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Methodology of Mosaicking and Georeferencing for Multi-Sheet Early Maps with Irregular Cuts Using the Example of the Topographic Chart of the Kingdom of Poland

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Abstract: The Topographic Chart of the Kingdom of Poland (pol. Topograficzna Karta Królestwa Polskiego, commonly referred to as 'the Quartermaster's Map', hereinafter: TKKP) is the first Polish modern topographic map of Poland (1:126,000, 1843). Cartographic historians acclaim its conception by the General Quartermaster of the Polish Army, noting its editorial principles and technical execution as exemplars of the early 19th-century cartographic standards. Today, it stands as a national heritage relic, furnishing invaluable insights into the former Polish Kingdom's topography. Although extensively utilised in geographical and historical inquiries, the TKKP has yet to undergo a comprehensive geomatic investigation and publication as spatial data services. Primarily, this delay stems from the challenges of mosaicking and georeferencing its 60 constituent sheets, owing to the uncertain mathematical framework and irregular sheet cuts. In 2023, the authors embarked on rectifying this by creating a unified TKKP mosaic and georeferencing the map to contemporary reference data benchmarks. This endeavour involved scrutinising the map's mathematical accuracy and verifying prior findings. The resultant product is accessible via the 'Maps with the Past' platform, developed by the Institute of History of the Polish Academy of Sciences The dissemination of raster data services adhering to OGC standards such as WMTS (Web Map Tile Service), ECW (Enhanced Compression Wavelet), and COG (Cloud Optimized GeoTIFF) facilitates the swift and seamless integration of the generated data into web and GIS tools. The digital edition of the TKKP emerges as a pivotal resource for investigations spanning natural and anthropogenic environmental transformations, sustainable development, and cultural heritage studies.

Keywords: TKKP; Quartermaster's Map; historical GIS; georeferencing; mosaicking; OGC services; 'Maps with the Past'

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1. Introduction

The idea of digitising the Topographic Chart of the Kingdom of Poland (pol. Topograficzna Karta Królestwa Polskiego, commonly referred to as 'the Quartermaster's Map', hereinafter: TKKP)—one of the most important achievements of Polish cartography—has, against all appearances, a rather complex history that does not result only from the relevance of this map for research into the history of cartography, historical cartography, or history and geography in general. The so-called Quartermaster's Map was of interest to researchers such as B. Olszewicz [1], who devoted a lot of space to it in his 'Polish Military Cartography', or B. Krassowski [2,3], who prepared an edition of it as part of the 'Monuments of Polish Cartography' series. It has been repeatedly used as a cartographic and historical source in research on the ancient landscape [4–6]. Its mathematical accuracy has also been analysed by S. Pietkiewicz and/or under his supervision [7–10]. Several attempts have been made to digitise and present the map online, but these have been limited to regional parts [11–13].

The desire to fully digitise the map stems not only from the cursory presentation of the work but, above all, from the fact that the Quartermaster's Map was one of the primary sources for drawing natural landscape elements (hydrography, forestation) for the series 'Historical Atlas of Poland. Detailed maps of the 16th century'—AHP [14–16]. Seemingly of less significance than the output of B. Olszewicz, B. Krassowski, and other researchers, in practice, it is nevertheless different. Indeed, the editors of the AHP decided that the result of the work on the Atlas should be not only a map, a commendation, and an index but also, as far as possible, an edition of the primary sources used in its preparation. In the case of written sources, these were the conscription registers from the second half of the 16th century, the vast majority of which were made available through a web application [17–19]. A similar edition was also supposed to concern early maps, primarily those from the turn of the 18th and 19th centuries, but due to the lack of methodology for developing digital editions of cartographic sources, preliminary research had to be carried out, resulting in a digital edition of the so-called Gaul/Raczyński maps [20]. Experience gained while working on this map and the launch of the 'Maps with the Past' website [21] by the Institute of History of the Polish Academy of Sciences allowed us to think about the digital development of cartographic sources for the AHP: maps from the turn of the 18th and 19th centuries, including the Quartermaster's Map.

1.1. Geoportals with Early Maps as Digital Editions of Cartographic Monuments

The geoportal 'Maps with the Past', which is part of the 'Atlas Fontium' platform [22,23], is a service that enables the viewing of georeferenced and mosaic sheets of the most important historical topographic and general geographic maps of Polish territories, mainly from the 19th and early 20th centuries. Its origins date back to 2011 when a geoportal with this name was launched by the company Cartomatic. It was the result of practical work by students specialising in cartography at the Department of Cartography (as it was known at the time) at the Faculty of Geography and Regional Studies of the University of Warsaw, during which students georeferenced, among others, maps from the Polish Military Geographic Institute (pol. Wojskowy Instytut Geograficzny; hereinafter: WIG). After a little over ten years of operation, in 2022, the geoportal was suspended.

Shortly thereafter, Cartomatic reached an agreement with the Department of Historical Atlas of the Institute of History of the Polish Academy of Sciences regarding the re-launch of the service and its subordinate digital resources. They were prepared in cooperation with the Warsaw University of Technology [24]. Since June 2023, the geoportal 'Maps with the Past' has been operational, containing both the existing resources of Cartomatic (including WIG maps, German maps, and city plans) and new ones, including the Quartermaster's Map. The service itself is built on the OpenLayers technology [25] and uses WMS services served by Geoserver [26] for operation. The services displayed in the map application can also be used directly in desktop GIS applications. Currently, the site offers 43 maps grouped into 6 categories: WIG maps, Polish maps, Austrian maps, Prussian and German maps, city plans, and historical maps (Figure 1). The maps are displayed on an OpenStreetMap base [27]. The application allows for adjusting the transparency of maps, zooming to layers, displaying layer information, searching for names via OSM Nominatim [28], copying coordinates, and making basic measurements.

The 'Maps with the Past' service is a geoportal allowing users to access georeferenced and mosaicked sheets of historical maps and can be considered a form of digital edition of cartographic monuments. Users do not need to visit libraries or archives or use digital repositories to download scans of individual sheets. Instead, they receive a pre-assembled and connected map, which undoubtedly facilitates its use but at the cost of the ability to delve into the content beyond the map frame. Geoportals with georeferenced maps are one type of digital edition of historical maps, alongside aforementioned libraries and archives enabling the download of scans; advanced geoportals contain not only raster maps but also vector data developed based on the map being edited [20]. In terms of functionality and the degree of map processing, these applications are situated between digital libraries/archives and geoportals with vector data.

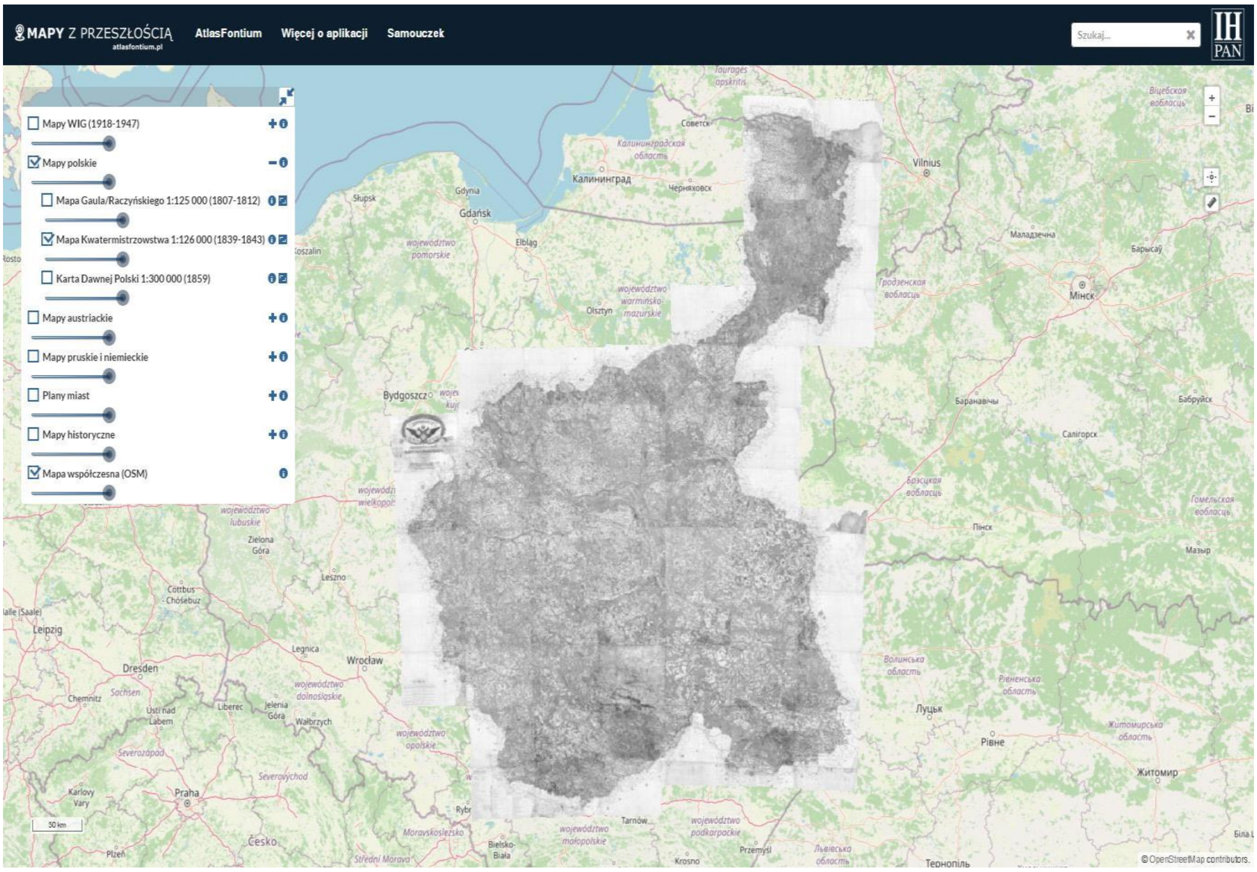


Figure 1. Georeferenced mosaic view of the TKKP in the 'Maps with the Past' application—a thematic section of the portal 'Atlas Fontium' (https://atlas.ihpan.edu.pl/pastmaps/ accessed on 8 July 2024).

'Maps with the Past' is not the only service of its kind available on the internet although it is the only one developed in Poland and mainly contains maps of broadly understood Polish territories. Its development was preceded by an analysis and evaluation of similar solutions, including primarily services such as 'Arcanum Maps' [29], 'GeoHistoricalData' [30], and 'A Vision of Britain' [31]. They share the functionality of enabling the browsing of multi-sheet georeferenced historical raster maps but differ in thematic scope, spatial coverage, and partly chronology, as well as in operating mode.

The primary content of 'Arcanum Maps' consists of Austrian and Austro-Hungarian maps, including first, second, and third topographic surveys, as well as selected German, Russian, Italian, and French maps. The service allows for searching for contemporary locations and using contemporary base maps [32]. An important feature of the geoportal is the fee for services displayed in the form of WMTS in desktop GIS applications (the web application is free). Included maps or, rather, the processing performed on them is, in many cases, discussed in the form of scientific articles [33–40].

While 'Arcanum Maps' offers users access to numerous maps, 'GeoHistoricalData' provides access to essentially one: the 'Carte géométrique de la France', i.e., the so-called Cassini map at a scale of 1:86,400 from the late 18th century [41]. The map sheets have been joined, georeferenced, and published on the geoportal. Its content also includes selected elements of the map in vector format: towns, roads, forests, and hydrography. Unfortunately, there is no option to display attribute data of vector layers although they can be downloaded. An important feature of the service, which may affect its further operation, is the fact that it has not been updated in any way for a long time (4 years). Issues with maintaining the stability of digital services are unfortunately well known, and so far, no satisfactory solution other than costly and time-consuming IT maintenance has been found.

The British 'A Vision of Britain through Time' is a service with a different philosophy than the previous two as old maps are only one of its components. Its main content consists of statistical data, lists of places, and descriptions of journeys, thus serving as sources and written data for the historical geography of Great Britain [42]. Nevertheless, historical maps constitute an important part of it. In the appropriate section, users have access to three categories of maps: topographic (11 series from 1805–1958), boundary (13 series from 1803–1949), and land coverage (3 series from 1925–1948). The gathered maps include products of private initiatives as well as official products (Ordnance Survey). Users can view individual map sheets in a mosaicked and georeferenced version, as well as individually, sheet by sheet. In this case, users also have access to basic metadata, such as the year of publication.

