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 missing measurements was completed using the Long Short-Term Memory (LSTM) method, applied to measurements taken at the Warsaw gauge and parallel measurements from downstream water level gauge stations along the Vistula. ~~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).

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 (Mikulski, 1978). 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 (e.g. Jankowski and Stolarska, 1978; Kuźniar, 1997; Bogdanowicz et al., 2000; Fal and Dąbrowski, 2001b; Wierzbicki, 2001; Magnuszewski and Gutry-Korycka, 2009; Kuźniar and Magnuszewski, 2010; Magnuszewski et al., 2012; Magnuszewski and Moran, 2015~~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.

2 Study area

The study focuses on the middle course of the Vistula River, particularly the section flowing through Warsaw (km 407–437, measured upstream from the river mouth at the Baltic Sea), 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" (Magnuszewski et al., 2012), with a fixed width of approximately 400 m. As a result, the area available for the flow of major floodwaters has been reduced to just 20–30% of the former floodplain (Magnuszewski et al., 2012), and water flow velocity has increased (Szymański, 1897), leading to accelerated channel incision (Gutry-Korycka, 2010). ~~This artificial narrowing is a direct result of the Vistula flowing through a densely populated and highly urbanized area.~~ Since the 1940s, there has been a weakening of the relationship between low water levels and the corresponding discherges. Although average low-flow rates have remained at a similar level over the last century, water levels have been steadily falling. This indicates that the cause of this trend is not a reduction in the river's supply, but the deepening of its channel within the urban area (Fal, Dąbrowski, 2001b). For a low-flow rate of Q=150 m^3s^{-1}, the corresponding water level in Warsaw fell by 205 cm between 1919 and 2010 (Magnuszewski et al., 2012). 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 (Kornacki, 1960; Jacewicz, 2000; Biernacki, 2000; Magnuszewski et al., 2012). This deepening of the ~~channel~~riverbed 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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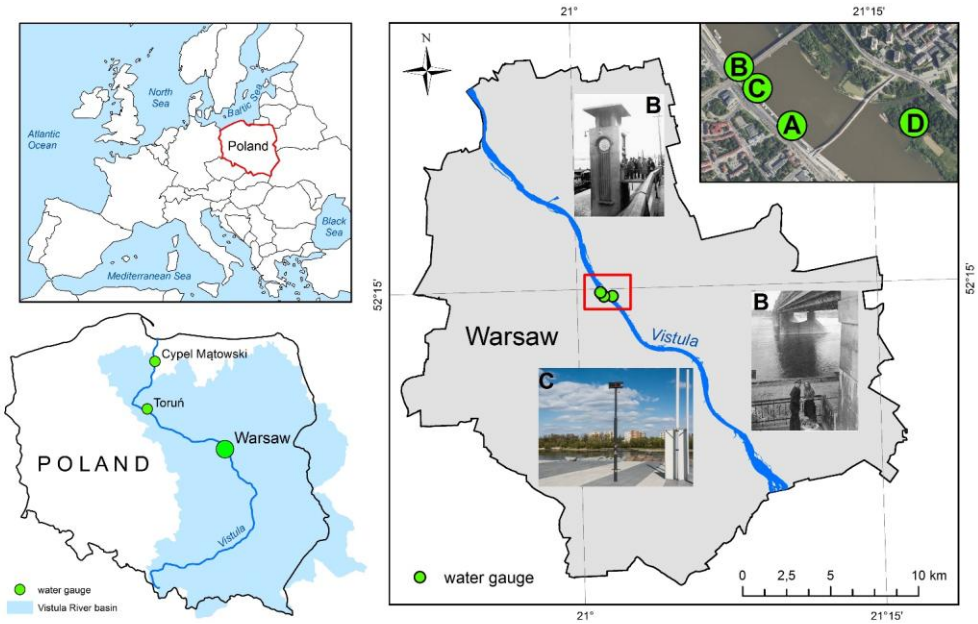

Figure 1: Location of historical Warsaw water gauges and auxiliary stations along the Vistula River: (A) Poniński Bridge 1799–1864, (B) Kierbedź Bridge 1864–1937, (C) Warsaw-Boulevards 1937–1959 and 2017–2024, (D) Praga Port 1959–2017. Map by the authors. Photograph sources: (B) National Digital Archives,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

