BRIEF HISTORY OF THE HEIGHT REFERENCE SYSTEMS USED ALONG THE ROMANIAN SECTOR OF THE DANUBE RIVER

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Abstract: *Both geodetic engineers and specialists in the fields such as Hydrology, Hydrotechnics or Geography have faced countless times the problem of using multiple height reference systems on the territory of our country. Over the years, several "zero" points or fundamental points have been used in Romania: "zero" Black Sea Sulina, "zero" Adriatic Sea or "zero" Baltic Sea (most often used). Regarding the Romanian sector of the Danube River, all bathymetric navigation maps use Sulina as a fundamental "zero" point. Unfortunately, the (absolute) heights of the gauges "zero" installed along the Danube River differ from each other depending on the reference surface from which these heights are measured. For this reason, the water level determinations cannot be performed in the same height reference system. In practice, the transformations between different vertical datums used along the river are still a real challenge. This paper supports those who want to understand the history of using the main height reference systems on the Romanian sector of the Danube River and, moreover, represents a review of the relationships between them. Although they were determined long ago, some of them have been transposed into the GIS format to facilitate the height transformations.*

Keywords: *datum, height reference system, fundamental "zero" point, Danube River*

1. Introduction

As a skyscraper needs a stable foundation in order to be raised, the datum is the basis for reporting all geodetic measurements, as well as for creating maps.

In general, the datum is defined as any numerical or geometric quantity (in the sense of a size) or a set of such quantities that serve as a reference or basis for other quantities/sizes [1].

Datums are used in many fields of activity. When we refer to the field of Geodesy, we are talking about **geodetic datum**. Throughout history, hundreds of datums have been used in Geodesy and these have evolved from considering the Earth to be flat or a sphere, to ellipsoidal models obtained using modern satellite technology. A datum is a reference surface or set of reference points used to perform position determination measurements and often a model associated with the shape and size of the Earth (such as the reference ellipsoid), in order to establish a geodetic coordinate system.

The usage of geodetic datum is vital in all activities that use spatial data because it defines the size, shape, orientation and position of the ellipsoid relative to the Earth's center of mass. With the help of the geodetic datum, considered to be a set of conventions or a set of error-free parameters, the spatial relations between the coordinate systems and the Earth are established. The datum represents the physical realization of a coordinate system. Without datum we would know neither the origin of a coordinate system, used for mapping the Earth's surface, nor the orientation of its axes in relation to the Earth.

A specific point on the Earth can have substantially different coordinates, depending on the datum used, because each datum is characterized by its own coordinates, its own orientation and its own undulations of the geoid.

The main reasons why the coordinates of the same point may differ significantly in two different datums are the following:

- different shapes of the ellipsoids used;
- the geometric centers of the ellipsoids are displaced from each other;
- the axes of the coordinate systems used are not parallel or there may be a difference in scale.

Referencing geodetic coordinates to a wrong datum can lead to position errors of hundreds or hundreds of thousands of meters (figure 1).