In summary, the 'Maps with the Past' service fits into current trends related to the possibilities of digitally disseminating cartographic sources in terms of content, form, and functionality. The operation principles of such services are similar due to the use of WebGIS tools, presenting a similar range of content consisting of the most important series of historical topographic maps, and are intended for a wide audience, from ordinary internet users to researchers and scientists from various disciplines. Differences—apart from the presented maps—mainly concern detailed functionalities and maintenance and development issues. It is essential to continuously expand the informational scope of services by developing and providing access to additional maps.

1.2. TKKP as a Cartographic and Historical Source

The preparation of a detailed Topographic Chart of the Kingdom of Poland was part of the contemporary trend of systematic surveying and field measurements in post-Napoleonic Europe. Although the neighbouring states, primarily Prussia and Austria (to a lesser extent Russia), began cartographic work of national significance as early as the second half of the 18th century, modern cartographic work in the Polish territories had to wait until the era of partitions and the beginning of the 19th century. The special maps of the Crown provinces prepared (albeit incompletely) by Karol Perthes, geographer to Stanisław August Poniatowski, noticeably differed in quality from the works of Prussian or Austrian cartographers mainly due to the lack of geodetic basis [43]. What the free Polish Commonwealth did not accomplish, the occupiers did by developing maps of newly acquired territories in the late 18th century or later through the establishment of the Topographic Bureau in the Duchy of Warsaw in 1807 and, after 1815, the General Quartermaster's Office of the Kingdom of Poland [1]. The Quartermaster's Office was one of the autonomous institutions of the Kingdom of Poland, independent of Russia, according to its constitution granted in 1815. During peacetime, its tasks included, among others, the preparation of maps, similar to the functions of analogous units in the neighbouring states' armies.

Work on the map began in 1822; previously, the Quartermaster's Office had been working on delimiting borders with Austria and Prussia. In the absence of previous models in this regard, Russian measures (versts) were applied to the projected map, with the intended scale set at 1:126,000, i.e., 3 versts (1066 m) to the English inch (2.54 cm). The Bonne pseudoconical projection known from French maps was adopted, with the Warsaw meridian intersecting the 52° parallel as the reference point (more details in Section 2.3). The Walbeck ellipsoid served as the reference surface [44]. Ground surveys were conducted at a scale three times larger, i.e., 1:42,000. According to B. Krassowski [2,3], this process can be described more as 'reambulating' and 'unscenening' the content of partition maps using field measurements and hastily conducted triangulation. Topographers relied on the content of previously printed maps: Gilly's (1:150,000, 1802–1803), Textor's (1:152,200, 1808), and Heldensfeld's (1:172,800, 1808). During the surveys conducted in spring, each topographer had a measuring table with working material derived from Prussian or Austrian materials brought to a scale of 1:42,000. Then, within this framework, they drew the situation and relief using instruments or by eye [41,45]. During chamber work, the drawing was generalised to the target scale, as claimed by B. Krassowski [3], by a constant group of cartographers (and according to uniform instructions), ensuring consistency. Unfortunately, the maps could not be completed and published before the outbreak of the November Uprising in 1830. By that time, approximately half of the planned 59 sheets had been prepared. In 1832, work on completing the map was taken over by a Russian corps of topographers led by General Karol Richter. By 1839, corrections were made to the work performed by the Quartermaster's Office, and missing sheets were drawn and engraved. The map was published in 1843 with a date four years earlier, with titles and explanations of symbols in French, Polish, and Russian, but with content exclusively in Polish ([41,44]; [46], pp. 181–185).

Topography on the map is represented by 54 clear and well-designed cartographic symbols, 30 abbreviations, and 10 typefaces [46–48]. The map depicts roads and railways, settlements and economic facilities, surface elements, waters, boundaries, and terrain relief (Figure 2). The road network consists of four categories: paved (highways), postal routes, ordinary routes, and side roads. The graphical expression of highways stands out from the rest not only by two thick edges but also by a straight course, clearly indicating their modernity and high quality. Along with roads, railway lines are also shown on the map, with the first edition from 1843 depicting only the Warsaw–Vienna line and its branch from Skierniewice to Łowicz, which was still under construction at that time. Settlements are marked by the outline of buildings, divided into wooden and brick structures, which was of significant importance for the military. Similar distinctions were made for churches, inns, or mills. The size of settlements is indicated by different typefaces, and the detail of descriptions is evidenced by the fact that they were also placed at small hamlets and settlements. Administrative boundaries, including states, gubernias, and counties, are depicted according to the 1841 state. This is evidenced by the already changed name of the Kielce gubernia (from Krakow), which took place based on the decree of 15 June 1841 [49]. Surface elements on the map are shown according to their military character, displaying various types of forests and meadows, which may pose obstacles in the terrain or provide shelter; however, uncultivated land or cultivated fields are not marked as areas of little strategic importance. The same philosophy guided the representation of hydrography: larger rivers are shown by surface, and various types of crossings and bridges are indicated in detail, even on low-category roads. Terrain relief is represented by modified hatching using the Lehmann method, which resulted in amplifying small forms. The representation of relief was assessed as the least realised element of the map [3,41,50].

The Topographic Chart of the Kingdom of Poland was the first and for a long time the only original Polish topographic map that met the contemporary high standards in terms of content, technicality, and functionality. As B. Krassowski asserted, it surpassed in quality (mathematical accuracy and detail of content) the Prussian 1:100,000 map developed during a similar period, which '(. . .) still represented the type of map from the late 18th century, whereas the Topographic Chart of the Kingdom of Poland, with its individual technical solutions and adaptation of symbols to the contemporary military needs, advanced into the 20th century' ([3], p. 21). The fact that the Russians largely based their cartographic work on the concept of the Quartermaster's map to create the so-called three-verst map [41] may also testify to its quality. Regarding mathematical accuracy, according to [7–11], errors in the positioning of points on the map were approximately 747 m (6 mm on the map scale). B. Krassowski [3] claimed that these values were increased by paper shrinkage, which, based on the comparison of various preserved copies of one of the sheets, could reach up to 2 mm (i.e., approximately 250 m in the field). Studies of the map's mathematical precision were also conducted using numerical methods by Bojarowski et al. [11], and the results indicated a high accuracy of the map, with positioning errors mostly not exceeding 100 m and rarely reaching 500 m. In the subsequent parts of the article (Sections 2.4 and 2.6), the authors present the verification of these observations.

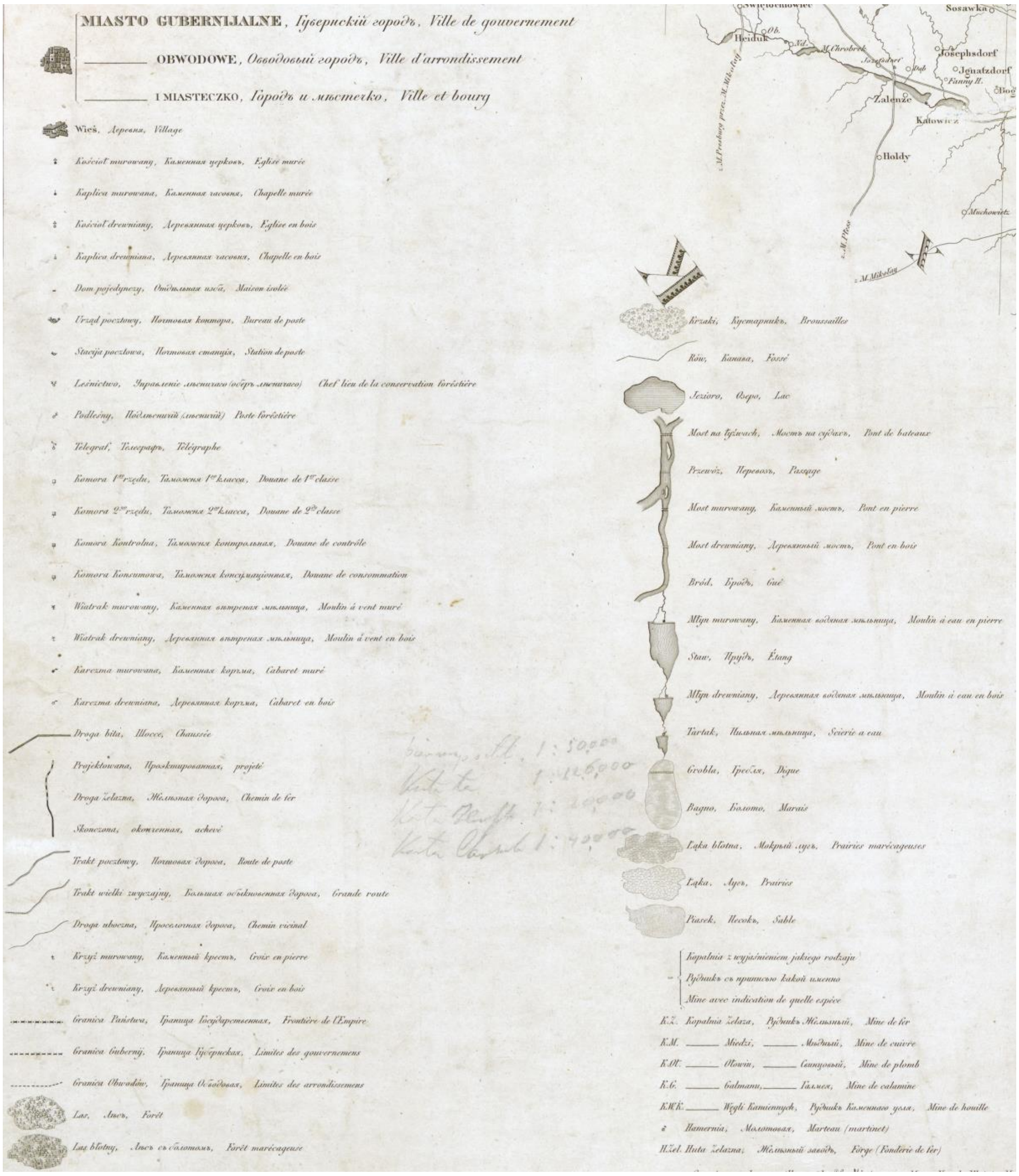


Figure 2. Fragment of the sheet Col. 2. Sect. 8. containing the legend of the TKKP. Sixty-five percent of the original size. Source: Jerzy Giedroyc University Library in Białystok (https://bg.uwb.edu.pl/TKKP/ accessed on 8 July 2024).

1.3. TKKP Digital Collections and Their Evaluation

The Topographic Chart of the Kingdom of Poland (TKKP) is a significant historical cartographic source with substantial informational and cultural importance. Due to its value, there is considerable interest in both its digitization and dissemination [12,51,52]. Digital copies of the Quartermaster's map are stored and made available by cultural institutions, libraries, and archives. This article focuses on portals through which users can browse and acquire scans exclusively through online queries. As part of various projects, institutions often collaborate to digitise and make available digital copies of the TKKP. These efforts have led to the creation of many copies, which are available through various platforms and portals. When undertaking project work, consideration was given to digital resources made available by:

1. Jerzy Giedroyc University Library in Białystok (https://bg.uwb.edu.pl/TKKP/ accessed on 8 July 2024);
2. Federation of Digital Libraries (https://fbc.pionier.net.pl/ accessed on 8 July 2024);
3. Jagiellonian Digital Library (https://jbc.bj.uj.edu.pl/dlibra/publication/242425/ accessed on 8 July 2024);
4. Kuyavian-Pomeranian Digital Library (https://kpbc.umk.pl/dlibra/publication/203143/ accessed on 8 July 2024);
5. Digital Platform of the Kórnik Library (https://platforma.bk.pan.pl/pl/search_results/195766/ accessed on 8 July 2024);
6. Podlasie Digital Library (https://pbc.biaman.pl/dlibra/publication/54779/ accessed on 8 July 2024);
7. Digital Repository of Scientific Institutes (https://rcin.org.pl/dlibra/publication/12322/edition/834 accessed on 8 July 2024);
8. Greater Poland Digital Library (https://www.wbc.poznan.pl/dlibra/publication/533840/edition/474741/ accessed on 8 July 2024);
9. Historical Maps of Poland and Central Europe/ MAPSTER (http://igrek.amzp.pl/mapindex.php?cat=TKKP126K accessed on 8 July 2024).