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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~~Cracow, 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 emphasized that knowledge of water levels, river ice formation, and break-up had been previously poorly examined, little

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disseminated, and unsystematized (an example of an original early nineteenth-century measurement sheet is shown in Figure 2). 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). In turn, observations from 1915–1918 (in the form of handwritten sources) we found in the state archives in Płock, Toruń, and Gdańsk (Archiwum Państwowe w Płocku; Archiwum Państwowe w Toruniu; Archiwum Państwowe w Gdańsku), and subsequently incorporated into the dataset. Observations from 1919 to 1980 were sourced from published hydro~~logical~~graphic 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~~yearbook titled "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~~yearbook titled "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/~~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.

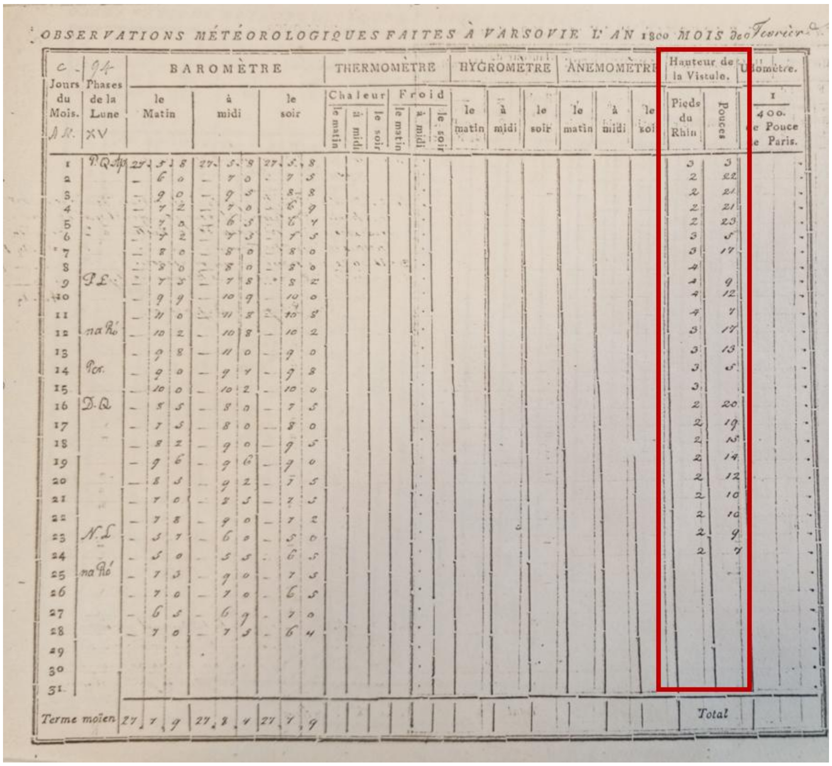

Figure 2: Facsimile of a record sheet containing meteorological measurements and water level observations from Warsaw, February 1800. The Vistula River stage is shown in the penultimate column. Held at the Library of the Institute of Meteorology and Water Management (IMGW) in Warsaw, reference no. C3052.

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 methods~~ology~~ and application of these reference series are provided in Section 3.8. Water level data from the Toruń gauge were published by Makowski

(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 Figure~~.~~ 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 421.6~~+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 421.3~~+300~~. In 1937, the gauge was moved approximately 90 m upstream, to km 421.4~~+400~~. In 1958~~9~~, it was transferred to the right bank of the river, near the Praga Port, at km 421.9~~+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 421.4~~+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 (Witkowski, 1907; Fal and Dąbrowski, 2001a~~; 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 Figure~~.~~ 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).~~ The gauge zero level was lowered once again on 1 November 1958, when measurements were transferred to the Praga Port site. On that date, the gauge datum was lowered by 200 cm to compensate for the long-observed lowering of the riverbed in the Warsaw section. 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 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.~~ However, because of the water-level slope in the river, readings at the new location (Warsaw–Boulevards) are approximately 14 cm lower than those previously recorded 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. The current zero level of the Warsaw-Boulevards gauge is therefore 75.08 m a.s.l. in the Kronstadt 60 system and 75~~7~~.17 m a.s.l. in EVRF2007.