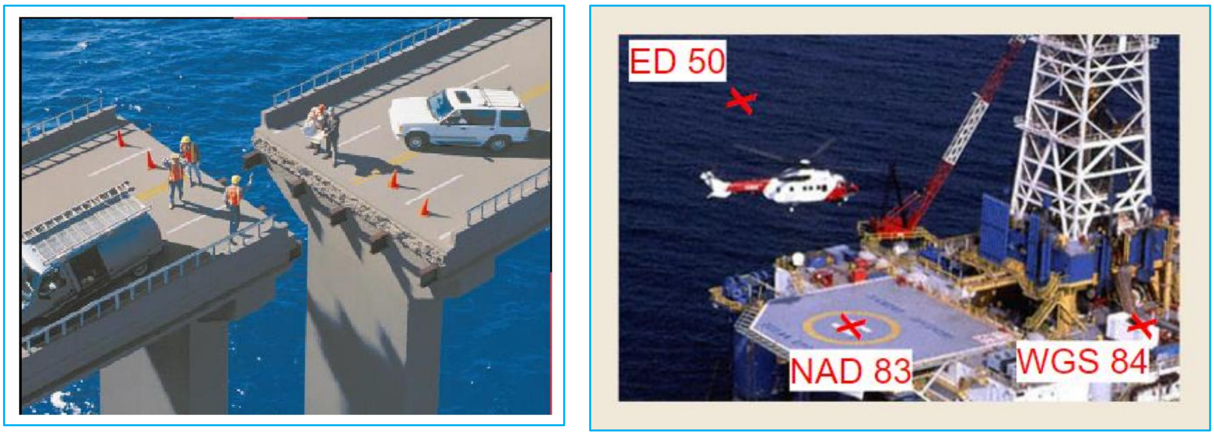

Figure 1. Examples of referencing geodetic coordinates to a wrong datum [2]

2. Definition of a height reference system

As a rule, at least one datum has been defined for each country on the globe, as actually each country has adopted at least one projection system, as well as a vertical datum.

The U.S. National Geodetic Survey (NGS) defines vertical datum as "a surface of zero elevation to which heights of various points are referred in order that those heights be in a consistent system. More broadly, a vertical datum is the entire system of the zero elevation surface and methods of determining heights relative to that surface" [3].

Currently, more than 300 regional vertical datums are used in the world. Most of them are based on the long term mean value of the local mean sea level observed at one or more primary tide gauge stations (mareographs) [4].

The height determined with respect to a tide gauge station is known as the orthometric height (height above the geoid). According to the classical Gauss–Listing definition, the geoid is the equipotential surface of the Earth's gravity field (the surface where the gravity potential has a constant value) that in a least squares sense best fits the undisturbed mean sea level [5] and represents a physical idealization of the irregular shape of the Earth.

One of the main goals of Geodesy has been the determination of a geoid model that accurately links the ellipsoidal height, the undulation of the geoid and the orthometric height. The actual determination of global geoids has been carried out by using gravimetric data, satellite- derived information related to the gravitational field of the earth, or a combination of the two techniques [6].

Over the past decades, every country or group of countries have established those mean sea level points which are normally located close to the area of concern: for the Netherlands and Germany, the local mean sea level is realized through the Amsterdam tide gauge (zero height), for Greece - Thessaloniki, Antwerp for Belgium, in England, the Ordnance Datum was determined at Newlyn from records extending from May 1915 to April 1921, in France the local mean sea level was determined at Marseille tide gauge, etc. [7].

These realizations of local mean sea levels (also called local vertical datums) are parallel to the Geoid but offset by up to a couple of meters. This offset is due to local phenomena such as ocean currents, tides, coastal winds, water temperature and salinity at the location of the tide gauge.

Due to variations in the Earth's gravitational field, the tide gauge (zero height) of the Netherlands differs -2.34 meters from the tide gauge (zero height) of the neighbouring country Belgium. Even within a country, heights may differ depending on to which tide gauge, mean sea level point, they are related. For example, the mean sea level from the Atlantic to the Pacific coast of the USA increases by 0.6 to 0.7 m.

The need to determine height reference systems arose in the second half of the eighteenth century, when hydrographic surveyors began to develop detailed bathymetric maps of the seafloor and topographic maps with contour lines.

A height reference system is defined in several steps:

- choosing a reference surface;
- adopting a definition in the physical or geometric sense describing the position of the points on the earth's surface relative to the chosen reference surface;
- specifying a fundamental “zero” point considered to be the mean level of the open seas and oceans, obtained through long term observations and to which all leveling works that use the respective datum refer.

Due to the fact that the sea level undergoes permanent changes, the datum has a temporary validity.

3. Height Reference Systems used along the Romanian sector of the Danube River

Currently, in our country, the reference system used to determine the altitudes is called the system of normal heights - Black Sea 1975 fundamental “zero” point (1990 Edition), located in Constanța.

