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A 225-Year (1799–2024) Homogenized Daily Water Level Series of the Vistula River in Warsaw

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Abstract.

We present a 225-year (1799–2024) homogenized daily water level series for the Vistula River in Warsaw, comprising 82,453 observations. The construction of this consistent dataset required adjustments for changes in gauge location, shifts in gauge zero, differences in historical measurement units, and calendar discrepancies between the Julian and Gregorian systems. A small number of observations were reconstructed using stage–stage relationships established between overlapping periods of observation at the Warsaw gauge and parallel measurements from downstream stations along the Vistula. The resulting dataset offers a robust foundation for long-term hydrological, climatic, and socio-environmental research. The dataset is openly available at Zenodo repository: https://doi.org/10.5281/zenodo.16919654 (Sobechowicz et al., 2025).

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1 Introduction

Long-term series of instrumental meteorological and hydrographic measurements are essential not only for documenting past weather conditions and water levels, but above all for reconstructing paleoenvironmental conditions and for calibrating climate and hydrological models (cf. Glaser and Stangl, 2004; Brázdil et al., 2006; Cyberski et al., 2006; Macdonald and Sangster, 2017; Brönnimann et al., 2019; Rottler et al., 2020; Nasreen et al., 2022; Sánchez-García et al., 2023). Particularly valuable are the rare hydrological records that extend back to the pre-industrial era. Such long-term datasets play a fundamental role in assessing historical variability, detecting long-term trends, and providing benchmarks for model validation. Prominent examples include two-hundred-year-long river water level records in Europe, such as the Lower River Rhine at the gauges in Nijmegen, Pannerden, and Emmerich (since 1772; Toonen, 2015), the River Rhine in Cologne (since 1782; e.g. Herget and Meurs, 2010), the River Rhine in Basel (since 1808; e.g. Wetter et al., 2011), the River Rhine in Maxau (since 1815; e.g. Lang et al., 2025), and the River Rhône in Beaucaire (since 1816; e.g. Pichard et al., 2017), among others.

The Vistula River, as Poland's longest river and a key element of the country's hydrological system, has been monitored in Warsaw since the end of the 18th century. Daily water level observations from the Warsaw gauge date back to 1799, making them potentially one of the longest hydrometric records in Europe. However, despite their historical value, these data have remained underutilized in scientific research due to their fragmented publication history, varying measurement units, changes in gauge location and zero reference levels, and calendar inconsistencies between Julian and Gregorian systems. Although portions of the dataset have been published in historical hydrological works (Kolberg, 1861; Słowikowski, 1881), they were never fully consolidated into a single, continuous, and comparable time series. The first attempts to reconstruct water levels of the Vistula River in Warsaw for the period 1799–2000 focused on the series of characteristic annual water levels, i.e., maximum, mean, and minimum values (Fal and Dąbrowski, 2001a, 2001b). Interest in reconstructing water levels of the Vistula River in Warsaw has primarily focused on the highest water levels, with the aim of reconstructing peak flow events of the Vistula in the Warsaw reach (Magnuszewski and Gutry-Korycka, 2009; Magnuszewski et al., 2012). Earlier, in the first half of the 20th century, interest was likewise limited to characteristic water level values, which were needed for designing hydraulic engineering works on the Vistula in Warsaw (Siebauer, 1929), or for calculating the probability of high-water events on the Vistula in Warsaw (Pomianowski et al., 1939). As a result, this limited perspective excluded the valuable long-term context provided by daily measurements. The aim of the present study is to reconstruct and publish a standardized daily time series of water levels for the Vistula River in Warsaw, covering the entire period from 1799 to 2024. This unified dataset, comprising over 82,000 daily observations, constitutes the longest continuous daily water level record available for the Vistula River and provides a robust foundation for long-term hydrological and environmental research.

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2 Study area

The study focuses on the middle course of the Vistula River, particularly the section flowing through Warsaw (km 407–437), where daily water level measurements have been recorded since 1799. Due to intensive urban development, flood protection measures, and infrastructure construction, the riverbed in Warsaw has been artificially confined to a much narrower channel, commonly referred to as the "Warsaw corset", with a fixed width of approximately 400 m. This artificial narrowing is a direct result of the Vistula flowing through a densely populated and highly urbanized area. Another major anthropogenic impact on the Warsaw reach is the progressive lowering of the riverbed, primarily driven by large-scale extraction of sand and gravel for construction purposes during the 19th and 20th centuries (Magnuszewski et al., 2012). This deepening of the channel not only altered local hydraulics but also necessitated multiple adjustments to the reference level (gauge zero) at the Warsaw gauging station. These changes had to be carefully accounted for in the homogenization process of the long-term water level series.

To support the reconstruction and verification of the Warsaw dataset, auxiliary observations were used from two downstream gauging stations: in Toruń (km 207 of the Vistula River), and in Cypel Mątowski - in the upper part of the Vistula River delta (km 55 of the Vistula River). These stations provided reference data for constructing stage–stage relationships and for identifying anomalies or discontinuities in the Warsaw record. Their location within the same river basin and main channel ensured hydrological comparability and consistency over time.

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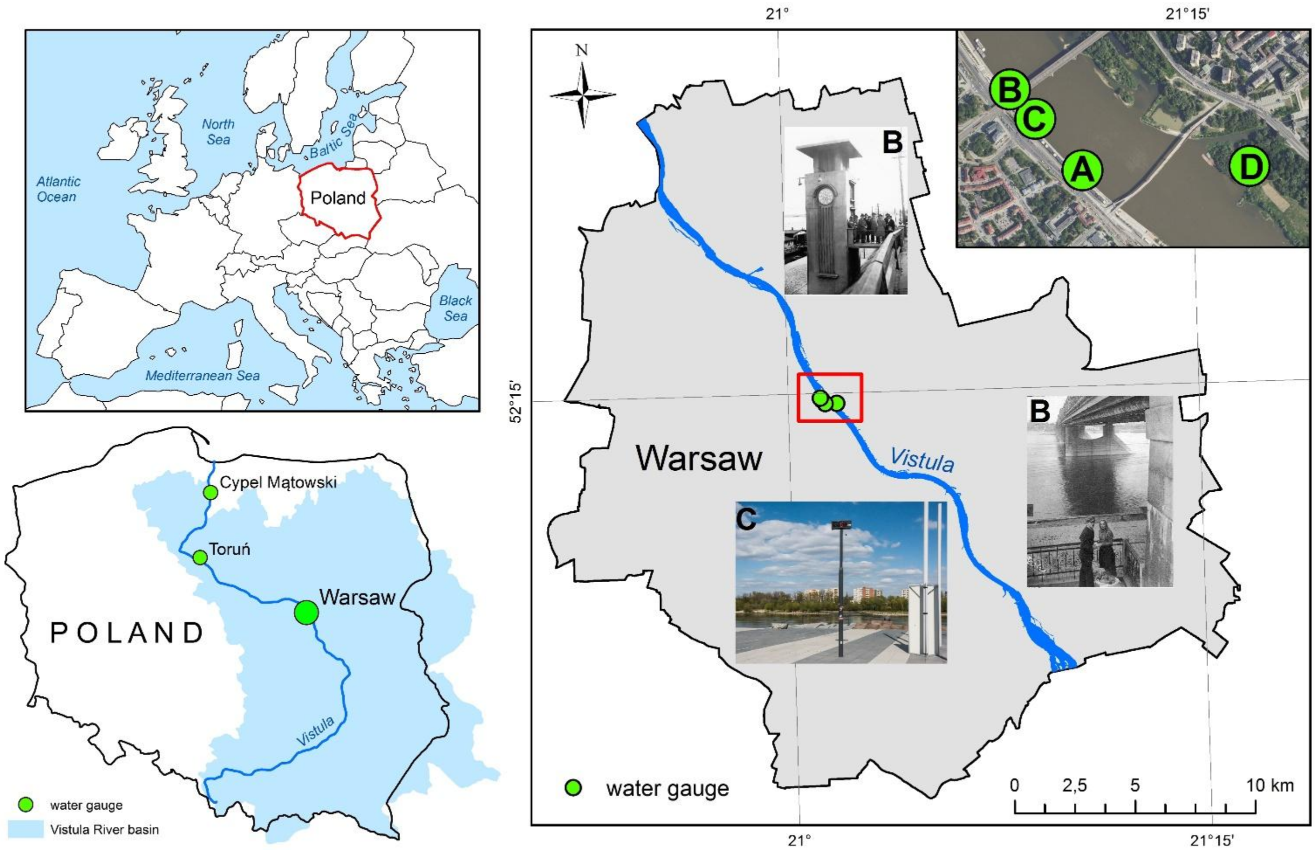