~~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 (1799–2025~~4~~)

Date (YYYY-MM-DD)		Gauge location	Correction to original readings	Comment
1799-02-01	1833-12-31	Left bank, near pontoon bridge km 421.6~~+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 421.3~~+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 421.9~~+900~~	-200 cm	Gauge zero lowered due to riverbed erosion (dredging, sand extraction)
2017-11-01	2024-10-31	Warsaw-Boulevards (left bank) km 421.4~~+400~~	-14 cm	Same zero as Praga Port, but readings are ~14 cm lower due to ~~further riverbed incision~~water-level slope in the river
2025-11-01		Same location	-100 cm	Gauge zero lowered due to prolonged ~~low-flow conditions~~riverbed

				erosion

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.

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).

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 2,374~~3,416~~ days, representing 2.9~~4~~% of the total dataset. The most significant gaps correspond to ~~three~~ two distinct periods: from 1 December 1815 to 13 July 1817, when ice ~~floes~~jam destroyed the bridge and the gauge located beneath it, ~~and~~ from 29 July 1914 to 16~~31~~ October~~December~~ 1915~~8~~, 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.**~~

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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	LSTM~~Gauge relationship 1801~~
3	1800-02-01	1800-03-31	59	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
4	1801-01-19	1801-03-02	43	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
5	1801-06-05	1801-06-30	26	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
6	1801-07-22	1801-07-26	5	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
7	1801-10-01	1801-10-20	20	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
8	1801-10-28	1801-12-04	38	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
9	1801-12-24	1802-03-09	76	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
10	1802-12-25	1803-03-06	72	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
11	1803-12-01	1803-12-10	10	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
12	1803-12-19	1804-01-02	15	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
13	1804-01-10	1804-01-19	10	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
14	1804-02-12	1804-03-21	39	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
15	1804-11-07	1804-12-31	55	Cypel Mątowski	366	4	~~Gauge relationship 1801~~ LSTM
16	1805-01-01	1805-02-28	59	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
17	1805-06-28	1805-07-15	18	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
18	1805-08-09	1805-08-31	23	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
19	1805-10-31	1805-11-06	7	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
20	1805-11-14	1805-11-25	12	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
21	1805-12-18	1805-12-31	14	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
22	1807-01-18	1807-02-18	32	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
23	1807-12-15	1808-02-05	53	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
24	1808-02-25	1808-04-04	40	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM

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~~ LSTM
27	1809-02-14	1809-06-30	137	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
28	1809-11-27	1809-11-30	4	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
29	1809-12-24	1810-01-07	8	Cypel Mątowski	366	4	~~Gauge relationship 1805~~ LSTM
30	1810-01-01	1810-01-07	7	Cypel Mątowski	366	4	~~Gauge relationship 1814~~ LSTM
31	1810-01-20	1810-01-31	12	Cypel Mątowski	366	4	~~Gauge relationship 1814~~ LSTM
32	1811-01-01	1811-02-28	59	Cypel Mątowski	366	4	~~Gauge relationship 1814~~ LSTM
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~~ LSTM
35	1812-12-11	1813-02-18	70	Cypel Mątowski	366	4	~~Gauge relationship 1814~~ LSTM
36	1814-01-01	1814-01-08	8	Cypel Mątowski	366	4	LSTM~~Gauge relationship 1814~~
37	1815-01-01	1815-02-28	59	Cypel Mątowski	366	4	LSTM~~Gauge relationship 1814~~
38	1815-12-01	1816-12-31	397	Cypel Mątowski	366	4	~~Gauge relationship 1814~~ LSTM
39	1817-01-01	1817-07-13	194	Toruń	214	2	~~Gauge relationship 1818~~ LSTM
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~~ LSTM
45	1915-10-31	1915-10-31	1	—	—	—	Linear interpolation
46	1915-11-03	1915-11-03	1	—	—	—	Linear interpolation
47	1917-03-25	1917-03-25	1	—	—	—	Linear interpolation
48	1918-11-11	1918-12-31	51	Toruń	214	2	LSTM
~~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, with the exception of gaps lasting seven days or less,~~,~~ ~~excluding gaps shorter than 7 days~~ were reconstructed using ~~regression-based~~ relationships with data from two other stations: the Vistula River in Toruń and in Cypel Mątowski (see Figure~~.~~ 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). ~~This~~It was, however, a demanding inter-gauge reconstruction problem rather than a simple transfer between neighbouring stations. The distance between Warsaw and Toruń is approximately 200 km, and 366 km to Cypel Mątowski. The contributing drainage area increases from about 80,000 km² at Warsaw to 170,000 km² at Toruń and more than 180,000 km² at Cypel Mątowski. Between Warsaw and Toruń, the Vistula receives major tributary inflows and the hydrological signal may be modified by channel storage, changing flow conditions, seasonal effects, and ice-related disturbances. The reconstruction model therefore had to learn a complex downstream relationship rather than a simple one-to-one correspondence between two nearby water-level series.