Over the years, several fundamental “zero” points have been used in Romania: “zero” Black Sea Sulina, “zero” Adriatic Sea or “zero” Baltic Sea (most often used). The connection between these reference surfaces has always been a challenge for both surveyors and specialists in the fields such as Hydrology, Hydrotechnics or Geography. In the Romanian sector of the Danube River, the bathymetric navigation maps use the Black Sea as a reference system, with fundamental “zero” point Sulina. Similarly, all the staff gauges on the maritime Danube (between Sulina and Brăila) were also referenced to this surface.

For the referencing of the contour lines in topographic maps, three reference systems have been adopted: the Adriatic Sea, the Baltic Sea and the Black Sea. In the hydrographic system of the Black Sea there are several reference surfaces: Sulina, Constanța, Varna, Odessa, Sevastopol, Kerci, Poti, Batumi, etc.

In the last 150 years, using the staff gauges, it has been possible to gather an important fund of reliable data on the water level regime of the Danube River, the Danube Delta and the Black Sea.

On the territory of our country, the first level measurements on the Danube River were performed by Austria in Orșova, in 1838, by means of a staff gauge whose "zero" elevation was referred to the surface of the Adriatic Sea ("zero" Trieste). The second staff gauge was installed in Drencova, in 1854, having its "zero" elevation also referred to the Adriatic Sea [8].

For as accurate information as possible regarding the staff gauges installed along the Danube River, journals of gauge stations or activity plans prepared by NIHWM (National Institute of Hydrology and Water Management) specialists, as well as national publications were consulted. In the end, it was deduced that the origin of the "zero" of the gauges placed along the Romanian sector of the Danube is related both to the "zero" Black Sea Sulina and to the "zero" Baltic Sea Kronstadt and partially to the "zero" Adriatic Sea Trieste (staff gauges from Baziaş, Moldova Veche, Drencova, Svinița, Orşova and Turnu Severin) [9]. Therefore, the determinations of the water levels cannot be obtained in the same height reference system.

It should be noted that, through a project whose beneficiary is AFDJ Galați ("Set up of a support system for hydrographical works on the Danube in order to ensure minimal navigation depths - BORD"), a network of geodetic points was created along the Romanian sector of the Danube River. The project comprises 144 locations, situated at less than 15 km from each other), for which the altitudes in the national system were determined with the possibility to make the transformation in the European Vertical Reference System (implementation EVRF2007), but also in the Bulgarian National Vertical Reference System (Baltic Sea 1982 - normal heights system) [10]. This support network, called AFDJ2014, is the basis for the correct redetermination of the "zero" height of the staff gauges, thus making it possible to determine as accurately as possible the (absolute) height of the free surface of the water.

Currently, the monitoring of the hydrological parameters on the Romanian sector of the Danube river is performed at the gauges stations on the main course of the river and the branches and channels of the Danube Delta. The monitoring network includes 97 gauges stations (with annual studies), 25 satellite gauges stations (with hydrometric studies every 5 years) and around 150 additional cross-sections for the analysis of hydromorphological changes of the Danube riverbed, performed once every 5 years [11].

3.1. The connection between the Black Sea "Sulina" and Black Sea "Constanța" height reference systems

In 1856, the European Commission of the Danube was founded, having the purpose of setting a fairway through the mouths of the Danube. At that point, there was no reference surface for the depths on the hydrographic maps of the Black Sea to be related to .

In December 1856, the CED installed three staff gauges graded with English measurements units (feet and inches): two at the mouth of the Danube River into the Black Sea, Sulina and Sfântu Gheorghe, and the third in Tulcea. In order to determine the "zero" level at Sulina, the measurements of water levels that were used were carried out through August 1857 until December 1858. This way, the mean sea level in the mentioned interval was determined as the reference surface.

All level measurements used to establish the Black Sea Sulina reference surface were recorded under low flow regime.

The fundamental "zero" point Black Sea Sulina was fixed at the base of the central lighthouse, located at an height of 4.88 feet (1.4874 m) and positioned behind the entrance to the lighthouse's base. It was materialized by sticking a concrete landmark to the circumference of the headlight's base, having a metal mark at its end [12].