Figure 1: Location of historical Warsaw water gauges and auxiliary stations along the Vistula River: (A) Poniński Bridge 1799–1864, (B) Kierbedź Bridge 1864–1937, (C) Warsaw-Boulevards 1937–1959 and 2017–2024, (D) Praga Port 1959–2017. Map by the author. Photograph sources: (B) National Digital Archives, Warsaw; (C) Wikimedia Commons.

3 Data processing

3.1 Data sources

The earliest preserved water level measurements of the Vistula River in Warsaw (1799–1860) were compiled, standardized, and published by Wilhelm Kolberg (1861). Kolberg was an engineer and member of the Corps of Engineers of the Polish Army, involved in major hydraulic and infrastructural projects, including the construction of the Augustów Canal, the largest hydrotechnical project of the Kingdom of Poland and the Warsaw–Vienna Railway, the first railway line in the country. Kolberg's publication was the first to consolidate daily water level observations and river freezing dates for Kraków, Warsaw, and Kwidzyn, representing the upper, middle, and lower reaches of the Vistula. His work was motivated by the conviction that reliable hydrological data were essential for improving navigation and designing hydraulic works. He

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emphasized that knowledge of water levels, ice formation, and break-up had been previously poorly examined, little disseminated, and unsystematized. Our database includes data from this publication for the years 1799 to 1859. For the subsequent period of 1860 to 1879, data were published by Józef Słowikowski in 1881. His work closely follows Kolberg's study and serves as a continuation of it. It includes water level measurements for the Vistula River in Warsaw and provided data for our database for the entire observation period from 1860 to 1879. In 1876, a new water gauge was installed that used the English Imperial measurement system, which was also adopted in the Russian Empire. For the years 1876 to 1880, Russian hydrologists published data in graphical form in a yearbook titled “Svedeniya o stoyaniyakh” (1881), which ran parallel to Słowikowski's publication. Data for 1880 were obtained by digitizing a drawing of a water level hydrograph from this publication. From 1881 to 1910, Russian hydrological yearbooks continued in tabular form over three volumes (“Svedeniya ob urovne”, published in 1907, 1909, and 1915), covering the periods 1881–1890, 1891–1900, and 1901–1910, respectively. The complete data from these three volumes were incorporated into our database. For the data spanning 1911 to 1914, we utilized information contained in German hydrological yearbooks for the Northern Germany region (within its borders at that time), published as “Jahrbuch für die Gewässerkunde Norddeutschlands” (1912–1915). Observations from 1919 to 1980 were sourced from published hydrological yearbooks, which underwent two name changes and were issued by Polish hydrological services. During the period from 1919 to 1944, these yearbooks were titled “Roczniki Hydrograficzne. Dorzecze Wisły” and published from 1920 to 1945. Post-war data from 1945 to 1960 appeared in the Hydrographic Yearbook “Rocznik Hydrograficzny. Wisła i rzeki przybrzeżne na wschód od Wisły”, with publication years ranging from 1946 to 1961. From 1961 to 1980, water level data were published in the Hydrographic Yearbook “Rocznik Hydrograficzny. Wody powierzchniowe”, corresponding to publication years from 1962 to 1981. From 1981 to 2024, daily water level data for the Warsaw station are available in digital format through the database of the Institute of Meteorology and Water Management in Warsaw (IMGW): https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/. All sources used in this study are listed in a separate supplementary file, which provides full bibliographic details for each volume, including information on the availability of digital copies.

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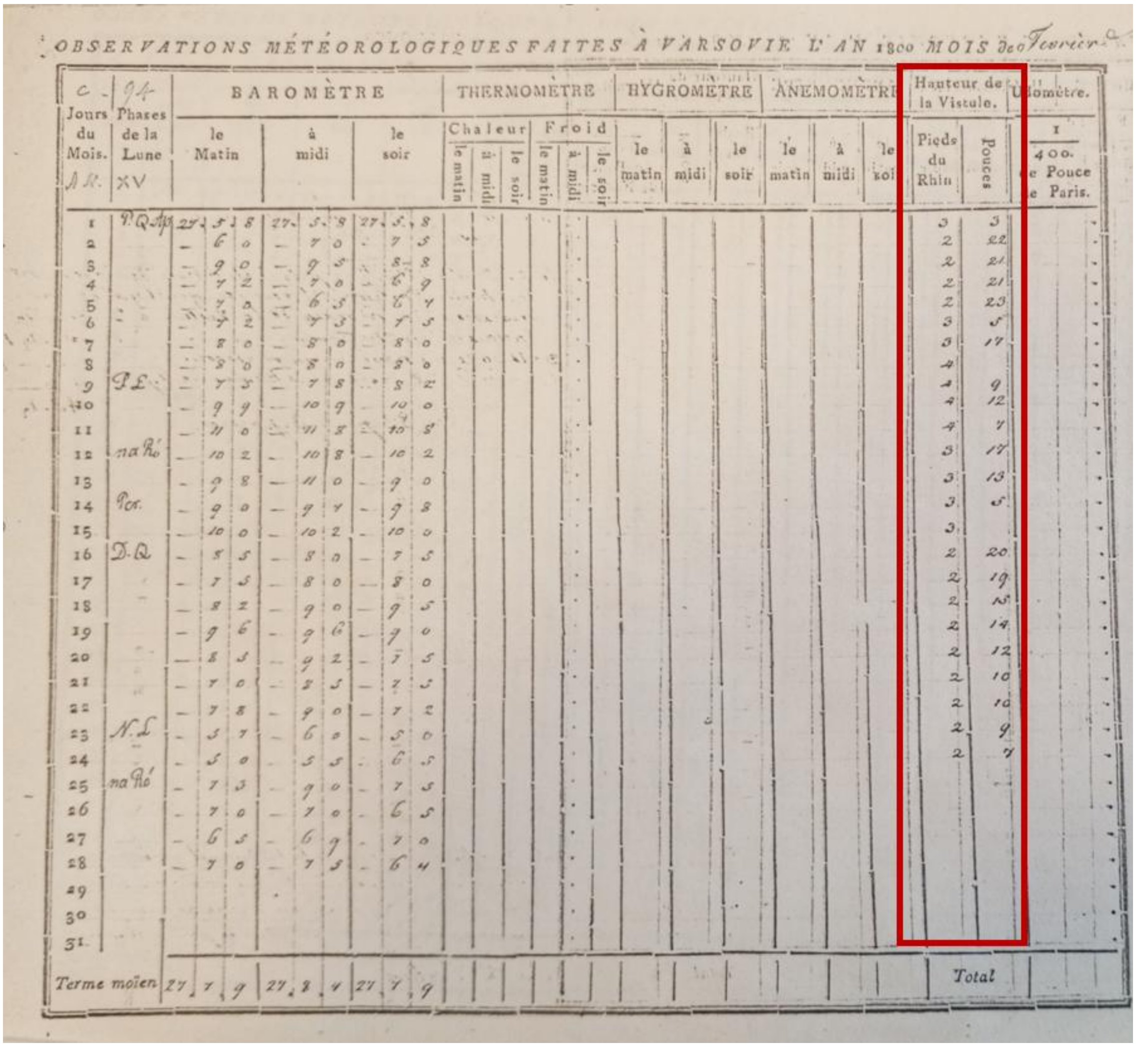

Figure 2: Facsimile of a record sheet containing meteorological measurements and water level observations from Warsaw, February 1800. The Vistula River stage is shown in the penultimate column. Held at the Library of the Institute of Meteorology and Water Management in Warsaw, reference no. C3052.