Analog versions of the Quartermaster's map made available in the form of digital copies by the above repositories are accessible at: Jerzy Giedroyc University Library in Białystok (1, 2, 6, 8), National Library (2, 8), Jagiellonian Library (2, 3, 8), Provincial and Municipal Public Library in Bydgoszcz (2, 4, 8), Kórnik Library of the Polish Academy of Sciences (2, 5, 8), Central Library of Geography and Environmental Protection of the Polish Academy of Sciences (2, 7, 8). The MAPSTER website [53,54] contains resources provided by all of the above repositories. All digitally analysed copies of the TKKP are in the public domain and open access, and repositories allow for their download (depending on repository policy) in JPEG, TIFF, or DJV format files. Detailed analysis is included in Table 1, which includes the location of the original digital copy.

Table 1. List of digital copies of the TKKP made available by selected repositories.

Original Location	Edition	Number of Sheets	Scan Type	Description of Scans	Index Sheet
National Library	No data	60	Colour scan	Maps pasted on canvas. Gaps between sheets.	Yes
Jagiellonian Library	II	60	Colour scan	Scans distorted in places.	Yes
Jerzy Giedroyc University Library in Białystok	IV, approx. 1863 r.	59	Colour scan	No defects. Resource after maintenance. One section is missing. Map frame cut off incorrectly.	Yes
Central Library of Geography and Environmental Protection of the Institute of Geography and Spatial Development of the Polish Academy of Sciences	No data	56	Colour scan	Maps pasted on canvas. Gaps between sheets.	Yes
PAN Kórnik Library	Probably 1863	55	Colour scan	Reduced and incomplete version. Maps pasted on canvas. Gaps between sheets.	No
Provincial and Municipal Public Library in Bydgoszcz	No data	60	Colour scan	Scans distorted in places.	Yes

In the implemented project, scans from the resources of the Jerzy Giedroyc University Library in Białystok [55] and the missing sheet (Col. 5 Sect. 5) from the Jagiellonian Library were utilised. The provided digital copies are characterised by high quality and influenced by a thoroughly conducted conservation process. As a result of conservation work, distortions of sheets were eliminated, and gaps between sections were removed, which is crucial for map georeferencing [55]. Additionally, the sheets are available in high-resolution and user-friendly format. The only drawback is the improperly cropped map frame (Figure 3).

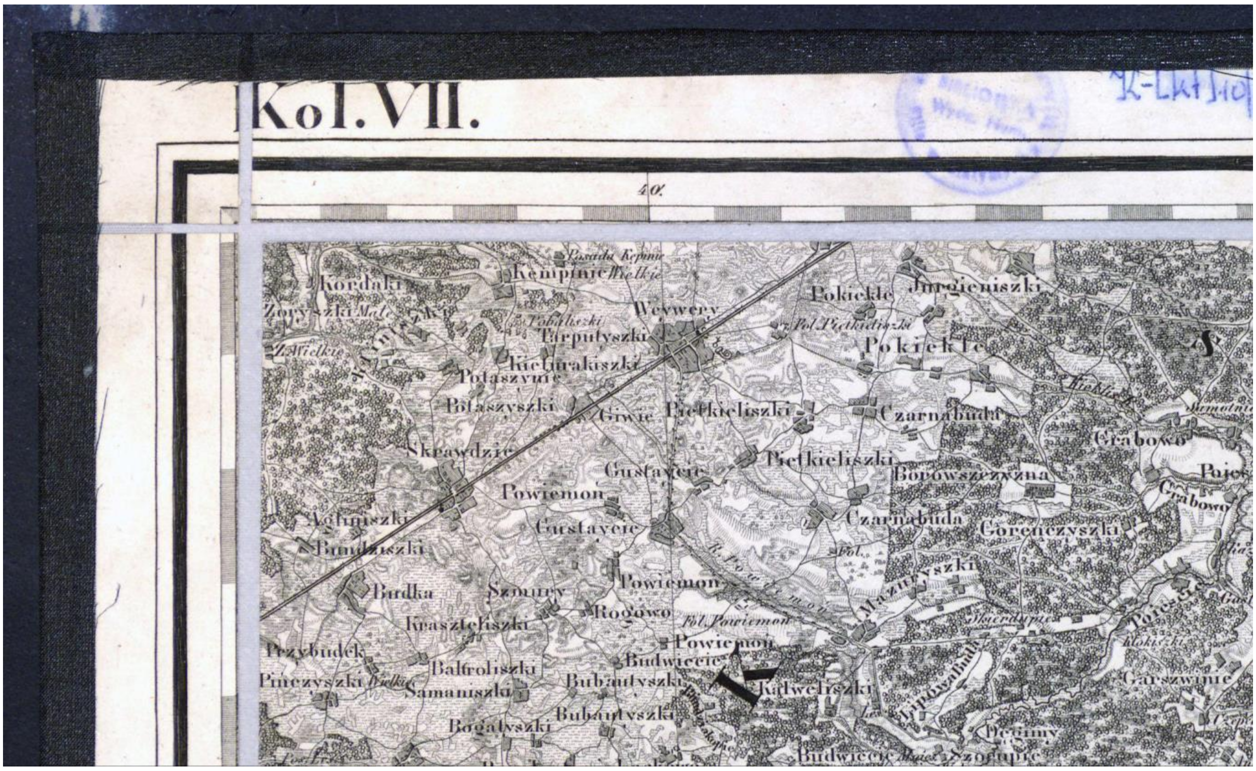


Figure 3. Fragment of the sheet Col. 7. Sect. 2. from the collections of the Jerzy Giedroyc University Library in Białystok [55]. Attention should be paid to the improperly cut border of the map, resulting in a loss of up to approximately 0.5 mm of map content (approx. 63 m in the field). Original size.

2. Research Procedure

The analysis of mathematical foundations of historical topographic maps is not a new research problem; the earliest works in this area date back to the 19th-century German researchers H. Walser and R. Wolf [56,57]. Pioneering studies for the territory of Polish lands are attributed to H. Merczyng [58], followed by R. Jacyk [59] and W. Hartnack [60]. In the second half of the 20th century, research led by S. Pietkiewicz continued at the Department of Cartography at the University of Warsaw, focusing on both early maps at general and topographic scales [8–10]. At the end of the 20th century, issues related to the mathematical foundations of maps were addressed by several authors [61–66], also with the use of computer methods [67–71]. Geometric distortions intentionally introduced as part of censorship practices were the subject of research by B. Konopska [72], continued by M. Kuźma [73,74]. With the development and widespread use of geographic information systems (GIS), the number of analyses concerning detailed maps, maps developed in local systems, and urban plans noticeably increased.

The georeferencing of historical topographic maps using GIS tools and various methods of raster image transformation has attracted the interest of international authors for over two decades [75–96]. In the Polish context, significant works in this area have been published [97–107]. Voices in the discussion regarding the use of GIS tools were also contributed [108–110].

A separate group of studies comprises considerations regarding the transformation of abolished geodetic coordinate systems (local and national) into modern coordinate systems [111–115]. Such works require the compilation of coordinates of measurement points from the old geodetic network with measurement values of the same objects in the contemporary reference system. Derived equations and ellipsoid transformation parameters provide the opportunity for direct georeferencing of early maps using natively registered coordinates (geographic or planar), which represents a significant facilitation.

From the perspective of this paper, the works of the Hungarian team [33–40,92] are particularly important, representing a systemic approach to georeferencing, mosaicking, and serial publication of archival maps on the Arcanum Maps portal [29]. These works involve the preparation of georeferenced archival maps (topographic, cadastral) in various regions and scales, with particular emphasis on the territories of the former Austro-Hungarian Monarchy. Methodologically, the Hungarian team combines both approaches: (1) transformation of systems → geodetic approach and (2) raster transformations → GIS approach.

2.1. Methods and Tools

The research procedure for developing the georeferenced mosaic of the TKKP was multi-stage and required the use of a standard set of tools for contemporary HGIS researchers: raster graphics editing software (Adobe Photoshop CS6), desktop GIS software (ArcMap 10.8.1, ArcGIS Pro 2.5, QGIS 3.16.7), Python libraries, GDAL and server environment for publishing the results in the form of spatial data services (Geoserver [26] for WMS service publication, OpenLayers [25] for web-map application). During the work, these programmes were used as appropriate, primarily guided by the ergonomics of the process, experience, and habits. The successive stages of work are illustrated in the form of a 'workflow' diagram in Figure 4. The general work scheme can be described as follows:

1. Acquisition of digital copies, saving them on the local disk;
2. Preprocessing, i.e., preparing raw map scans, removing scan defects, tonal adjustment, and optimising input formats;
3. Georeferencing of sheet Col. 4. Sect. 4. (TPS/adjust function for local control points) and determining the starting point of the Bonne coordinate system;
4. Development of the mathematical basis, i.e., determining reference ellipsoid parameters and generating a cartographic grid in $10' \times 10'$ cells;
5. Rectification of sheets using the generated 10 min grid (TPS/adjust function, from 20 to 60 points per sheet);
6. Alignment of sheet junctions;
7. Development of a vector index of sheets and modification of edges to the actual extent of the sheets (irregular polygons);
8. Cropping of sheets using the vector index and creation of a transparency mask;
9. Development of layer stack and mosaicking of sheets into a unified resulting raster;
10. Proper georeferencing of the unified raster map to ETRF200/PL-1992 coordinate system with TPS/adjust function;
11. Transformation (creation of duplicates) of files into WGS84/Web-Mercator coordinate system, format conversion, and network optimisation;
12. Development of metadata set for network services;
13. Publication of the raster Topographic Chart of the Kingdom of Poland on the 'Maps with the Past' [21] as part of the 'Atlas Fontium' [22] and as OGC raster data services (WMS/WMTS, ECW, COG).

Individual steps, the software used, and exemplary methodological solutions are discussed in detail in the following subsections.

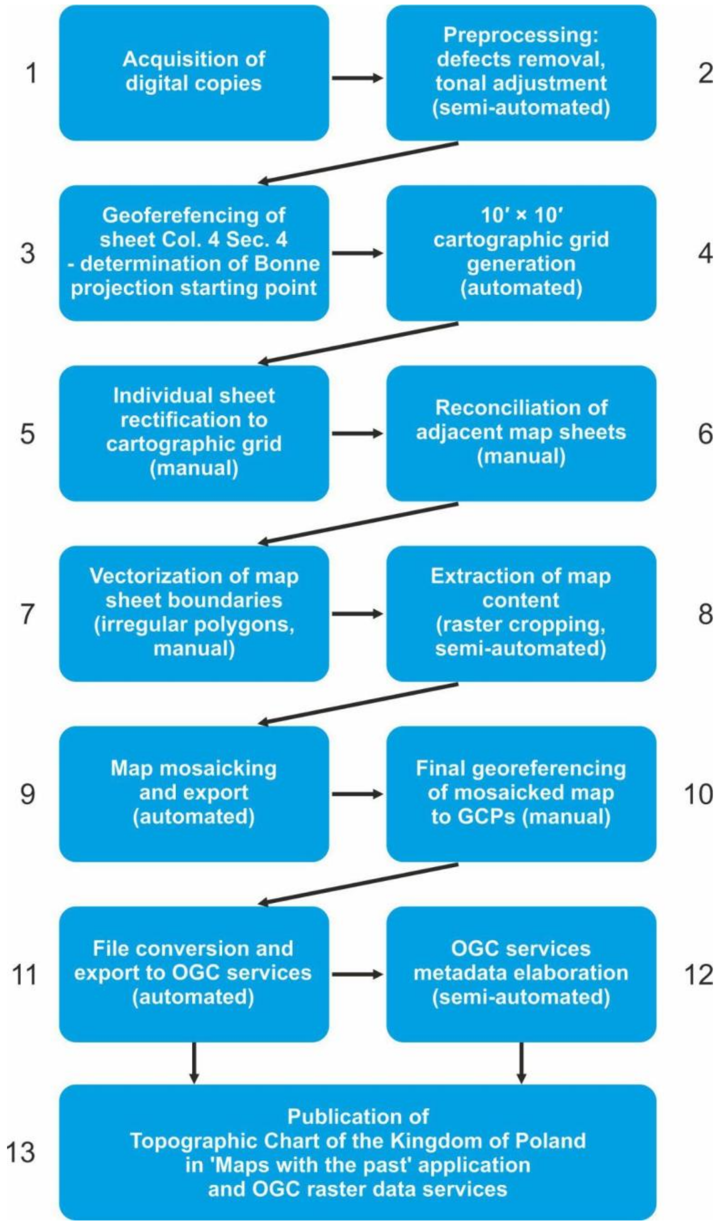


Figure 4. Workflow diagram for the development and publication of a uniform TKKP mosaic.