In the port of Sulina, regular level observations started in 1858, using a staff gauge located at about 1.4 km from the mouth of the sea. The three daily sea level readings, recorded since 1859, contributed to the leveling works along the Danube.

The staff gauges installed between Sulina and Brăila, on the route of the maritime Danube, were graded with English measurements units, while at Turnu Severin, Calafat, Bechet, Turnu Măgurele, Zimnicea, Giurgiu, Olteniţa and Calăraşi, for the first time, staff gauges graded with centimeters were installed. The installation of staff gauges was later extended to the ports of Moldova Nouă and Sviniţa in 1893, to Gruia in 1898, to Cetate and Bistreţ in 1899, to Cernavodă in 1896, to Hârşova in 1898 and to Isaccea in 1895. The origins of the staff gauges were placed vertically at the average of the lowest levels of the Danube, observed for a period of at least 10 years.

In 1904, all the staff gauges installed on the Danube upstream of Brăila were re-leveled by the Romanian Hydraulic Service, by relating their origin to the Black Sea reference surface with fundamental "zero" point Sulina.

Wishing to establish a height reference system for maritime and geodetic hydrographic tasks, the Military Geographical Institute installed in 1895 a Lallemand-type tide gauge in Constanţa, near the Genovese Lighthouse, to measure the multiannual level of the Black Sea. The installation of this tide gauge helped the Romanian Navy to elaborate, between 1898 and 1901, the first hydrographic map referenced in geographical coordinates of the Romanian coast, at a scale of 1:20000.

Between 1895 and 1916, the level of the Black Sea was continuously monitored, until the destruction of the tide gauge in 1916, during the First World War, by the occupiers. Based on the records from 1896-1903, the mean level of the Black Sea was calculated and was used to establish the leveling line Constanta - Bucharest. At the same time, a height of 64,4517 m was transmitted near the gate of the Metropolitan Church of Bucharest.

In 1919, the Hydraulic Service within the Administration of Ports and Water Communications (PCA) installed staff gauges on the Chilia arm of the Danube Delta, but also in the ports of Ismail, Chilia Nouă and Valcov.

In 1932, the Directorate of Maritime Ports (DPM) installed in Constanţa a German tide gauge of OTT type, between berths 10 and 11 in the port, which still operates in the niche of the pool "boatmen" near the maritime rail station. This made it possible to continuously record changes in the sea level. In the same year, a fundamental landmark (type I DTM - Military Topographic Directorate) was placed in the courtyard of the Military Chapel in Constanţa, which still exists and which was considered to be the fundamental "zero" point for the national leveling network until 1982.

In the period 1934-1935, the Directorate of the Hydraulic Service elaborated the map of the Danube River at a scale of 1/50000, including Chilia and Sf. Gheorghe arms from the Danube Delta. The bathymetry was related to the Black Sea Sulina height reference system, without planimetric referencing.

It is very important to mention that, between 1933-1935, the hydrographic survey of the Black Sea coast between Cape Midia and Cape Tuzla was carried out by the Maritime Ports Directorate (DPM), elaborating bathymetric maps at 1/10000 scale related to the Black Sea Constanţa height reference system, also without planimetric referencing.

With the help of the tide gauge observations from 1933-1975, IGFCOT Bucharest conducted a study on the variation of the Black Sea level, which highlighted a sinking movement of the tide gauge, in fact of a bronze plate embedded in the platform of the respective quay, near the tide gauge. Following this finding, IGFCOT (Institute of Geodesy, Photogrammetry, Cadastre and Territorial Organization of Bucharest) installed two other tide gauges, during 1974 and 1975, one in the Genoese Lighthouse area and another in the port of

Mangalia. It should be noted that the bronze plate had inscribed its altitude of 2.48 m compared to "zero tide gauge", i.e. compared to mean sea level accepted or assumed at the time of installation of the tide gauge.