3.2 Reference data

In addition to the primary sources for the Warsaw gauge, we used daily water level series from two downstream stations on the Vistula River: Toruń (river km 207) and Cypel Mątowski (river km 55). These long-term records served as reference data for reconstructing missing observations in the Warsaw dataset. Their hydrological continuity and proximity within the same river basin made them suitable for deriving stage–stage relationships. Further details on the methodology and application of these reference series are provided in Section 3.8. Water level data from the Toruń gauge were published by Makowski

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(2002). Observations from Cypel Mątowski for the years 1799–1828 are preserved in the State Archive in Gdańsk, reference number 7/431. These early measurements have been described and analysed in detail by Kazusek (2025).

3.3 Changes in the location of water level observations in Warsaw

The first water gauge in Warsaw was installed on the left bank of the Vistula River, near the wooden pontoon bridge known as the Poniński Bridge (see Fig. 1). The bridge was located along the extension of Bednarska Street on the Mariensztat side and Kłopotowskiego Street on the Praga side, at river km 421+600. After the construction of the first permanent bridge (Kierbedź Bridge) in 1864, the Warsaw gauge was relocated to the western pier of the new crossing, at river km 421+300. In 1937, the gauge was moved approximately 90 m upstream, to km 421+400. In 1959, it was transferred to the right bank of the river, near the Praga Port, at km 421+900. Initially, it was mounted on the western wall of the southern pier of the bridge over the canal leading to the port. Later, a new gauge staff was installed on the dock of the Praga Port. Since the beginning of the 2018 hydrological year, water level measurements have been restored in the area of the original 19th-century observation site. After the construction of the new river boulevards on the left bank at km 421+400, a new gauge staff with an electronic water level display was installed and designated as the Warsaw-Boulevards station.

3.4 Changes in the zero reference level of the Warsaw gauges

Initially, the Warsaw water gauge did not have a defined zero level referenced to any fixed point. Only from 1 January 1834, was the gauge zero established relative to the high water mark from the 1813 flood (permanently marked on one of the buildings on Bednarska Street), in such a way that the mark corresponded to 21 *stopy* on the gauge scale (*New Polish system*, 21 *stopy* = 604.8 cm). Earlier readings should be increased by 14 cm, as the gauge zero was raised by that amount during the first leveling. In 1848, the gauge zero was tied to the newly established national leveling network. Its elevation was set at 76.991 m above the level of the Baltic Sea near Palanga, without changing the physical location of the gauge (Fal and Dąbrowski, 2001; Witkowski, 1907). On 23 October 1855, the zero was lowered by approximately 5 cm. After the gauge was relocated to the pier of the Kierbedź Bridge (see Fig. 1) in 1864 (taking into account the river's water surface slope), the gauge zero was adjusted again on 13 April 1867, raising it back by 5 cm to 76.876 m above the Baltic Sea level near Palanga. On 13 December 1886, a minor correction was made, lowering the gauge zero by 8.5 cm to 76.791 m, due to a prolonged low-flow period. The zero level was lowered once again on 1 November 1958, when measurements were transferred to the Praga Port site. This change accounted for the long-observed lowering of the riverbed in the Warsaw section, and the new gauge zero was adjusted so that readings would be approximately 200 cm higher, reflecting the vertical shift in water surface elevation caused by riverbed erosion (a process identified since the 1940s). During the most recent relocation on 1 November 2017, the zero level remained unchanged at 76.076 m a.s.l. (Kronstadt 60). However, due to

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further lowering of the water surface, readings at the new site (Warsaw-Boulevards) are approximately 14 cm lower than those recorded previously at the Praga Port gauge. Due to the ongoing erosion of the Vistula riverbed, the reference point of the Warsaw-Boulevards gauge was once again lowered by 1 metre at the end of the 2025 hydrological year. When extending the presented database with future observations, this change in the reference point must be taken into account, or alternatively, all data should be expressed in metres above sea level (EVRF2007, m a.s.l.) to ensure consistency.

Table 1. Corrections to original water level observations at the Warsaw gauge (1799–2024)

Date		Gauge location	Correction to original readings	Comment
1799-02-01	1833-12-31	Left bank, near pontoon bridge km 421+600	+14 cm	First leveling in 1834 raised zero by 14 cm; earlier readings adjusted upward
1834-01-01	1855-10-22	Same location	0 cm	Stable gauge zero
1855-10-23	1864-11-21	Same location	-5 cm	Gauge zero lowered by ~5 cm
1864-11-22	1867-04-12	Kierbedź Bridge (western pier) km 421+300	-5 cm	New location
1867-04-13	1886-12-12	Same location	0 cm	Zero raised back by 5 cm
1886-12-13	1958-10-31	Same location	-8.5 cm	Gauge zero lowered due to prolonged low-flow conditions
1958-11-01	2017-10-31	Port Praga (right bank) km 421+900	-200 cm	Gauge zero lowered due to riverbed erosion (dredging, sand extraction)
2017-11-01	2024-10-31	Warsaw-Boulevards (left bank) km 421+400	-14 cm	Same zero as Praga Port, but readings are ~14 cm lower due to further riverbed incision

3.5 Measurement units used at the Warsaw gauges

In the past, water level measurements on the Vistula River in Warsaw were recorded using various national and regional systems, including Warsaw units, Dutch units, New Polish units, English Imperial units, and Russian units. A consistent transition to the metric system, with centimetre-level precision, was not implemented until World War I. Table 2 summarizes the periods during which different measurement systems were in use, along with the conversion factors applied to harmonize them with the metric system.

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Table 2. Measurement units used at the Warsaw gauges

Period	Unit	Measurement system	Metric conversion	Accuracy
February 1799–February 1810	1 *Rheinfuß* (foot) = 12 *zoll* (inches)	Dutch units	0,31385 m	~2,61 cm
March 1810–December 1833	1 *stopa* (foot) = 12 *cali* (inches)	Warsaw units	0,2978 m	~2,48 cm
January 1834–February 1866	1 *stopa* (foot) = 12 *cali* (inches)	New Polish units	0,288 m	~2,40 cm
March1866–December 1879	1 foot = 12 inches	English Imperial system	0,3048 m	~2,54 cm
January 1880–July 1914	1/100 *sazhen* (fathom)	Russian units	0,02134 m	~2,13 cm
August 1914–December 2024	1 metre = 100 cm	Metric system	-	1 cm

3.6 Timing and accuracy of water level readings

The water levels collected in the database differ in the way they were compiled in the respective historical period, as well as due to the progress of the digital revolution in the 21st century. Data up to the end of the 20th century are time-based observations, collected within the obligatory deadline defined as the morning hours, specified as 6:00 a.m. (Instrukcja dla obserwatorów stacyj wodowskazowych, 1923) from 1950 onwards as 7:00 a.m. local time (Rocznik Hydrograficzny. Wisła i rzeki Przymorza na wschód od Wisły, 1950). In contrast, in 2001/2005 in Poland, within the framework of the Monitoring System for National Protection project, the measurement network was upgraded with automatic hydrological stations (Szumiejko et al., 2015). Therefore, from that period on, the data on daily water levels on the Vistula River were processed and stored in the Central Historical Database of the Institute of Meteorology and Water Management in Warsaw, which is a chronological average of measurements recorded every 10 minutes. It has to be pointed out that water levels presented in the database are not extraordinary observations but daily values - defined as timely values until the end of the 20th century and since the beginning of the 21st century calculated as chronological averages.