Before constructing the reconstruction model, the dominant time lag between the Warsaw and Toruń, and Warsaw and Cypel Mątowski gauges was estimated empirically. The analysis was performed using first differences of daily water levels rather than raw stage values. This choice was intended to focus on the timing of short-term hydrological fluctuations and to reduce the influence of strong autocorrelation in the original water-level series. Cross-correlation analysis indicated that a two-day lag provided the most stable relationship between Warsaw and Toruń gauges, and a four-day lag between Warsaw and Cypel Mątowski. Those lags produced the strongest association in most monthly subsets and in the main water-level classes. It was therefore adopted as the reference temporal offset for the reconstruction procedure. At the same time, the lag was not treated as a perfectly fixed hydrological constant. The propagation of water-level changes can vary with flow conditions, season, channel state, and ice ~~effects~~phenomena.

The reconstruction was carried out using a long short-term memory neural network. LSTM models are designed for sequential data (Hochreiter and~~,~~ Schmidhuber, 1997) and are therefore well suited to problems in which the target value depends not only on one predictor value at a fixed time lag, but also on the shape and recent evolution of the input sequence. LSTM neural networks have already been successfully applied to hydrological reconstruction tasks (Ren et al., 2022). In the present case, the aim was not to forecast future water levels, but to reconstruct missing historical observations in Warsaw using the available hydrological information from Toruń and Cypel Mątowski. For this reason, the LSTM model was not restricted to a single lagged value. Instead, it was supplied with a sequence of observations around the estimated lag, allowing it to learn a broader local representation of the downstream hydrograph.

The target variable was the daily water level of the Vistula River in Warsaw. The main predictor was the daily water level recorded at Toruń or Cypel Mątowski. Two additional types of information were added to the input structure. First, seasonality was represented by cyclic calendar variables, allowing the model to learn annual variation without imposing an abrupt division between seasons. Second, the day-to-day change in water level at Cypel Mątowski was included as a measure of hydrograph state. This variable informed the model whether the river was rising or falling and how rapidly water level was changing. The model was trained on rolling windows of daily observations. Two window designs were considered during model development. A causal window used only antecedent observations from Cypel Mątowski. A centered window used a sequence centered on the Cypel Mątowski observation corresponding to the estimated two-day or four-day inter-gauge lag. Because the task was retrospective reconstruction rather than real-time forecasting, the centered design was hydrologically justified: observations before and after the reconstructed day could be used to describe the local geometry of the flood wave or low-flow episode recorded downstream. Only uninterrupted input sequences were used. Windows that crossed a gap in the predictor chronology were excluded, so that the model did not learn artificial sequences created by joining observations from opposite sides of a missing interval. This rule was essential for preserving the temporal and physical coherence of the input data.

The LSTM architecture consisted of a single LSTM layer followed by dropout regularisation, a fully connected hidden layer with ReLU activation, and a final one-unit output layer producing the reconstructed Warsaw water level. The model was trained using the Adam optimiser and mean squared error as the loss function. Gradient clipping was applied to stabilise optimisation. Input variables and the target series were standardised using parameters estimated only from the training data. These fitted transformations were then applied to the corresponding validation or reconstruction subsets. This prevented information from the validation data from entering the training procedure through scaling. Hyperparameter tuning was performed separately for each predictor specification. The search included alternative window lengths, numbers of LSTM units, dropout rates, learning rates, and batch sizes. The candidate values considered for each hyperparameter during the grid-search procedure are listed in Table 4. Training was run with early stopping based on validation loss, with the best weights restored. The order of observations was not shuffled, because the model relied on the temporal structure of the sequences. To reduce dependence on a single random initialisation, candidate configurations were trained repeatedly using different random seeds, and model selection was based on average validation performance.