The difference between the "zeros" of the staff gauges from Sulina and the "zero" tide gauge from Constanţa could be determined in two ways, namely by geometric leveling and by comparing the heights of the high waters regime.

Initially, this height difference was determined by geometric leveling in the ports of Cernavodă and Tulcea. Between 1955 and 1957, the Civil Navigation Directorate found, through determinations made in the port of Cernavodă, that Constanţa reference surface is 22 cm higher than Sulina reference surface.

In 1959 and 1961, the State Water Committee carried out new inspections in the port of Tulcea. The closure error resulting from the two measurements were of 18.8 cm, respectively 21.9 cm, Constanţa reference surface being again higher than Sulina.

The second way of checking and ascertaining the difference between the "zero" elevations was made by comparing the high water levels, in the period 1957-1961, at the tide gauge from Constanţa and at the staff gauges from Sulina. The measurements were performed in calm weather on the same days and by correlating monthly average levels. Also, in this case it turned out that Constanţa reference surface is higher than Sulina, but by 22.4 cm. Simultaneously, the difference between the Black Sea Constanţa and the Black Sea Odessa was determined, Constanţa being 42.5 cm lower.

3.1. The connection between the Black Sea "Constanţa" and the Baltic Sea "Kronstadt" height reference systems

A big step in the standardization of topo-geodetic works in Romania was the adoption, in the period 1954-1974, of the Baltic Sea Height System (with Kronstadt tide gauge), as a vertical datum for the national leveling networks.

Between 1963-1972, the Land Improvement Directorate of the State Water Committee (CSA) realised a highly accurate geodetic reference network on the left bank of the Danube River. The heights of this network were related to the Baltic Sea reference surface.

At the same time, DTM executed the second order leveling on the left bank along the Romanian sector of the river, referencing the "zero" elevations of the staff gauges also to the Baltic Sea Height System (Kronstadt). For the common Romanian-Bulgarian border sector, the Romanian geodetic engineers (ISPIF) together with the Bulgarian specialists determined the height difference between the Baltic Sea "Kronstadt" and the Black Sea "Sulina" as equal to -0.628 m (+/- 5 cm), the Sulina height reference system being placed below the Baltic Sea "Kronstadt".

Based on the records of the tide gauge from 1933-1975, DTM and IGFCOT determined a new conventional "zero" level for the Black Sea, in the 1975 era, in order to adjust the leveling network. Compared to the "zero" elevation of the tide gauge, the result was an increase in sea level by +0.139 m, so that the altitude of the bronze plate was set this time at 2,341 m.

The fundamental "zero" point was considered the benchmark fundamental point of the Military Chapel of Constanța (type I – DTM). Its altitude was determined by means of geometric leveling works repeated in 1962, 1963, 1964, 1970, 1972, but also using gravimetric measurements [13].

Theoretically, the reference level is considered invariable. Basically, however, there is a variation in sea and ocean levels caused by phenomena such as global warming, tectonic plate movement or seasonal variations caused by the influence of the planet's position on the Sun and Moon and even diurnal variations produced by tides (ebb and flow).

Fortunately, for the elimination of diurnal and even seasonal variations, statistical methods have been identified that provide an average value of sea or ocean level, respectively an average reference level. However, the rest of the variations need to be monitored and studied in their relativity.

In Romania, geological studies and determinations have shown a sinking of the coastal plate of 2 mm annually, which can be interpreted by an increase in the "zero" reference level of the Black Sea in relation with the littoral coast. In reality, the phenomenon is much more complex, because the tectonic plate has continuity on the seabed.

In order to better highlight the variation of the reference level and for a greater stability in time of the fundamental point, the absolute height was transferred from the seashore to approximately 53 km N-NW of Constanţa, between the Dobrogean localities Tariverde and Cogealac, in an area with green shales (stable tectonic zone). Thus, the "fundamental point of the leveling network" was built, and its connection with the Black Sea tide gauges was made through a network of high-precision geometric leveling polygons, which also connects with the tide gauges of Varna and Burgas in Bulgaria. .