Information on the accuracy of water level readings has been provided since 1919, when the centimetre scale gauges appeared. The accuracy of the reading is 1cm, on water gauge patches which in most cases have a two-centimetre scale (Instrukcja dla obserwatorów stacyj wodowskazowych, 1923).

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3.7 Calendar systems

In the 19th century, both the Gregorian and Julian calendars were used in Polish territories, depending on the administrative and political context. Daily water level measurements of the Vistula River from 1799 to 1879 were recorded according to the Gregorian calendar. However, from 1880 to 1910, official Russian publications, which reported water levels, used the Julian calendar. The difference between the two calendars amounted to 12 days until 1 March 1900; after that date, it increased to 13 days. This distinction is essential for the correct interpretation and chronological alignment of hydrological data from different periods.

3.8 Gaps in the dataset and methods of reconstruction

The dataset comprises 82,453 daily water level observations for the Vistula River. Missing data account for 3,416 days, representing 4% of the total. The most significant gaps correspond to three distinct periods: from 1 December 1815 to 13 July 1817, when ice floes destroyed the bridge and the gauge located beneath it, and from 29 July 1914 to 31 December 1918, coinciding with World War I and the German occupation of Warsaw. A complete list of all data gaps, along with the methods used for their reconstruction, is provided in Table 3.

Figure 3 illustrates the process of filling missing values using interpolation based on data from another gauging station on the Vistula River.

Table 3. Gaps in the dataset and methods of reconstruction

ID	Missing data period (YYYY-MM-DD)		Number of days	Parallel series location	Distance (km)	Lag (days)	Reconstruction method
1	1799-02-25	1799-02-28	4	—	—	—	Linear interpolation
2	1799-12-14	1800-01-27	45	Cypel Mątowski	366	4	Gauge relationship 1801
3	1800-02-01	1800-03-31	59	Cypel Mątowski	366	4	Gauge relationship 1801
4	1801-01-19	1801-03-02	43	Cypel Mątowski	366	4	Gauge relationship 1801
5	1801-06-05	1801-06-30	26	Cypel Mątowski	366	4	Gauge relationship 1801
6	1801-07-22	1801-07-26	5	Cypel Mątowski	366	4	Gauge relationship 1801
7	1801-10-01	1801-10-20	20	Cypel Mątowski	366	4	Gauge relationship

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							1801
8	1801-10-28	1801-12-04	38	Cypel Mątowski	366	4	Gauge relationship 1801
9	1801-12-24	1802-03-09	76	Cypel Mątowski	366	4	Gauge relationship 1801
10	1802-12-25	1803-03-06	72	Cypel Mątowski	366	4	Gauge relationship 1801
11	1803-12-01	1803-12-10	10	Cypel Mątowski	366	4	Gauge relationship 1801
12	1803-12-19	1804-01-02	15	Cypel Mątowski	366	4	Gauge relationship 1801
13	1804-01-10	1804-01-19	10	Cypel Mątowski	366	4	Gauge relationship 1801
14	1804-02-12	1804-03-21	39	Cypel Mątowski	366	4	Gauge relationship 1801
15	1804-11-07	1804-12-31	55	Cypel Mątowski	366	4	Gauge relationship 1801
16	1805-01-01	1805-02-28	59	Cypel Mątowski	366	4	Gauge relationship 1805
17	1805-06-28	1805-07-15	18	Cypel Mątowski	366	4	Gauge relationship 1805
18	1805-08-09	1805-08-31	23	Cypel Mątowski	366	4	Gauge relationship 1805
19	1805-10-31	1805-11-06	7	Cypel Mątowski	366	4	Gauge relationship 1805
20	1805-11-14	1805-11-25	12	Cypel Mątowski	366	4	Gauge relationship 1805
21	1805-12-18	1805-12-31	14	Cypel Mątowski	366	4	Gauge relationship 1805
22	1807-01-18	1807-02-18	32	Cypel Mątowski	366	4	Gauge relationship 1805
23	1807-12-15	1808-02-05	53	Cypel Mątowski	366	4	Gauge relationship 1805
24	1808-02-25	1808-04-04	40	Cypel Mątowski	366	4	Gauge relationship 1805
25	1808-05-30	1808-05-31	2	—	—	—	Linear interpolation
26	1808-12-01	1809-02-02	64	Cypel Mątowski	366	4	Gauge relationship 1805
27	1809-02-14	1809-06-30	137	Cypel Mątowski	366	4	Gauge relationship 1805
28	1809-11-27	1809-11-30	4	Cypel Mątowski	366	4	Gauge relationship 1805
29	1809-12-24	1810-01-07	8	Cypel Mątowski	366	4	Gauge relationship 1805
30	1810-01-01	1810-01-07	7	Cypel Mątowski	366	4	Gauge relationship 1814
31	1810-01-20	1810-01-31	12	Cypel Mątowski	366	4	Gauge relationship

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							1814
32	1811-01-01	1811-02-28	59	Cypel Mątowski	366	4	Gauge relationship 1814
33	1811-05-31	1811-05-31	1	—	—	—	Linear interpolation
34	1811-12-22	1812-02-29	70	Cypel Mątowski	366	4	Gauge relationship 1814
35	1812-12-11	1813-02-18	70	Cypel Mątowski	366	4	Gauge relationship 1814
36	1814-01-01	1814-01-08	8	Cypel Mątowski	366	4	Gauge relationship 1814
37	1815-01-01	1815-02-28	59	Cypel Mątowski	366	4	Gauge relationship 1814
38	1815-12-01	1816-12-31	397	Cypel Mątowski	366	4	Gauge relationship 1814
39	1817-01-01	1817-07-13	194	Toruń	214	2	Gauge relationship 1818
40	1831-05-25	1831-05-31	7	—	—	—	Linear interpolation
41	1832-04-20	1832-04-23	4	—	—	—	Linear interpolation
42	1834-10-12	1834-10-16	5	—	—	—	Linear interpolation
43	1834-10-26	1834-10-27	2	—	—	—	Linear interpolation
44	1914-07-29	1915-10-06	434	Toruń	214	2	Gauge relationship 1919
45	1915-10-07	1918-12-31	1095	Toruń	214	2	Gauge relationship 1919

Missing daily water level values for the Vistula River in Warsaw were reconstructed using regression-based relationships with data from two other stations: the Vistula River in Toruń and in Cypel Mątowski (see Fig. 1). The relationships established between water levels in Warsaw and those recorded at Toruń, as well as between Warsaw and Cypel Mątowski, are referred to as gauge relationships. This method relies on the observation that similar hydrological events (such as floods or low flows) occur successively at gauging stations located along the same river or on neighbouring rivers, with a certain time lag (Byczkowski, 1996). To build reliable regression models, we selected calendar years with the most complete daily water level records available. Furthermore, we accounted for the fact that such relationships may change over time, most often due to modifications in the river cross-section at one of the gauging sites. This step was crucial to ensure the accuracy and reliability of the reconstructed values (Ozga-Zielińska and Brzeziński, 1997). Therefore, missing values in the Warsaw dataset were reconstructed using multiple regression models developed for the years 1801, 1805, 1814, 1818, and 1919. These years were selected to lie as close as possible, both before and after the periods of missing observations.