2.2. Preprocessing

As mentioned in Section 1.3, the source material for the study consisted of a set of 60 map sheets in the form of high-quality scans. Standard sheet files were obtained in TIFF format with a resolution of 600 dpi, dimensions of approximately 14,000 × 10,000 pixels, 24-bit RGB colour depth, LZW compression, and size of approximately 0.5 GB. The total volume of source data exceeded 21 GB! To optimise memory usage, the set of raster files underwent (lossy) conversion to JPG format, achieving about a 20-fold reduction in the file size. The conversion was performed in Adobe Photoshop CS6 using batch processing, allowing semi-automatic execution of repetitive tasks on the entire file set. At the preprocessing stage, automatic adjustment of contrast, colour, and tones was also performed.

An interesting technical challenge in the preprocessing phase was preparing the georeferencing of a scan of sheet Col. 5 Sect. 5, originating from the Digital Library POLONA [116]. The sheet is preserved on six cards glued on canvas (Figure 5). The width of the gaps between the folds reaches approximately 2.7 mm. Georeferencing such source material from the outset is subject to significant error—in the analysed case, approximately 340 m on the ground. Even in the latest publications (e.g., Bozzano et al. ([117], Figures 2 and 5) and reputable foreign portals such as Arcanum Maps ([29] topographic maps of the Kingdom of Bavaria and the Russian Empire in the 19th century, etc.), examples of georeferencing of segmented maps are encountered. Analyses of raster transformation models and attempts to assess mathematical accuracy based on such data are at least questionable. To avoid this problem, it is necessary to cut individual panels from the scan and then reassemble the sheet, removing the gaps at folds. Regardless of the interference with the physical sheet of the map, cutting folds and reassembling can be performed in raster graphics software (e.g., Photoshop) or using cutting and zero georeferencing in GIS programs. The term zero georeferencing refers to registering the map in the coordinate system of the native pixel coordinates of the bitmap (Column, Row) or in a system that takes into account the physical size of the map sheet (X, Y, in mm). Zero georeferencing precedes proper georeferencing and can be used for (1) merging segmented map sheets, (2) joining multi-sheet maps in rectangular cutting, or (3) rectifying maps to a rectangular grid. Achieving pixel-perfect alignment with the original drawing is very difficult, but reducing discrepancies to below 0.2 mm on the map scale is sufficient.

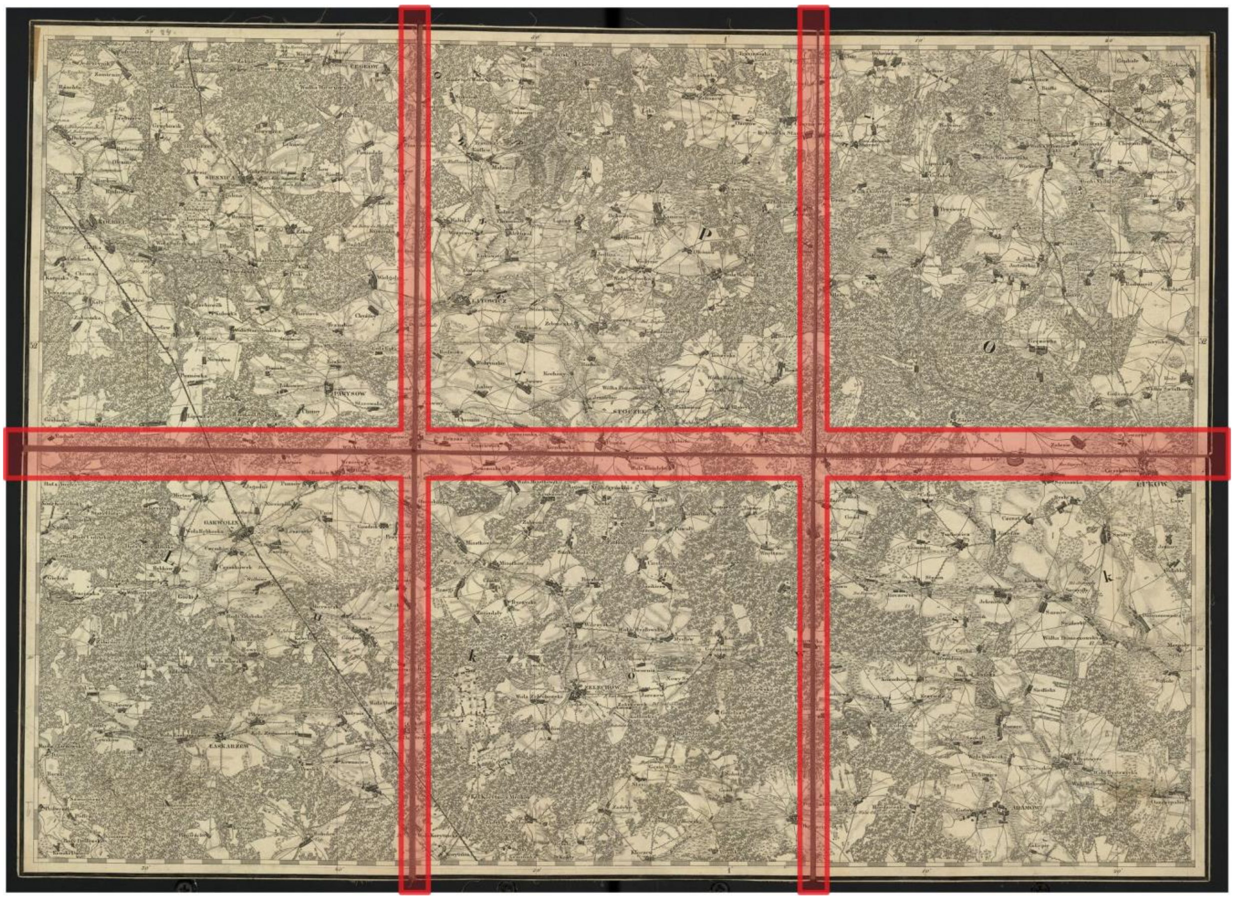


Figure 5. Col. Sheet 5. Sect. 5. from the collections of the POLONA Digital Library. The red areas indicate the map's division into 6 parts and glueing panels on canvas. The width of the gaps reaches approximately 2.7 mm (approximately 340 m on the ground). Thirty percent of the original size.

2.3. Development of the Mathematical Basis

From the perspective of the adopted research methodology, the most crucial stage of the project was the development of the mathematical foundation for georeferencing the TKKP. Defining mathematical foundations in a GIS environment requires precise determination of three sets of parameters:

1. Characteristics of the reference ellipsoid (equatorial semi-axis—a, polar semi-axis—b, flattening—f);
2. Its relationship to the applicable geoid (shift of the ellipsoid centre in the dX, dY, dZ axes);
3. Type and parameters of cartographic projection.

Due to the lack of Wallbeck ellipsoid parameters, experimentation was conducted using the Bessel 1841 ellipsoid with parameters (a = 6,377,397.155, b = 6,356,078.962818189, 1/f = 299.1528128, [118]), but its reference to terminated German and Austro-Hungarian coordinate systems [118–122] did not yield the desired results. Ultimately, the decision was made to use the WGS84 ellipsoid [123] and manipulate the remaining parameters. Authors verified assumptions from earlier publications on this matter [1,2,41], and the Bonne's pseudoconical equal-area projection was utilised with values of the central meridian $\lambda0 = 21.025$ E and standard parallel $\varphi1 = 52.003$ N. The position of the starting point was determined experimentally (Figure 6) based on detailed local georeferencing of sheet Col. 4 Sect. 4, containing the intersection of the Warsaw Meridian with parallel 52 N [1,41]. According to B. Olszewicz [1], the Warsaw Meridian assumes the value of $38°42'30''$ E from Ferro; taking into account the Austrian correction ($-17°40'$) relative to Greenwich, we obtain the value of $21°2'30''$ E, i.e., 21.041666666... [DD]. Considering the German correction ($-17°39'57.6''$), we obtain $21°2'32.4''$ E, i.e., 21.04233333... [DD]. The Warsaw Meridian line experimentally determined in GIS is slightly shifted towards the west, reaching the value of $21°1'30''$, i.e., 21.025 [DD]. The error in the position of the parallel 52° N calculated by S. Pietkiewicz [8] was $11.8''$, while the vector determined experimentally was 0.003 DD, i.e., $10.8''$. In this created mathematical foundation, a grid of meridians and parallels at 10 min intervals was generated (Figure 7). The procedure involved generating a rectangular grid in the geographic system, mapping it to Plate Carree, shifting the grid by vector X = +0.025, Y = +0.003 (DD), and transforming the grid into the trapezoidal shape in the Bonne projection. The parameters of the *Bonne_Kingom_of_Poland2* projection in WKT format are provided below:

Figure 6. Location of the origin point of the coordinate system, i.e., the intersection of the Warsaw Meridian and the parallel 52 N on the TKKP sheet Col. 4. Sect. 4. (50% transparency). TKKP coordinates—red line, WGS 84 coordinates—blue line. Shift vector of the 10 min grid from point 21 E, 52 N to the origin point of the TKKP. OSM base map.

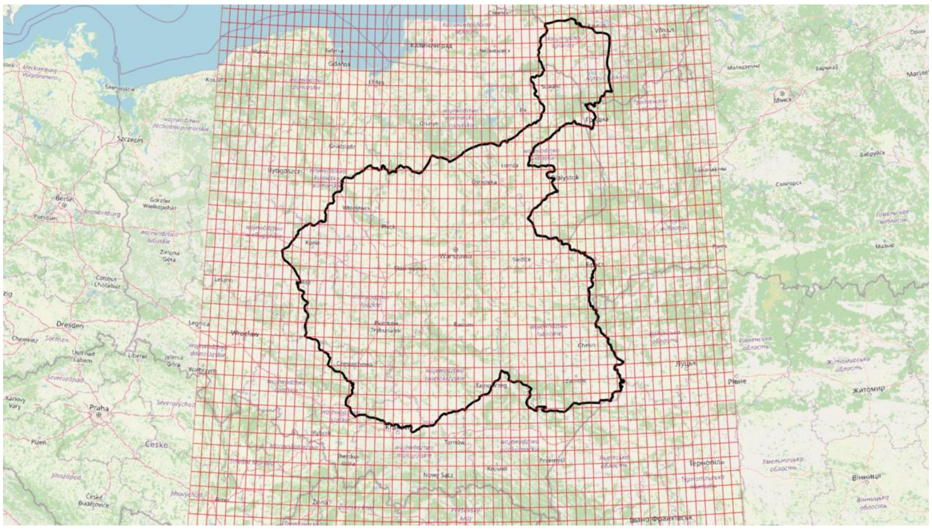


Figure 7. Computer-generated 10 min grid of the TKKP and boundaries of the Kingdom of Poland. Bonne's pseudoconical conformal projection using the parameters presented in the WKT definition (Listing 1). OSM base map.