The National Center for Geodesy, Cartography, Photogrammetry and Remote Sensing performed new measurements in the national leveling network and, obviously, a new processing of the network. As the measurements were more accurate than those obtained by DTM, the network was called a **zero-order network**. Also, this network contains a larger number of polygons than the first order network made by DTM. As the height system remained the same (Normal system of heights with fundamental "zero" point Black Sea 1975), but the heights were also recalculated for the landmarks of the leveling networks of order II, III and IV, this is officially called **"1990 Edition"**.

Through the TransDatRo software, there is the possibility to transform the heights from the national reference system (system of normal heights - Black Sea 1975 fundamental "zero" point, 1990 edition, located in Constanța) into the European Vertical Reference System (EVRS).

The leveling networks sustained by fundamental points that have the height determined by different tide gauges located either on the coast of different seas or on the coast of the same sea or ocean, but at sufficiently large distances between them, define different reference surfaces.

The transformation parameters between two reference surfaces are determined by the intersection of the leveling networks based on different reference surfaces, resulting in different variations between them, depending on the spatial position of the intersection.

In the field, the intersection of two leveling networks materializes through common leveling landmarks, for which the height in both reference systems is known. In theory, these differences should be equal, which is not the case due to differently adjusted measurement errors when processing the two networks.

For both the leveling network calculated against the Baltic Sea reference surface and the leveling network calculated against the Black Sea reference surface, these variations were calculated for each trapezoid at a scale of 1:25000 and are available at the National Geodetic Fund. The variations are considered "artificial" because they result artificially from interpolation calculations. Moreover, they are arbitrarily considered zonal fixed, due to the fact that the errors resulting from the modelling on the surface represented at the scale of 1:25000 do not propagate significantly.

The map in which we find the values of the variations between the two height reference systems, called "Height transformation coefficients/triangulation transformation points from the Baltic Sea to the Black Sea 1975" (source Military Topographic Directorate), was georeferenced within NIHWM, using the function " Georeferencing" from the ArcMap 10.6 software.

In a polygon shapefile, 2898 trapezoids were created, representing the grid at a scale of 1:25000. They were populated with the values of the corrections, according to the original map, resulting in a shapefile containing values of height transformation from the "Baltic Sea" reference system to the "Black Sea 1975" reference system (figure no. 2).

Of the 2898 values, 2825 are on the territory of our country. The values vary from 0 to 0.403 m and there are lower values in the north, northwest and higher in the southwest and in the Dobrogea area.

Their transposition into the GIS format facilitates the transformation of different data from the "Baltic Sea" heights system into the "Black Sea 1975" height system, by making the trapezoid easier to locate and adding the appropriate correction.