To establish the gauge-to-gauge relationships, daily water level series from both stations were visualized to identify hydrologically corresponding values (e.g., peaks, local minima, or the onset of flood waves). An essential part of the

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procedure was accounting for the travel time of water between stations (Kiciński et al., 1994). This travel time is not constant, as it depends on flow velocity, which typically increases with channel filling (Ozga-Zielińska and Brzeziński, 1997). In our reconstructions of water levels for the Vistula in Warsaw, we used average travel times reported by (Dębski, 1958), based on earlier work by (Kollis, 1938), which align with our independent estimates. The adopted average delays were two days from Warsaw to Toruń, and four days from Warsaw to Cypel Mątowski. The parameters of each linear regression model are presented in Table 4.

Table 4. Parameters of linear regression models used for gauge relationships

Year	Reference gauge station	Regression equation $y = a \cdot x + b$	R^2	Number of corresponding daily values (n)
1801	Cypel Mątowski	$y = 1.0459x - 43.413$	0.92	21
1805	Cypel Mątowski	$y = 1.0332x - 21.62$	0.90	22
1814	Cypel Mątowski	$y = 0.9245x - 70.055$	0.96	17
1818	Toruń	$y = 0.9147x - 27.259$	0.91	29
1919	Toruń	$y = 0.6515x + 82.709$	0.92	19

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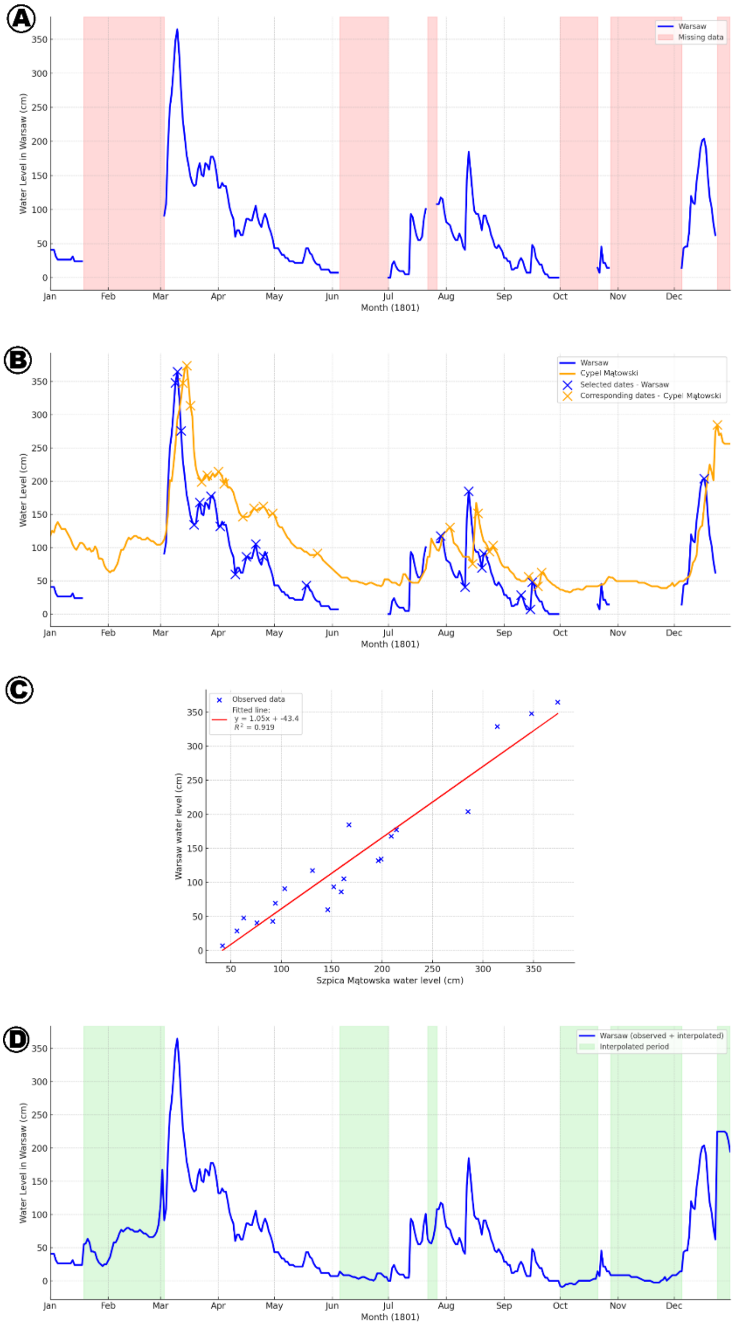

Figure 3: Reconstruction of daily water levels in Warsaw (1801) using data from another gauging station in Cypel Mątowski

Figure 3. illustrate the step-by-step procedure used to interpolate missing data, exemplified by the case of the year 1801:

(A) Identification of missing data periods

(B) Matching key points between stations

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(C) Construction of a linear regression model

(D) Reconstruction of missing data

Daily water level observations for Warsaw in 1801 are incomplete (A), with a total of 140 missing days scattered throughout the year. These gaps are highlighted in red. To address this, daily measurements from the Cypel Mątowski station were used to identify hydrologically meaningful points, known as corresponding values, such as peaks, local minima, or the onset of flood waves, which are visible in both time series. These matched dates provide the basis for constructing the gauge relationship (B). A linear regression model was fitted. The resulting model shows a strong correlation ($R^2 = 0.92$), enabling reliable reconstruction of the missing values in the Warsaw series (C). The fitted regression equation was applied to estimate missing water levels in Warsaw, incorporating the assumed travel time of water between the two stations. The interpolated periods are indicated in green (D).

3.9 Technical validation

The long, over two-hundred-year series of daily water level observations on the Vistula River holds exceptional research value, but also presents significant challenges related to data quality and consistency. In order to make reliable use of these data, both in hydrological and historical analyses, a critical assessment of the series' credibility and homogeneity was necessary. This need is justified by two main considerations:

1. Filling gaps in historical data

Numerous gaps are present in the daily records from the early decades of the 19th century. These were filled using either linear interpolation or data from nearby gauging stations (Toruń and Cypel Mątowski). While these are standard techniques in hydrological data reconstruction, they may compromise the quality of the resulting dataset. Not all reconstructions are equally reliable. The considerable distance between Warsaw and the auxiliary stations used, Toruń (214 km downstream) and Cypel Mątowski (366 km downstream), means that local hydrological phenomena could occur at those sites but not in Warsaw. The largest tributary of the Vistula, the Narew River, joins the main stem between these stations and Warsaw. Due to its distinct hydrological regime, it can significantly affect the relationship between gauges. Reconstructing winter data presents an even greater challenge, as ice jams may have caused sudden surges in water level that could be incorrectly attributed to the Warsaw gauge. Because the reconstruction methods cannot fully eliminate such risks, it is essential to identify and clearly mark sections of the dataset that are potentially subject to greater uncertainty.

2. Quality and accuracy of early measurements

In the earliest decades of the observational series, water levels were recorded using a variety of measurement systems, including *Warsaw*, *New Polish*, *Dutch*, *English*, and *Russian* units, which were later converted into the metric system. While

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these conversions were necessary and the entire series has been homogenized, the accuracy and consistency of the original data remain uncertain. Early records may contain rounding, duplication, or transcription errors, and no formal assessment of potential discontinuities or changes in measurement precision had been conducted prior to this study. A critical evaluation of these issues is essential to avoid misinterpretation of hydrological patterns in long-term analyses.