Listing 1. WKT definition for the Bonne_Kingdom_of_Poland2 reference frame. The system uses the Bonne projection for the WGS84 ellipsoid [123], central meridian 21.025, and standard parallel 52.003. The system does not take into account the transformation between the Bessel 1841 ellipsoid [118] and WGS84 [123].

```
WKT
PROJCRS(‘Bonne_Kingdom_of_Poland2’,
BASEGEOGCRS(‘WGS 84’,
DATUM(‘World Geodetic System 1984’,
ELLIPSOID(‘WGS 84’,6378137,298.257223563,
LENGTHUNIT(‘metre’,1)),
ID(‘EPSG’,6326)),
PRIMEM(‘Greenwich’,0,
ANGLEUNIT(‘Degree’,0.0174532925199433))),
CONVERSION(‘unnamed’,
METHOD(‘Good’,
ID(‘EPSG’,9827)),
PARAMETER(‘Latitude of natural origin’,52.003,
ANGLEUNIT(‘Degree’,0.0174532925199433),
ID(‘EPSG’,8801)),
PARAMETER(‘Longitude of natural origin’,21.025,
ANGLEUNIT(‘Degree’,0.0174532925199433),
ID(‘EPSG’,8802)),
PARAMETER(‘False easting’,0,
LENGTHUNIT(‘metre’,1),
ID(‘EPSG’,8806)),
PARAMETER(‘False northing’,0,
LENGTHUNIT(‘metre’,1),
ID(‘EPSG’,8807))),
CS(Cartesian,2),
AXIS(‘(E)’,east,
ORDER(1),
LENGTHUNIT(‘metre’,1,
ID(‘EPSG’,9001))),
AXIS(‘(N)’,north,
ORDER(2),
LENGTHUNIT(‘metre’,1,
ID(‘EPSG’,9001))))
```

2.4. Rectification of Sheets and Seam Adjustment

Developing the 10 min grid for the TKKP extent was a crucial step for the correct rectification of the map. The method of calculating coordinates and drawing the cartographic grid, the passage of time, paper distortions, and errors occurring during scanning all contributed to the creation of local deformations in the map content, which negatively affected the georeferencing process. To minimise these deformations, all sheets underwent a rectification process (Figure 8), i.e., stretching the points marked on the map at the intersection of the cartographic grid to corresponding intersections of the computer-generated 10 min grid [11,39,99,107]. Depending on the size and location of the sheet, the number of intersection points varied from several to several dozen, averaging about 41 points per sheet. The distribution of points was very uniform and corresponded well with the elements of content and the minute frame. During the rectification of sheets, particular attention was paid to the locations where the 10 min grid lines exited at the edges and corners—these elements were used to adjust the seams between sheets [11,93,107]. In special circumstances, control points were adjusted multiple times for better alignment of adjacent sheets. A table of 2513 rectification points for individual sheets is included in the .CSV file (Supplementary Data—*TKKP_rectification.csv*).

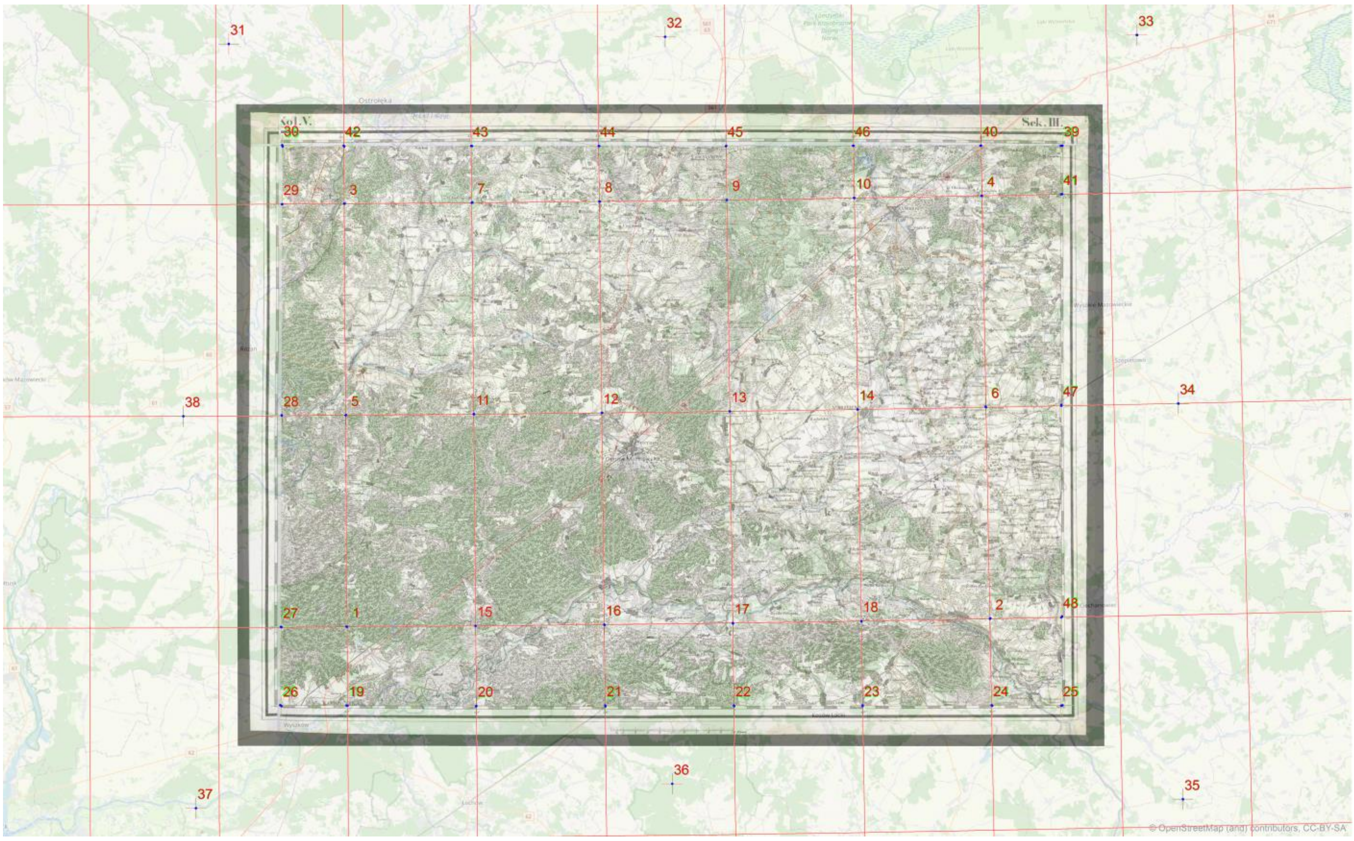
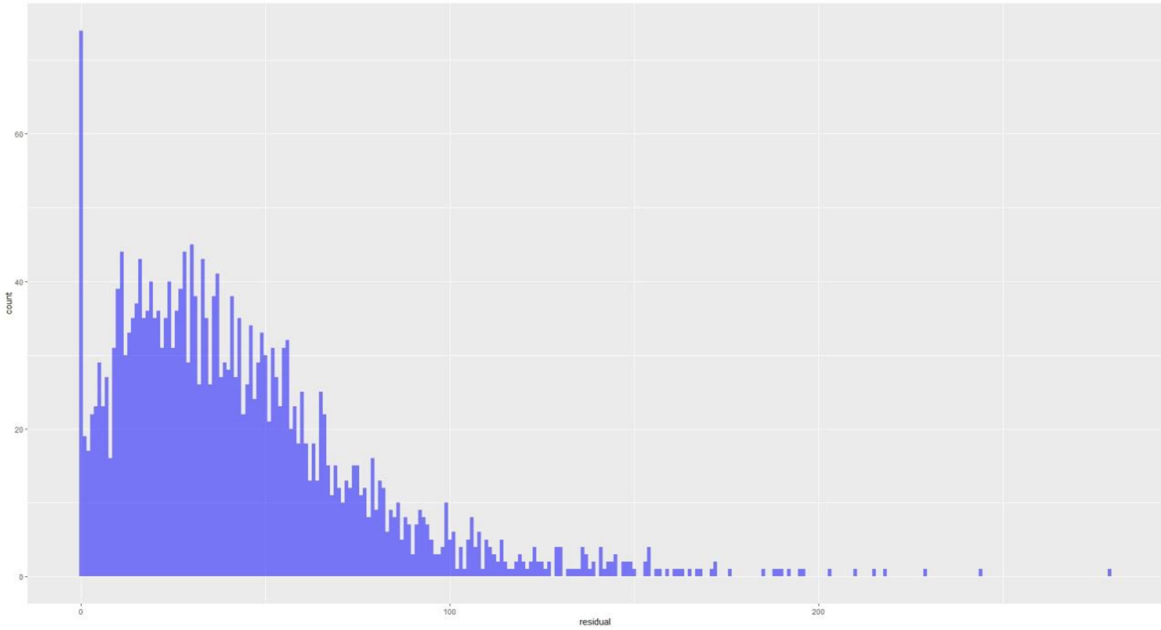


Figure 8. Sheet Col. 5. Sect. 3. Ostrów Mazowiecka. Initial georeferencing to the 10 min grid using a 1st-degree polynomial. Note the distribution of peripheral points 19–47 to adjust the seams and preserve the outer form of the sheet. The spline function TPS/adjust rectification removes internal map distortions caused by paper deformation or scanning. A table of 2513 rectification points for 60 individual sheets is available in .CSV format in Supplementary Data. OSM base map.

The identification of corresponding nodal points and the simulation of georeferencing with a 1st-degree polynomial revealed local distortions in content ranging from several cm to nearly 250 m on the ground (average about 43 m on the ground, i.e., 0.34 mm on the map), confirming findings of Bojarowski et al. ([11], p. 238) regarding the correctness of the cartographic grid geometry (Figure 9). The fitting error did not exceed the threshold value of 25.2 m on the ground (0.2 mm on the map) for over 25% of all control points, with a further 50% of points falling within the range of 25.2–63 m on the ground (0.2–0.5 mm on the map). Considering the scale and age of the map, even an extreme shift of 280 m on the ground is not an excessively large value (corresponding to an error of 2.2 mm on the map and concerns the intersection of grid lines outside the map content area). Despite promising rectification results, the authors found the information regarding the deviation of topographic points reaching 500 m ([11], p. 238) concerning—differences in the position of the mathematical framework relative to the actual topographic content could lead to further error accumulation during the mosaicking and georeferencing stages. Bearing in mind the high requirements of contemporary users, the authors performed rectification of all 60 sheets using the raster segmentation method and spline functions TPS/adjust [75–77].

(**a**)



(**b**)

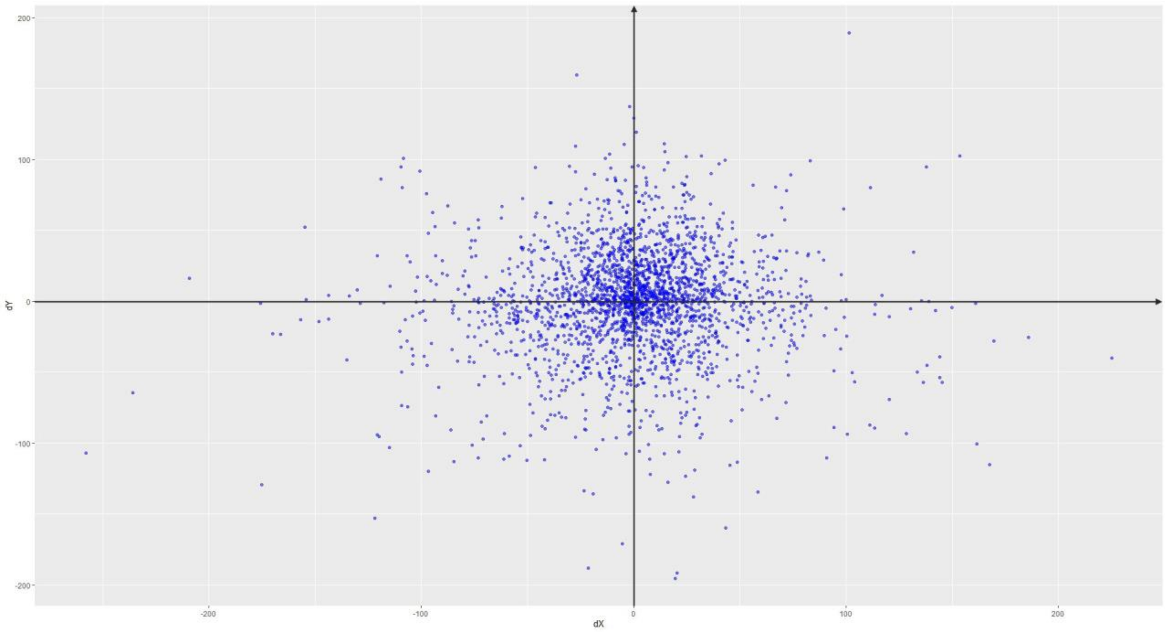


Figure 9. Distortions of the TKKP obtained as a result of rectification of individual sheets to the 10 min grid in the generated Bonne's projection. (**a**) The statistical analysis predominates the values of residual error around 20–40 m on the ground (approx. 0.16–0.32 mm on the map). Left-skewed (positive) asymmetric histogram. Statistical indicators: minimum = 0.0 m; quartile 1 = 18.79 m;

median = 36.28 m; mean = 43.25 m; quartile 3 = 58.21 m; maximum = 279.1 m. (**b**) Shifts dX, dY of control points. Differences between affine transformation (1st-degree polynomial) and spline transformation (TPS/adjust) reach up to ±250 m in the W–E axis and ±200 m in the N–S axis. The average values of dX, dY are extremely close to 0, meaning that despite the dispersion of individual points, sheet distortions do not have a specific directional character. High-resolution plot images are added in Supplementary Data.

