delta in relation to the reference system Black Sea - Sulina for Danube level at Tulcea of 100 cm

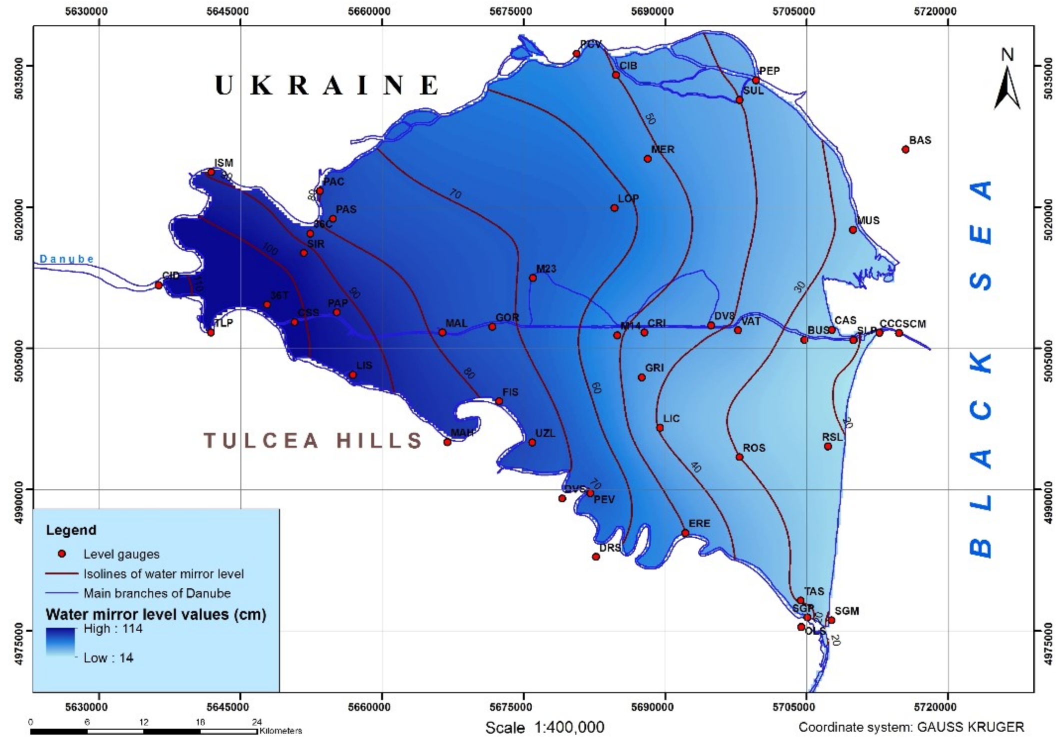

Fig. 12. The relief of the water surface level in Danube Delta in relation to the reference system Black Sea - Sulina for Danube level at Tulcea of 50 cm

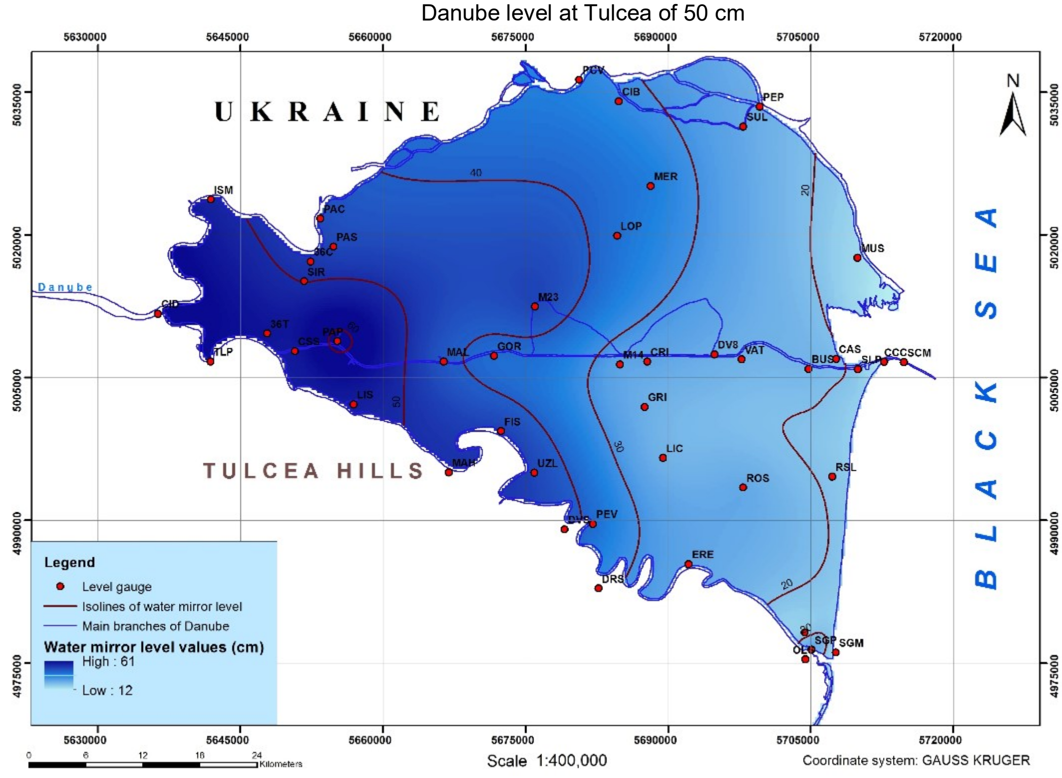

Fig. 13. Map showing the topography of the water surface level in the Danube Delta in relation to the Black Sea – Sulina reference system for the Danube level at Tulcea of 0 cm.

CONCLUSIONS

Long term observations of levels in the Danube Delta (the time span of 1858-2013) revealed that the Earth's crust suffered a slow process of subsidence, the point with the highest stability being the hydrometric gauge in the Tulcea harbor. The calculations show that the subsidence is minimum in Tulcea area and maximum in Sulina area, decreasing from upstream to downstream.

The absolute levels of water surface levels uniformly decrease downstream, while the gradients of variation in absolute levels reveal the water drainage directions within the Danube Delta.

Previous informations and interpretations of results represented a necessary tool to validate monitoring-type services, based on InSAR technology (Poncos at al, 2011a, 2011b, 2013) and applicable to wetlands, in this case tested and applied to the Danube Delta. InSAR technologies enable to obtain maps of wetland extension, water flow directions, predictive models, etc. All these products obtained through spatial techniques may be improved through hydrologic observations and measurements carried out on the ground.

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