3.9.1 Uncertainty in reconstructed data gaps

During the reconstruction of water levels for the Vistula River in Warsaw using the gauge relationship, several difficulties were encountered in winter periods of the years 1804, 1805, 1809, and 1815. Ice phenomena occurring during these winters disrupted flow conditions, which in turn distorted the hydrological relationship between gauging stations (Kiciński et al., 1994). According to (Byczkowski, 1996), winter ice phenomena tend to raise water levels both within and upstream of the affected river section. If the magnitude of this backwater effect ΔH is similar at both gauging stations, the gauge-to-gauge relationship remains stable. However, if the ice phenomena occur only at one station, or their effect differs significantly between the two, the relationship becomes unreliable.

Such variability must be taken into account, as the timing, duration, and hydraulic impact of ice phenomena may differ between the middle course of the Vistula in Warsaw and its lower course near the bifurcation point at Cypel Mątowski. In several of the examined winter periods, the reconstructed water levels for Warsaw deviated markedly from the adjacent observed values before and after the missing intervals. These deviations often manifested as abrupt upward shifts, inconsistent with the surrounding daily data. This suggests a high degree of uncertainty in the accuracy of the reconstructed water levels for those specific periods. In all four winters, 1804, 1805, 1809, and 1815, where reconstruction uncertainty was identified, independent ice phenomena were reported in Cypel Mątowski. Information about the presence of ice conditions during this time is well documented for both Cypel Mątowski (Kazusek, 2025) and Warsaw (Kolberg, 1861).

Table 5. Periods of uncertainty in the reconstruction of water levels for the Vistula River in Warsaw

Period (YYYY-MM-DD)		Characteristics of ice phenomena in Cypel Mątowski
1804-02-12	1804-03-21	River freeze-up
1805-12-18	1805-12-31	Ice run after freeze-up
1809-02-14	1809-02-14	River ice
1815-12-01	1815-12-08	River freeze-up

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3.9.2 Quality and accuracy of early measurements

To assess the accuracy of early water level measurements, we proposed two indicators: Unique Daily Values (UDV) and Days Without Change (DWC). The first indicator (UDV) measures the number of unique daily water level values (in cm) recorded within a given year, while the second (DWC) counts the number of instances where the same value was reported on consecutive days. We assume that increasing measurement precision should result in a higher number of unique values, reflecting less rounding, and a lower number of unchanged days, due to the detection of smaller water level fluctuations. The results are presented in Fig. 4. Panel (A) shows year-by-year changes in UDV, while panel (B) presents trends in DWC. For both indicators, we calculated linear trends using linear regression. The average number of UDV was significantly higher in the period 2000–2023 (M = 169, SD = 16) compared to 1800–1830 (M = 103, SD = 21). Welch's t-test confirmed that the difference between these periods is statistically significant (t = -13.36, $p < 0.001$, df = 52.99). In the case of DWC, we observed a marked decline in the number of days without change: 2000–2023 (M = 31, SD = 10) versus 1800–1830 (M = 90, SD = 33). Again, Welch's t-test indicated a statistically significant difference (t = 9.31, $p < 0.001$, df = 37.129).

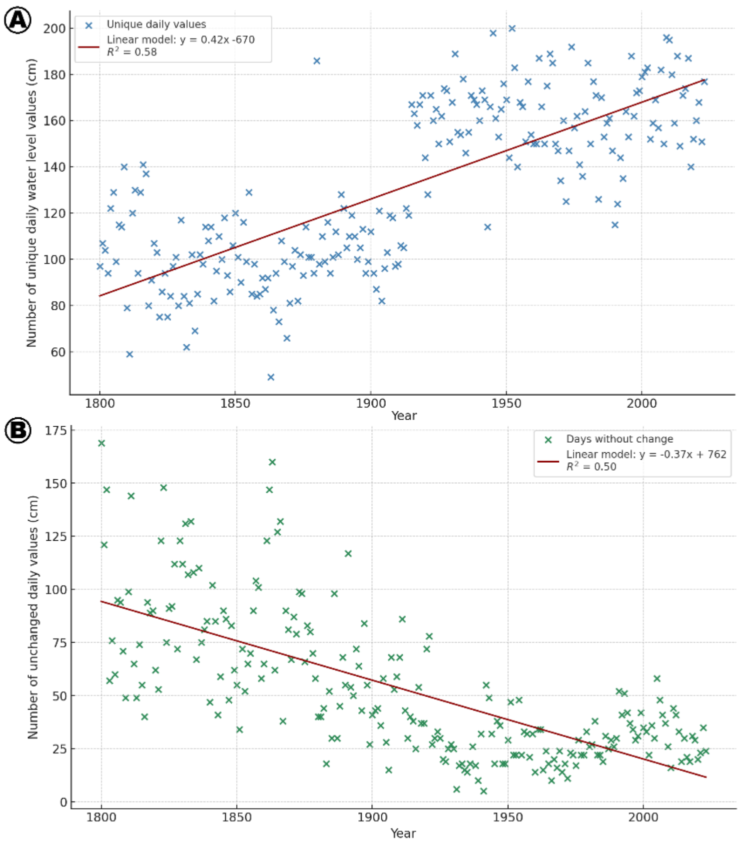

Figure 4: Annual number of Unique Daily Values (A) and Days Without Change (B) in water level observations, 1800–2023.

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To further assess the quality of the historical daily water level data, we applied the Standard Normal Homogeneity Test (SNHT) to the UDV metric. Prior to conducting the test, we removed the linear trend from the annual UDV series in order to focus on potential abrupt changes in data characteristics unrelated to gradual improvements in measurement precision or data processing. The SNHT was then applied to the detrended series. The results identified two statistically significant change points: the year 1818, with a test statistic value of 18.5, and the year 1915, with a value of 21. Based on critical values provided by (Khaliq and Ouarda, 2007), where the threshold at the 99% confidence level for a series with over 200 observations is 12.982. Both change points can be considered statistically significant. Figure 5 presents the potential change points.

The first point, 1818, marks the beginning of uninterrupted daily records in our dataset, as earlier years (1799–1817) contained gaps that were reconstructed using data from other gauges (1,964 of 5,305 days; 37%). The second point, 1915, corresponds to the historical switch of the Warsaw gauge to the metric system, a transition likely associated with changes in measurement resolution.