Table 4. Hyperparameter search space used for LSTM model tuning

Hyperparameter	Candidate values
Window size (days)	7, 15, 31
LSTM units	32, 64

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Dropout rate	0.1, 0.2
Batch size	32, 64

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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 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

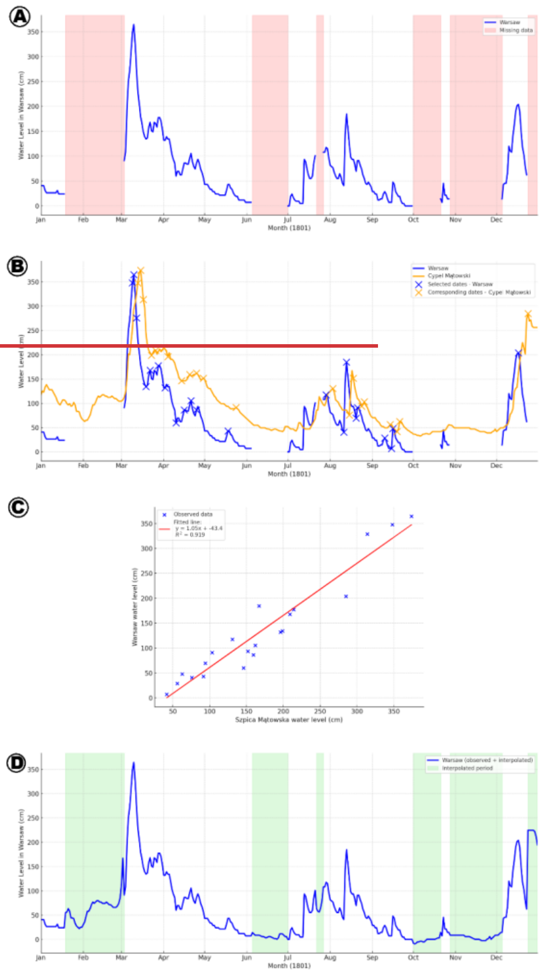

Figure 3: Reconstruction of daily water levels in Warsaw (1801) using data from another gauging station in Cypel Mątowski

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

(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 used in hydrological data reconstruction (Ren et al., 2022), 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 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 Validation of reconstructed data

The predictive ability of the model was assessed using out-of-sample validation rather than in-sample fit. This was crucial because the purpose of the model was not to describe observed values already available in the Warsaw series, but to estimate missing observations. The validation procedure was therefore designed to test whether the model could reconstruct observed Warsaw values that had been withheld from training. The main validation scheme used leave-one-hydrological-year-out cross-validation (LOHYO). In each validation cycle, one hydrological year was withheld from model training and then reconstructed using the model fitted on the remaining data. This approach provided a historically realistic test of model performance, because it assessed whether the model could generalise to unseen sections of the early record.

Model performance was evaluated using four complementary metrics: mean absolute error (MAE), root mean square error (RMSE), Nash–Sutcliffe efficiency (NSE)~~,~~ (Nash and~~,~~ Sutcliffe, 1970; McCuen et al., 2006) and Kling–Gupta efficiency (KGE~~,~~) (Gupta et al., 2009; Kling et al., 2012). MAE measured the average magnitude of daily reconstruction errors. RMSE gave greater weight to larger errors. NSE assessed the ability of the model to reproduce the observed hydrograph relative to a mean-value benchmark, while KGE provided a broader hydrological efficiency measure combining correlation, bias, and variability components. The final model specification was selected not solely on the basis of the lowest daily error, but on the best balance between pointwise accuracy and preservation of hydrograph dynamics. The selected model used a centered input window and included both cyclic seasonality variables and the day-to-day stage-change feature. This configuration was chosen because it provided the strongest overall balance between reconstruction accuracy and hydrograph-level fidelity. The LSTM models achieved good overall predictive performance for the Warsaw series. Detailed results for the tested models are reported in Table 5.