2.5. Development of Vector Index and Sheet Cutting, Raster Mosaicking

After rectification, the next step was to prepare the sheet index in vector form. The main difficulty of this stage was the irregular shape of the sheets—although they appear rectangular at first glance, in reality, the extent of each sheet forms an individual polygon. It became necessary to manually draw the boundaries between sheets. An important aspect of this stage was to maintain topological consistency between polygons representing individual extents—for this purpose, it was decided to first create an outer outline of all 60 sheets and then cut out individual polygons in subsequent steps.

Subsequently, the vector index was used to cut individual sheets and create a transparency mask (alpha channel) for elements outside the inner frame area. This resulted in a set of 'net' copies containing only the map content (Figure 10). The files were organised as a stack of layers, and a visual check was performed again to ensure seam alignment. However, minor faulty seam alignments remained due to inaccurate physical trimming of the frame in the source material (Section 1.3, Figures 11 and 12).

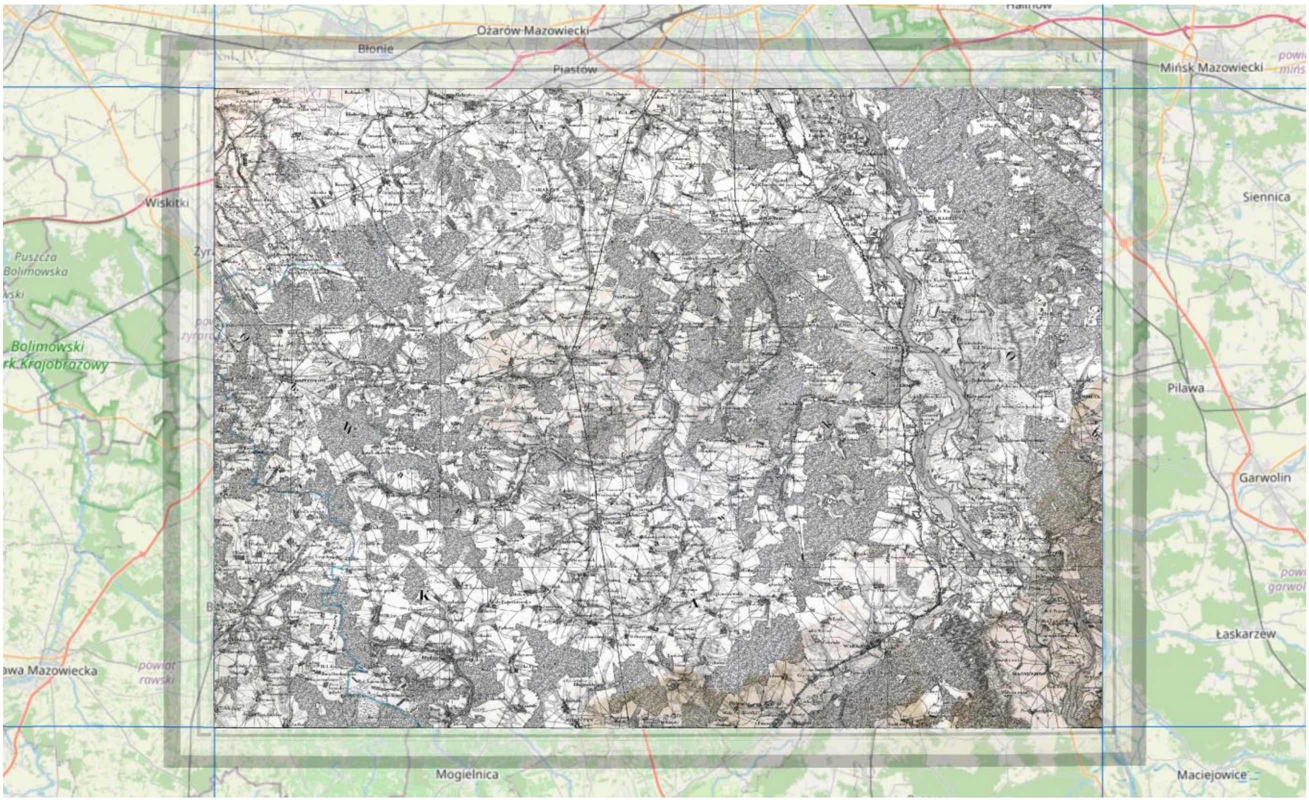


Figure 10. Sheet Col. 4. Sect. 4. Piaseczno netto copy after cutting with a vector mask. Erased parts of the original sheet shown with 75% transparency. Forty percent of the original size. OSM base map.

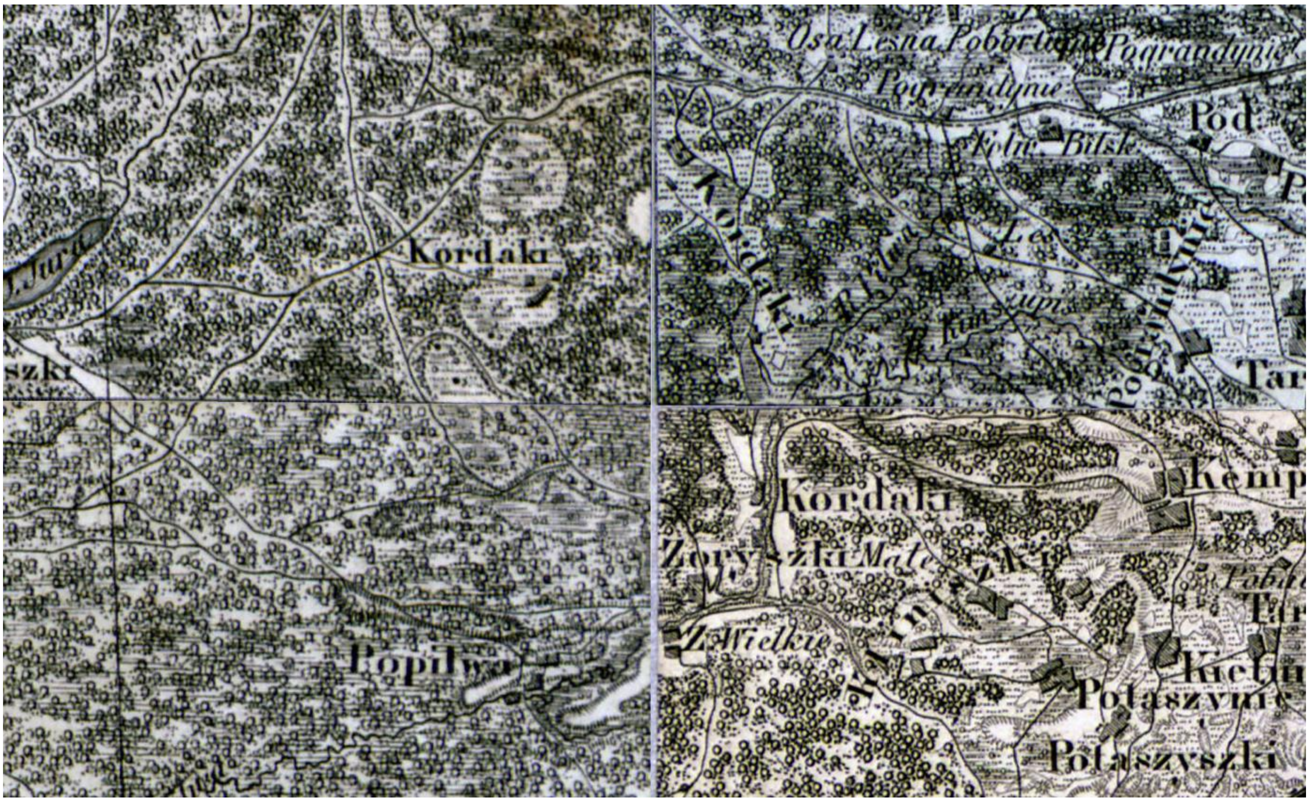


Figure 11. Seam alignment of four peripheral sheets: Col. 6. Sect. 1., Col. 6. Sect. 2., Col. 7., Sect. 1., and Col. 7. Sect. 2. Note the lack of content on the left edge of sheet Col. 7. Sect. 2. due to improper physical trimming of the edge in the source material. Two hundred percent of the original size.

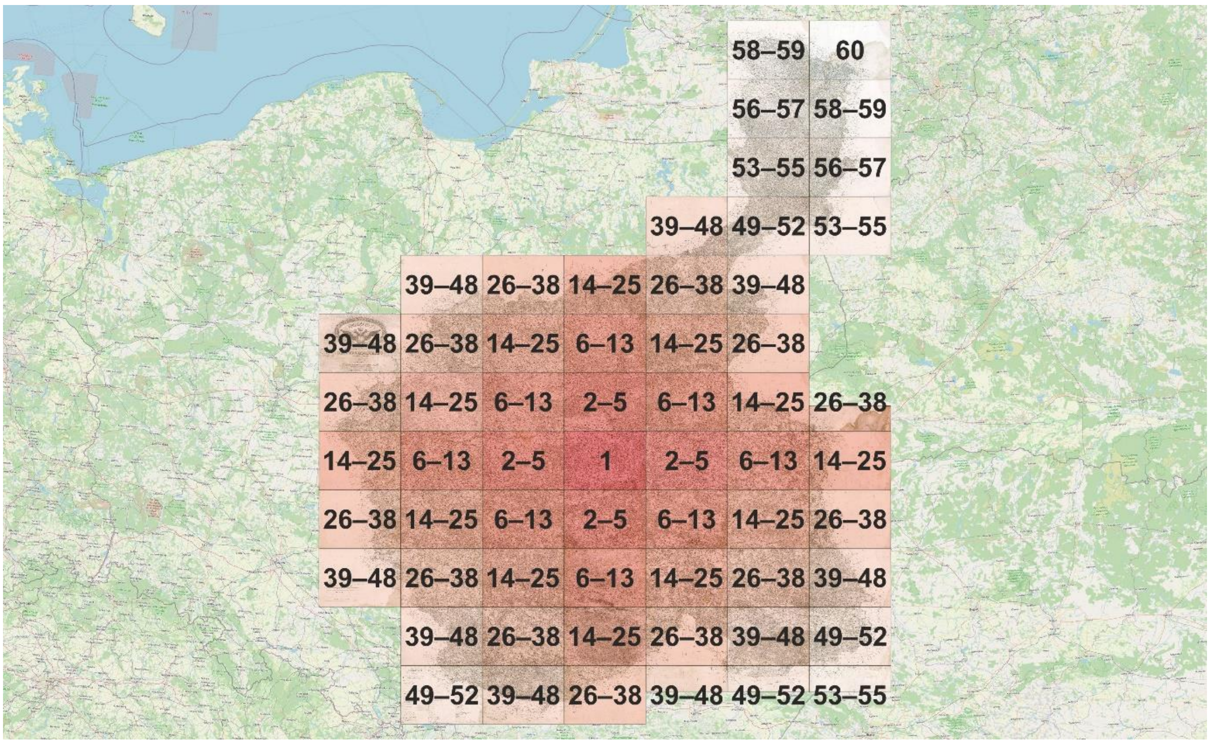


Figure 12. The order of rectification and seam alignment from the centre outward. Thanks to such planned actions, it was possible to align two edges of most sheets already at the initial rectification stage. OSM base map.

Upon approval, the project was exported into a unified mosaic file in the BigTIFF format. Due to the need for resource optimisation, the final file is in the form of a matrix with dimensions of approximately 75,000 × 92,000 pixels, a resolution of 500 dpi, and 8-bit colour depth (grayscale). The uncompressed GeoTIFF file size exceeds 13 GB! Manipulating such a large file in desktop GIS software requires very large computer resources (the program loads the entire file contents into the RAM cache), so before starting the actual georeferencing, the file underwent further cloud optimisation using GDAL libraries [124].