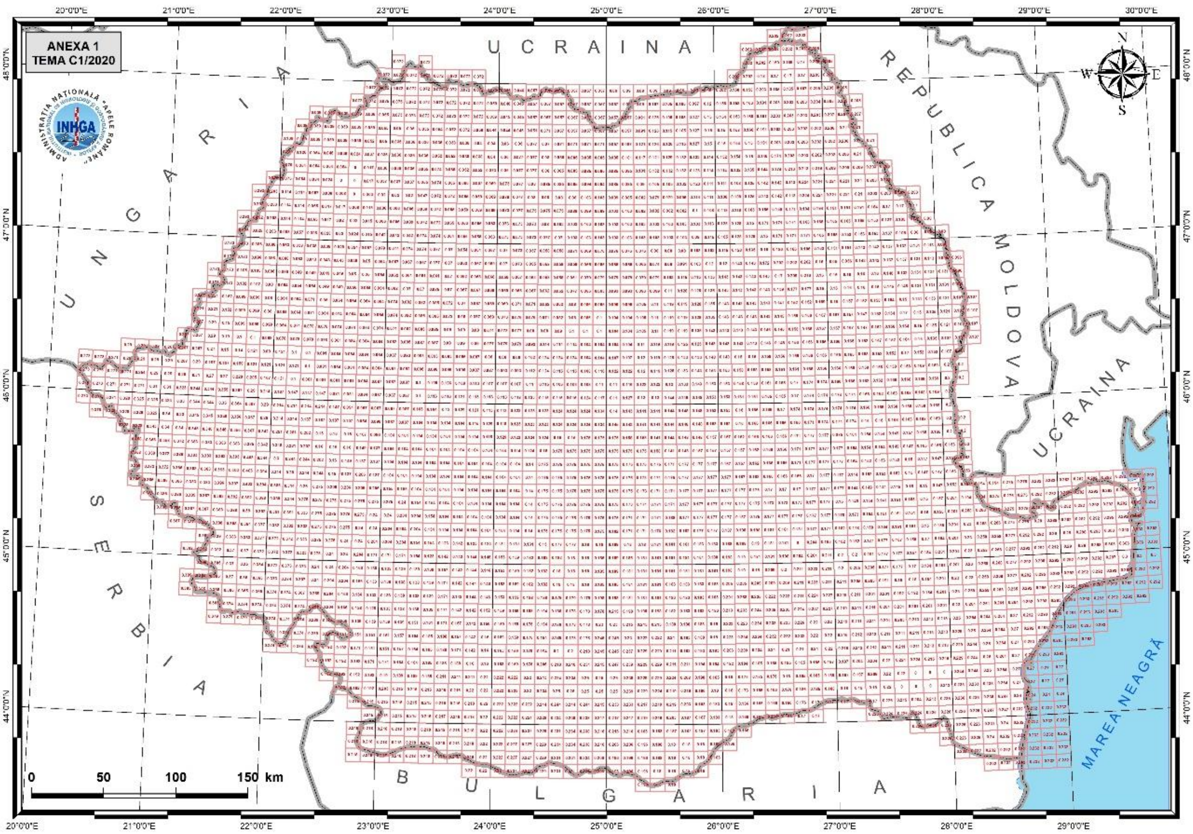

Figure 2. Height transformation coefficients/ triangulation transformation points from the Baltic Sea to the Black Sea 1975 (adapted from DTM)

4. Conclusions

Regardless of the height reference systems used in the past, for the improvement and extension of waterways, as well as for monitoring the dynamics of the Danube riverbed, it was and is necessary to interconnect the topo-hydrographic measurements in a unitary geodetic system, respecting current European and international standards: ETRS89 for horizontal and EVRS/EVRF2007 for vertical.

It is also recommended to establish a common coordinate reference system (CRS) for all gauge stations that monitor the Danube River level, including determining again the height of the gauges "zero" on the banks of the river in the new CRS.

Regarding the tide gauges currently used on the globe, one of the issue is the influence of changes in the terrain on which they are mounted. These errors can be eliminated by performing GNSS observations.

Water level data obtained at different times, using country-specific metrological standards and methods of analysis, have led to a lack of homogeneity that does not provide an overview of relative and absolute sea level changes.

Currently, GNSS observations performed at tide gauges stations help to separate relative sea level variations from the vertical movements of the Earth's crust. From water level data can be extracted separately both the vertical movements of the crust, but also the absolute variation of the level in relation to the geocenter.

In the future, the implementation of this method would be beneficial for our country as well.

Globally, between 1993-2018, sea level rose on average by 3.2 mm a year, while in 2013-2018, there was an average increase of 4.8 mm a year [14].

Over the next decade, the identical Copernicus Sentinel-6A and then Sentinel-6B satellites aim to measure sea surface topography with high accuracy and reliability to support ocean forecasting systems, environmental monitoring and climate monitoring [15], continuing the Franco-American Topex-Poseidon and Jason missions. Each satellite will be equipped with a radar altimeter that will bounce signals off the ocean surface. Sea surface height will be determined based on the time it takes each pulse to travel from the satellite to the ocean and back again [16]. The Copernicus Sentinel 6 mission (2020) is the result of cooperation between ESA, NASA, NOAA and Eumetsat [17].

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