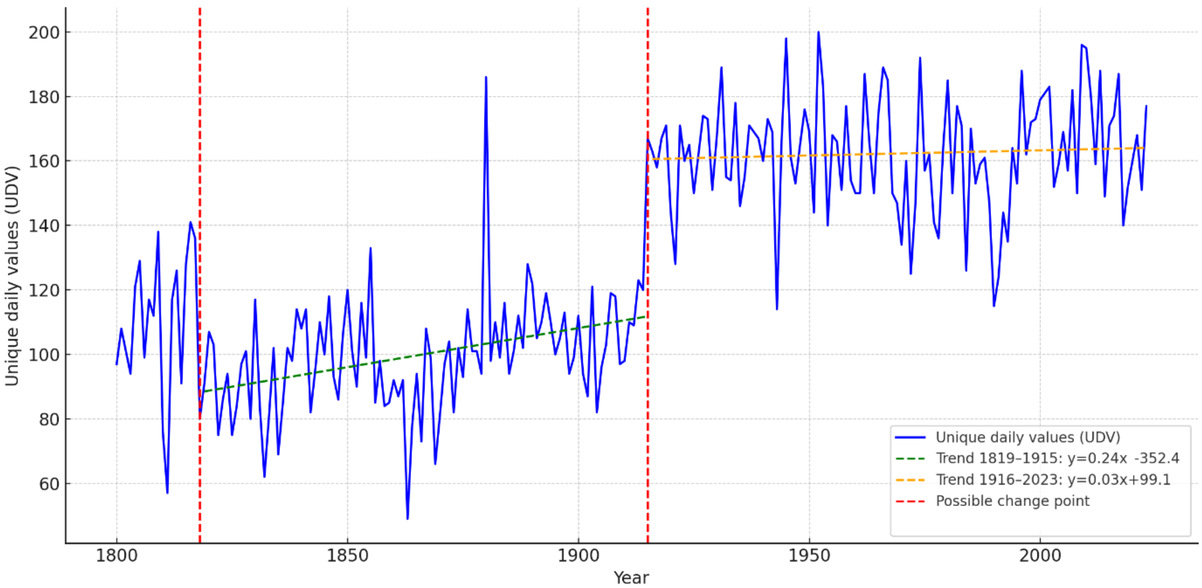

Figure 5: UDV index and potential change points in daily water level resolution, 1800–2023.

The identification of two potential change points, around 1818 and 1915, divides our dataset into three distinct periods: 1799–1818; 1819–1915; 1916–2024. The high precision of daily measurements observed in the early part of our dataset (1799–1817) can likely be explained by the use of data from the gauge at Cypel Mątowski, located on the lower Vistula River. To verify this hypothesis, we compared UDV index for the Cypel Mątowski and Warsaw stations using Welch's t-test for independent samples. We conducted three comparisons:

1. Cypel Mątowski 1800–1828 vs Warsaw 1800–1828. For the first 18 years of this period, about 37% of daily observations in Warsaw were interpolated based on data from Cypel Mątowski (Warsaw: M = 103, SD = 21; Cypel Mątowski: M = 130, SD= 16; t = -5.61, df = 51.79, p < 0.001);
2. Cypel Mątowski 1800–1828 vs Warsaw 1818–1846. The first period in which Warsaw's series contains no missing values and thus no interpolations (Warsaw: M = 94, SD = 15; Cypel Mątowski: M = 130, SD= 16; t = -9.09, df = 55.84, p < 0.001);
3. Cypel Mątowski 1800–1828 vs Warsaw 1886–1914. The last period before Warsaw switched to the metric system in 1915 (Warsaw: M = 107, SD = 11.5; Cypel Mątowski: M = 130, SD= 16; t = -6.37, df = 51.06, p < 0.001).

In each case, the UDV index was consistently higher for Cypel Mątowski than for Warsaw, indicating greater measurement resolution. Welch's t-test confirmed that these differences were statistically significant, providing strong evidence that the early precision seen in Warsaw was due to the influence of interpolated values based on a more finely resolved gauge.

The fitted trend line for the years 1818–1915 reveals a gradual increase in measurement precision, as indicated by the steady rise in the annual number of UDV. The linear trend shows a growth rate of approximately 0.24 UDV units per year, reflecting progressive improvements in manual measurement practices throughout the 19th century. In contrast, after 1915, when the Warsaw gauge transitioned to the metric system, the data show no significant upward trend in measurement precision, despite the implementation of more advanced technologies, such as limnigraphs, continuous recording, and later electronic sensors. This suggests that the shift to metric units brought about an immediate structural improvement in data resolution, but further technological innovations did not translate into a continued increase in the number of unique daily values recorded per year.

To further assess the impact of the transition to the metric system on measurement resolution, we conducted a simulation experiment. Our aim was to evaluate how the UDV indicator would behave if modern 20th- and 21st-century measurements had been recorded using pre-metric units. We used data from the period 1916–2023, consisting of nearly 40,000 daily observations, originally recorded in metric units with a precision of 1 cm. We converted these values into the *New Polish* units *cal*, defined as 1 *cal* = 2.4 cm. The simulation was performed under two rounding scenarios:

Variant 1: values were rounded to the nearest full *cal* (precision: 2.4 cm),

Variant 2: values were rounded to the nearest half *cal* (precision: 1.2 cm).

After rounding, we reconverted the values back to cm and rounded them to full cm, mimicking the historical reporting process. We then recalculated the UDV index for both variants and compared the results to the original metric dataset. The simulation showed that in Variant 1, the loss of precision was substantial, with the UDV reduced by an average of nearly 40%. In Variant 2, the reduction was smaller but still notable, around 10%. These findings clearly demonstrate how the resolution of measurement units directly affects the quality and interpretability of long-term hydrological records. As shown

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in Fig. 6, if river levels in the 20th and 21st centuries had still been recorded in non-metric units with a precision close to 1 inch, then despite the technical progress in measuring instruments the effective resolution of these measurements would have been comparable to that of the 19th century.

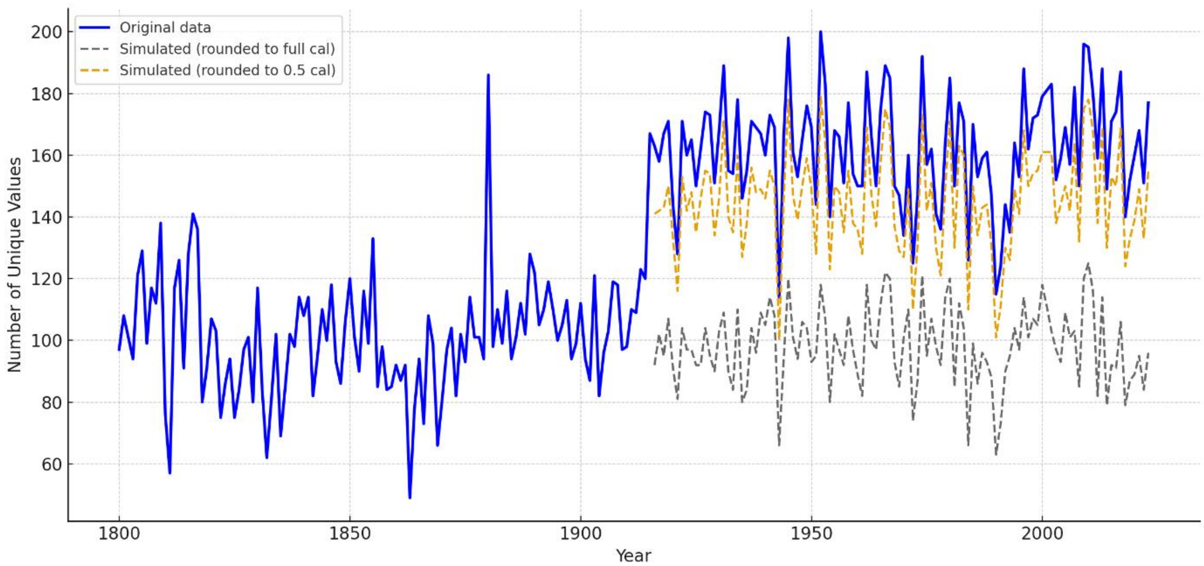

Figure 6: UDV index, based on historical Vistula River measurements and simulations, 1800–2023.

Although the SNHT test identified two potential shifts in measurement precision, around 1818 and 1915, we argue that the dataset remains homogeneous overall. This is due to a series of critical adjustments made to the original data: identifying the exact location of historical water gauges in Warsaw and accounting for changes in water level reference points, converting original measurements into the metric system, and linking historical data with the currently operating Warsaw-Boulevards gauge. While 19th-century measurements were less precise (approx. 25 mm resolution vs. 10 mm today), this difference does not compromise the consistency of the dataset and still allows for robust scientific analysis.