Cloud Optimized GeoTIFF files (COG) [124,125] change the data structure—the raster is internally divided into a series of smaller data packets called tiles, which are given a hierarchical (dependent on the view zoom) and spatial index (within the raster matrix). Proper index construction allows for loading only selected (visible at the moment) raster fragments into the program temporarily, without the need to load the entire file into the cache. Using JPEG compression allowed for the reduction of the file size to 1.2 GB, approximately 10 times, at the cost of slight quality loss. COG files are read by desktop-type programs just like standard GeoTIFF files, and a full range of raster operations can be performed on them, including georeferencing, mosaicking, etc.

2.6. Actual Georeferencing

The georeferencing of the unified TKKP COG mosaic proceeded similarly to standard methods of georeferencing historical maps, albeit on a much larger spatial scale. To maintain compatibility with popular spatial data services in Poland, ETRF2000/PL-1992 [126] was chosen as the target coordinate system. Georeferencing was conducted based on control points (CPs). The primary reference was the BDOT10k Visualization provided by GUGiK as a WMTS service [127]. For sheets of the Quartermaster's Map, whose content extended beyond the borders of contemporary Poland, OpenStreetMap was used as a reference. In a few cases where stable points could not be located on the contemporary reference map, the WIG Tactical Map of Poland at a scale of 1:100,000 provided as a WMS service by the 'Maps with the Past' project was used. The number of CPs from this source was not significant, so the analysis did not specify which map served as the reference in those cases.

During georeferencing, a hierarchy for selecting reference points was established. Analogous to the mathematical precision analyses conducted in the mid-20th century [7], priority was given to selecting religious objects present on both the archival map and the reference map. In the absence of such objects, road intersections were preferred as alternative locations for stable points, especially in remote areas. A total of 884 situational matching points and 11 peripheral points were marked to preserve the consistent shape of the map after segmentation. The table of 895 ground control points is included in the .CSV file (Figure 13; Supplementary Data—*TKKP_georeferencing_points.csv*).

The marking of control points resulted in affine transformation parameters (translation, rotation, scaling in one or both axes, skewing) expressed in the matrix form (Figure 14). The values B and C, equal to 0, indicate the conformal nature of the transformation. Globally, there is no rotation of the meridian axis or skewing of any axis of the coordinate system—in fact, the transformation conditions are reduced to a two-parameter function (translation, uniform scaling).

Analysis of distortion distribution based on estimating the minimum mean distances for the conformal 1st-degree polynomial showed displacements ranging from 7 to 4134 m in the terrain, corresponding to values from 0.05 to 32.8 mm on the physical map sheet (Figure 15). The root-mean-square error (RMSE) of the entire transformation matrix was 1209.8 m in the terrain, i.e., 9.6 mm on the map scale. This value is almost twice as high as the value calculated by D. Kwiatkowski [7] under the direction of S. Pietkiewicz ([8], p. 106–107). It is difficult to determine unequivocally whether the difference is due to the analysis being conducted on a unified mosaic of the map ([7] analysed only two selected sheets); the use of over 40 times more measurement points, including undeveloped areas; or the use of more accurate reference data (WIG's Tactical Map versus contemporary BDOT10k [127] and OSM data [27]). Considering the differences in the original projection (pseudo-conical conformal) and the target projection (transverse cylindrical conformal), the age of the map, the size of the area covered, technical flaws in the original archives, and their digital copies, the achieved result should be critically assessed. The difference in the position of map content and reference objects in 99.9% of cases exceeded 25.2 m in the terrain (0.2 mm on the map scale). Only 14 control points (1.5%) achieved a value below 126 m in the terrain (1 mm on the map scale). For 70% of all points, the error was within the range of 126–1260 m (1–10 mm on the map scale). A total of 26.5% of points obtained a displacement value above 1260 m in the terrain (10 mm on the map scale). The histogram of 1st-degree polynomial transformation errors has a positively skewed (left-sided) distribution. The arithmetic mean value (996.6 m) exceeds the median value (861.4 m) by over 15%, indicating that few outliers inflate the average error of the entire fit.

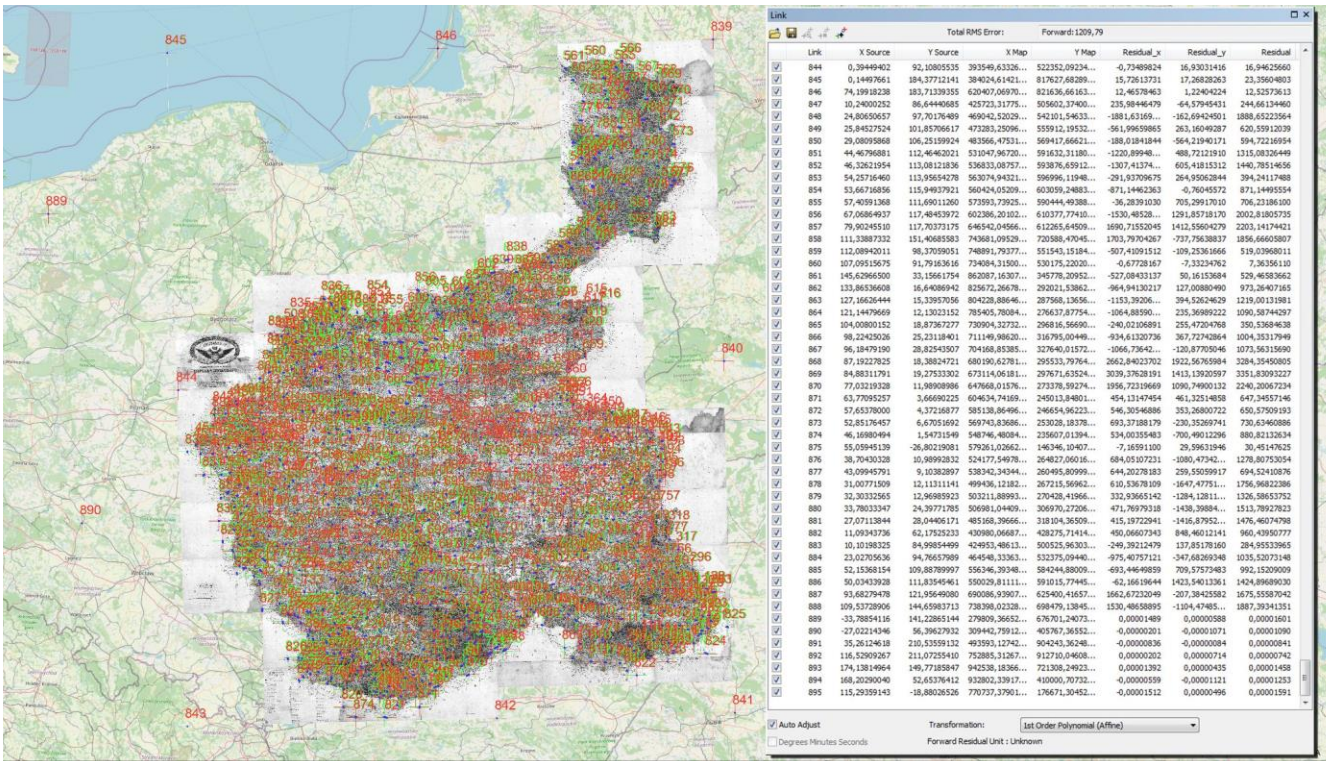
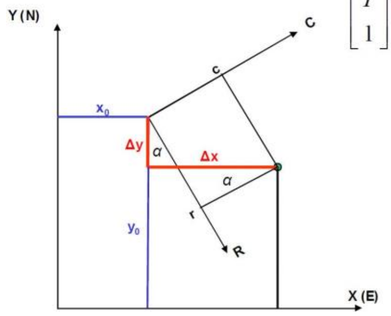


Figure 13. Distribution of georeferencing points for the unified TKKP—884 matching points and 11 peripheral points for maintaining consistent map shape after segmentation. OSM base map. All georeferencing points are included in the CSV format in the Supplementary Data package.

$$\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} A & C & E \\ B & D & F \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c \\ r \\ 1 \end{bmatrix}$$

$$\Delta X = c\cos\alpha + r\sin\alpha$$

$$\Delta Y = c\sin\alpha - r\cos\alpha$$



$$A = k\cos\alpha$$
$$B = k\sin\alpha$$
$$C = k\sin\alpha$$
$$D = -k\cos\alpha$$
$$E = x_0$$
$$F = y_0$$

A = 6.5857710000
B = 0.0000000000
C = 0.0000000000
D = −6.5857710000
E = 382552.6397292779
F = 829815.1735793545

Figure 14. Mathematical assumptions and calculated parameters of the affine transformation (1st-degree polynomial) of the unified mosaic TKKP raster.

(**a**)

(**b**)

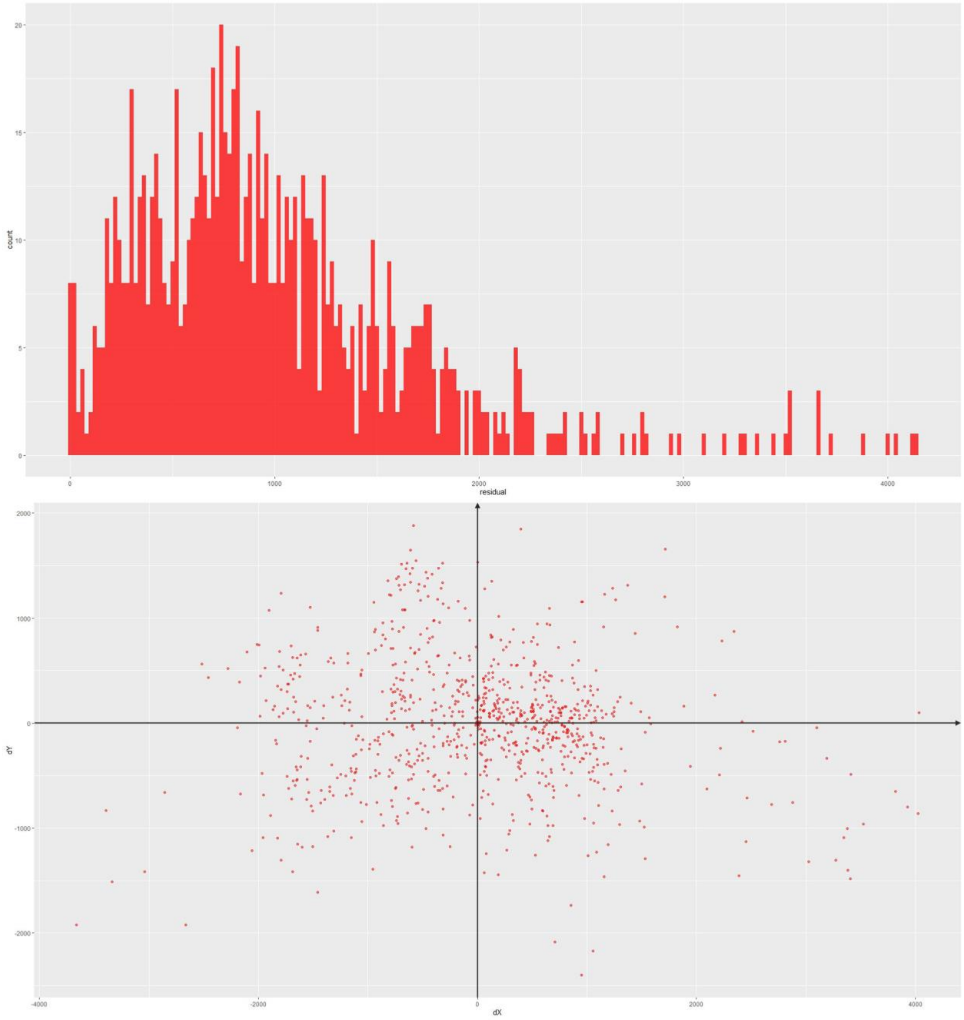


Figure 15. Distortions in the TKKP resulting from georeferencing of the unified mosaic on topographic points. (**a**) In the statistical analysis, residual error values of approximately 800–900 m in the terrain dominate (approximately 6–7 mm on the map scale). Positively skewed (left-sided) histogram. Statistical indicators: minimum = 0.0. . . m; quartile 1 = 520.0 m; median = 861.4 m; mean = 996.6 m; quartile 3 = 1293.7 m; maximum = 4134.5 m. (**b**) Shifts dX, dY of control points. Differences between affine transformation (1st-degree polynomial) and spline transformation (TPS/adjust) reach ±4000 m in the E–W axis and −3000/+2000 m in the N–S axis. The average dX, dY values are extremely close to 0, indicating that despite the significant spread of individual points, the centre of gravity of the transformation (Bonne_Kingdom_of_Poland2 reference frame) has been correctly determined. High-resolution plot images are added to the Supplementary Data.