4 Overview of the dataset

A homogenized daily water level series for the Vistula River in Warsaw covering the period from 1 February 1799 to 31 October 2024, comprising 82,453 daily observations. A total of 3,416 missing days (4%) were identified and filled using either interpolation from parallel gauge records along the Vistula River or linear interpolation, depending on data availability and proximity. The resulting time series is consistent and gap-free, providing a robust basis for long-term hydrological analysis.

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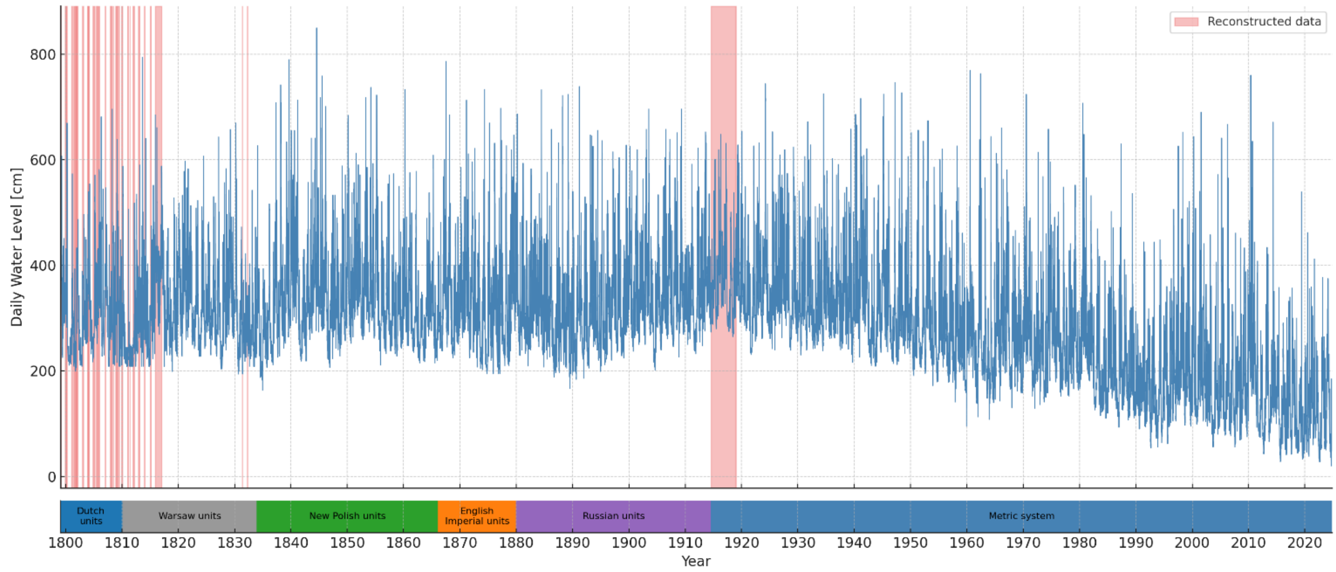

Figure 7: Daily water level in Warsaw since 1 February 1799 to 31 October 2024.

5 Data availability

The complete and open-access dataset has been published in the ZENODO repository under the title *Daily Water Levels of the Vistula River at Warsaw, 1799–2024: A Complete and Homogenized Long-Term Record*. DOI: https://doi.org/10.5281/zenodo.16919654, (Sobechowicz et al., 2025).

6 Summary

The homogenized daily water level series for the Vistula River in Warsaw (1799–2024) provides a unique dataset for multidisciplinary research, spanning hydrology, climate science, historical studies, and risk management. Its exceptional temporal extent and continuity allow for a wide range of applications, which can be grouped into the following categories:

1. Hydrological and climate research

- Trend analysis and variability studies: The series enables detection of long-term changes in river regimes, including shifts in the timing and magnitude of floods and low flows, which may reflect broader climatic trends.
- Reconstruction of historical extremes: The dataset allows the identification and analysis of historical flood and drought events, offering insight into natural variability prior to significant anthropogenic influence.
- Cross-regional comparisons: The series may serve as a benchmark for comparative studies with other major European rivers.

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2. Hydrological modelling and machine learning

- Model calibration and validation: The length and continuity of the series make it suitable for testing hydrological models under a wide range of climatic and anthropogenic conditions.
- Data-driven approaches: The dataset can support machine learning and statistical modelling aimed at pattern recognition, anomaly detection, or water level forecasting.

3. Socio-environmental and historical research

- Hydrosocial interactions: Researchers can explore how historical communities responded to hydrological stressors such as floods or prolonged low flows, and how these events shaped land use, settlement patterns, and agricultural strategies.
- Integration with historical data: When combined with demographic, economic, or meteorological records, the series offers a basis for investigating the environmental dimensions of historical resilience and vulnerability.

4. Flood risk assessment and water management

- Long-term flood risk analysis: The series can support probabilistic flood modelling, scenario planning, and the evaluation of changes in flood hazard over time.
- Urban and regional planning: Insights from the dataset can inform adaptive strategies for river management, infrastructure planning, and climate resilience in the Warsaw region and beyond.

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7 Author contributions

ŁS conceived the study, performed the formal analysis, and led the writing of the manuscript (original draft preparation; review and editing).

DB contributed to the study design, data curation, methodology, and writing (original draft preparation; review and editing).

EK contributed to data curation, formal analysis, methodology, and writing (original draft preparation; review and editing).

MN contributed to data curation and writing (review and editing).

WAS contributed to data curation and writing (review and editing).

MW contributed to data curation, formal analysis, methodology, and writing (original draft preparation; review and editing).

JW contributed to data curation and writing (review and editing).

8 Competing interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

We would like to note that, to improve the clarity and linguistic consistency of selected parts of the text, we used a language tool based on artificial intelligence (ChatGPT). These edits were purely linguistic and did not affect the scientific content of the work. In addition, we employed the same tool for technical assistance in generating figures based on datasets that had been previously compiled and processed by the authors. The tool was used solely for graphical rendering; the scientific interpretation of the results and the underlying analyses remain entirely the responsibility of the authors.

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Figure captions

Figure 1: Location of historical Warsaw water gauges and auxiliary stations along the Vistula River: (A) Poniński Bridge 1799–1864, (B) Kierbedź Bridge 1864–1937, (C) Warsaw-Boulevards 1937–1959 and 2017–2024, (D) Praga Port 1959–2017. Map by the author. Photograph sources: (B) National Digital Archives, Warsaw; (C) Wikimedia Commons

Figure 2: Facsimile of a record sheet containing meteorological measurements and water level observations from Warsaw, February 1800. The Vistula River stage is shown in the penultimate column. Held at the Library of the Institute of Meteorology and Water Management in Warsaw, reference no. C3052.

Figure 3: Reconstruction of daily water levels in Warsaw (1801) using data from another gauging station in Cypel Mątowski

Figure 4: Annual number of Unique Daily Values (A) and Days Without Change (B) in water level observations, 1800–2023.

Figure 5: UDV index and potential change points in daily water level resolution, 1800–2023.

Figure 6: UDV index, based on historical Vistula River measurements and simulations, 1800–2023.

Figure 7: Daily water level in Warsaw since 1 February 1799 to 31 October 2024.

Table 1. Corrections to original water level observations at the Warsaw gauge (1799–2024)

Table 2. Measurement units used at the Warsaw gauges

Table 3. Gaps in the dataset and methods of reconstruction

Table 4. Parameters of linear regression models used for gauge relationships

Table 5. Periods of uncertainty in the reconstruction of water levels for the Vistula River in Warsaw

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