Interestingly, the spatial distribution of distortions is highly irregular (Figure 16). Points with very high displacement values cluster in the northern part of the map, from the Vistula River (Nowy Dwór Mazowiecki-Płock) towards the border with Prussia (Dobrzyń-Mława). This region was partially covered on Gilly's map (1802–1803) and fully covered on Textor's map (1808). The largest displacements in this area are generally to the west (the map was originally to far east), but with different magnitude ranging from 1000 to over 4000 m. A second area of increased mismatch values is noticeable in the southern part of the map near Połaniec (Świętokrzyskie Province). This area was covered on Heldensfeld's map of West Gallicia (1808). The biggest displacements in this region are to northeast, reaching around 4000 m in the Vistula River Valley. Comparing the results of initial sheet rectification (Section 2.4) and actual georeferencing (Section 2.6), it can be inferred that the main cause of georeferencing inaccuracies is indeed the low mathematical precision of the source material, and other errors resulting from scan deformations, inaccurate sheet cutting, and changes in the cartographic projection of the map should be considered marginal. It is not surprising that the biggest distortions occur in remote densely forested areas (marshes in the north, mountainous areas in the south); however, it is surprising that this is generally the central part of the Polish Kingdom. Was the Topographic Chart of the Kindom of Poland a mere compilation of early 19th-century maps? Were these regions considered less strategically important and omitted in the field survey? Answering this, however, requires analogous analyses on source maps (Gilly's, Textor's, Heldensfeld's), 19th-century triangulation networks, and deeper historical investigation.

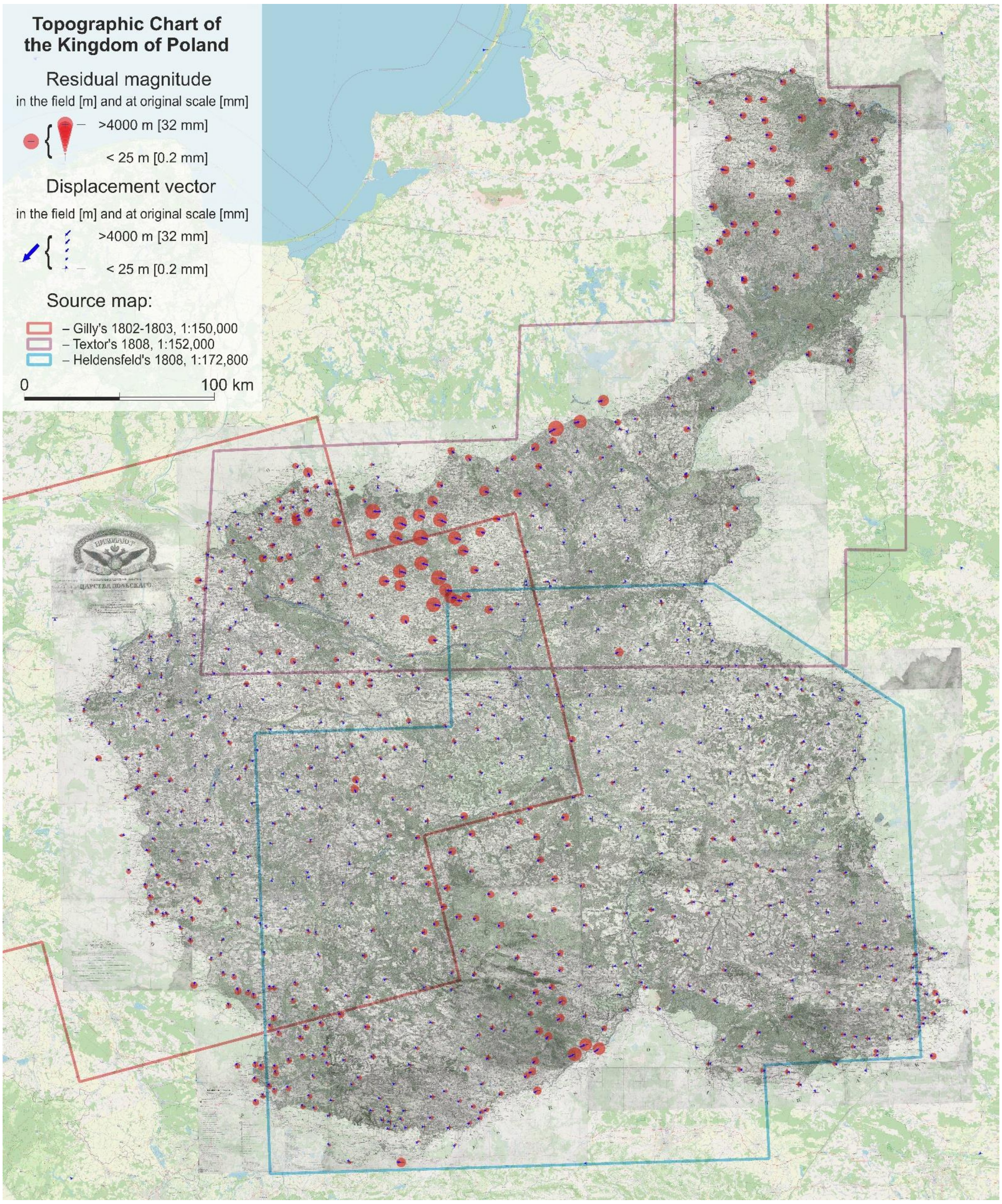


Figure 16. Distribution of TKKP residual magnitude and displacement vectors resulting from georeferencing the unified mosaic for 895 control points in the PL-1992 coordinate system (EPSG: 2180).

The red circle radius corresponds to the actual error size in the terrain. Blue arrows indicate displacement vectors. Coloured edges indicate source material (Gilly's, Textor's, Heldensfeld's) used during the surveys. Original size of the figure: 420 × 350 mm, scale: 1:1,500,000, resolution: 600 dpi. High-resolution georeferenced map available in the .JPG format along with .JGW georeference file in the Supplementary Data package.

Ultimately, the map raster was transformed using the TPS/adjust rubber-sheeting function, which resulted in image segmentation into an irregular network of triangles and absolute matching of the map content to the control points. The prepared file was generated as a new copy and saved in the ETRF2000/PL-1992 coordinate system [126]. After this, another copy was saved in WGS84/Web-Mercator [128] for OSM-based web-map applications.

3. Conclusions

The Topographic Chart of the Kingdom of Poland is an invaluable and epoch-making source of information about the past territories of the Kingdom of Poland. The richness and detail of its content, the aesthetics of the drawing, graphic consistency, and reproduction technique are testimony to the achievements of science and technology in the first half of the 19th century (Section 1.2).

The conducted research (Section 2.4) confirms the findings of Bojarowski et al. [11] regarding the very high precision of the cartographic grid drawing in Bonne's projection. The mean rectification error of sheets to the grid was 43 m on the ground (i.e., 0.34 mm on the map), and only 3% of the grid's nodal points were shifted by more than 126 m on the ground (up to approximately 280 m on the ground (2.2 mm on the map)). The analysis challenged the negative opinion of B. Krassowski [3] on paper distortion, although he likely examined a different set of TKKP sheets.

On the other hand, the analysis of the position of map content elements relative to ground control points (Section 2.6) revealed significantly larger displacements than described previously in the literature [7,8,11]. The average value of 996 m is nearly 1.5 times higher than that indicated by S. Pietkiewicz [8]. For 99.9% of cases, it exceeds 25.2 m on the ground (0.2 mm on the map scale), with only 1.5% falling within the range of 25.2–126 m (0.2–1.0 mm on the map scale), and over 70% of points have displacements in the range of 126–1260 m on the ground (1.0–10.0 mm on the map scale). These are typical values for maps of the analysed era, but without proper correction, these distortions would disqualify the TKKP as a source for mathematical quantitative analyses (measurements of lengths and areas of topographic elements). Unfortunately, over 26% of points have displacements above 1260 m on the ground (10.0 mm on the map scale)—with such a large number of points and their local clustering, there can be no question of a misinterpretation of content elements.

The above observations allow for three general conclusions:

1. Despite excellent geometric parameters, without establishing the correct relationships between the Wallbeck ellipsoid and WGS84, the geographic grid of the Bonne projection is not a reliable element of the mathematical framework (Figures 7 and 9). This direction requires further in-depth research into the position of triangulation network elements in the 19th century, and the issue goes beyond the scope of this article.
2. The uneven distribution of displacements of topographic content elements shown in charts and maps (Figures 15 and 16; Supplementary Data) dispels the myth of high mathematical precision and the uniform nature of the work.
3. Precise mapping of the distortions of the Topographic Chart of the Kindom of Poland (Section 2.6) provides interesting insights, raises new research questions, and sets directions for further research.

The merging and georeferencing of the unified TKKP mosaic posed a significant challenge. It was not possible to determine the exact parameters of the Bonne projection transformation allowing for direct georeferencing using map coordinates. The developed mathematical basis provides a satisfactory approximation of the grid shape for sheet rectification (Figure 7). Unfortunately, due to the irregular extent, manual vectorisation of the index was necessary. Despite content losses near physically cut frames, the alignment of seams is satisfactory—the mosaic is coherent and, with few exceptions, represents the terrain in a continuous form (Figure 11). Actual georeferencing using topographic objects was very labourious, but it allowed for the processing of the TKKP into a form as consistent as possible with contemporary reference data (Figures 1 and 13). The included tables of control points (Supplementary Data) and cartographic visualisation of distortions (Figure 16) serve as a proverbial 'certificate of quality' for digital editing. The authors hope that the publication of the TKKP on the 'Maps with the Past' portal [21] and in the form of OGC services [125] under the Creative Commons licence [129] will contribute to the scientific community of Poland and Central Europe and will be the basis for many further studies in the field of spatial humanities. The conducted methodological procedure is universal and can be used to develop multi-sheet maps with both regular and irregular sectional cuts. This opens the way to the development of many other maps—from local scales (survey plans of cities and rural areas) to maps of the entire world.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi13070249/s1, Data 1 *TKKP_rectification.csv*; Data 2 *TKKP_georeferencing_points.csv*.

Author Contributions: Conceptualization: Jakub Kuna, Tomasz Panecki, and Mateusz Zawadzki; research: Jakub Kuna, Tomasz Panecki, and Mateusz Zawadzki; abstract: Jakub Kuna; Section 1: Tomasz Panecki and Mateusz Zawadzki; Section 2: Jakub Kuna; Section 3: Jakub Kuna, Tomasz Panecki, and Mateusz Zawadzki; literature review: Jakub Kuna, Tomasz Panecki, and Mateusz Zawadzki; GIS analyses: Jakub Kuna and Mateusz Zawadzki; figures: Jakub Kuna; tables: Mateusz Zawadzki; Supplementary Data: Jakub Kuna; translation: Jakub Kuna and Tomasz Panecki; proofreading: Tomasz Panecki; funding: Tomasz Panecki. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: (1) The study data are included in this article and its Supplementary Data Files in WGS84 (EPSG: 4326), .CSV format. File *TKKP_rectification.csv* including rectification points of 60 separate sheets of the Topographic Chart of the Kingdom of Poland as described in the article. File *TKKP_georeferencing_points.csv* includes georeferencing points of mosaicked Topographic Chart of the Kingdom of Poland as described in the article. (2) The georeferenced mosaic of the Topographic Chart of the Kingdom of Poland is available via OGC raster data services as described in the article. The Cloud Optimized GeoTIFF file address for QGIS users is https-encrypted at *portal.analytics.umcs.pl/repo/COG/TKKP_126k_cogc_3857.tif*.

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Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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