Table 5. Predictive performance of the LSTM reconstruction models

Period of	Parallel	Training	Period and	No. of	MAE	RMSE	NSE	KGE

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reconstruction	series	data	method of validation	observations used for validation				2012
1800-1816	Cypel Mątowski	1800-1828	1800-1815; LOHYO	4537	29.04	39.75	0.74	0.83
1817	Toruń	1822-1830	1817-1819; Chronological split	898	23.38	30.06	0.74	0.87
1914-1915, 1918	Toruń	1908-1924	1908-1924, LOHYO	5658	17.36	24.21	0.89	0.94

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3.9.2~~1~~ Uncertainty in reconstructed data gaps

During the reconstruction of water levels for the Vistula River in Warsaw using LSTM models based on~~the~~ inter-gauge relationship, several difficulties were encountered in winter periods of the years 1804, 1805, 1809, and 1815. These difficulties were most likely related to ice phenomena, which could disrupt flow conditions and distort the hydrological relationship between gauging stations (Kiciński et al., 1994). ~~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 less reliable~~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~~Toruń or 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; see Table 6).

Table ~~5~~6. 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

To assess whether these uncertainties were limited to individual problematic winters or reflected a broader seasonal pattern, the validation results were additionally summarized by season for all LSTM reconstructions (see Table 7). The comparison shows that reconstruction accuracy was not uniform throughout the year. In the Cypel Mątowski 1800–1815 model, winter produced the highest errors, with MAE reaching 43.26 cm and RMSE 55.81 cm, while summer was reconstructed much more accurately, with MAE of 23.50 cm and RMSE of 32.63 cm. A similar seasonal contrast is visible in the Toruń 1908–1924 model, where winter again had the highest seasonal MAE, whereas summer showed the best performance, with the lowest errors and the highest efficiency scores. The short Toruń 1817–1819 validation period shows a less regular pattern, probably because it is more sensitive to individual hydrological episodes. In this case, spring produced the largest MAE, while autumn had the lowest absolute errors but also a lower KGE value than the other seasons. This suggests that, in short validation windows, individual events may have a stronger influence on seasonal performance metrics. Nevertheless, the broader pattern remains consistent: the most accurate reconstructions were generally obtained during summer and early autumn, whereas winter and spring were more problematic. These results support the interpretation that uncertainty in the reconstructed gaps had a seasonal component. The greatest risk of reconstruction error occurred during periods when local ice effects, backwater conditions, snowmelt, or rapid hydrological changes could disturb the relationship between the reference station and Warsaw. Therefore, the winter reconstructions for 1804, 1805, 1809, and 1815 should be treated with particular caution, even though the overall validation results indicate that the LSTM models performed well at the annual scale.

Table 7. Seasonal validation metrics for LSTM-based water-level reconstructions

Period of reconstruction	Parallel series	Season	No. of observations used for validation	MAE	RMSE	NSE	KGE 2012
1800-1815	Cypel Mątowski	Winter	572	43.26	55.81	0.51	0.66
		Spring	1273	37.13	48.62	0.66	0.66
		Summer	1370	23.50	32.63	0.75	0.71
		Autumn	1325	28.24	37.09	0.63	0.79
1817-1819	Toruń	Winter	211	25.99	34.00	0.58	0.82
		Spring	184	29.36	35.57	0.65	0.77
		Summer	233	21.43	29.71	0.60	0.75
		Autumn	273	18.95	21.89	0.73	0.67

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1908-1924	Toruń	Winter	1379	23.31	31.92	0.76	0.87
		Spring	1472	19.61	27.50	0.87	0.90
		Summer	1438	12.96	17.64	0.94	0.97
		Autumn	1369	14.36	25.07	0.80	0.87

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3.9.3~~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 Figure~~.~~ 3~~4~~. Panel (A) shows year-by-year changes in UDV, while panel (B) presents trends in DWC. We applied the Standard Normal Homogeneity Test (SNHT) to the UDV and DWC metrics. Prior to conducting the test, we removed the linear trend from the annual UDV and DWC series in order to focus on potential abrupt changes in data characteristics unrelated to gradual improvements in measurement precision or data processing. In case of UDV metric the results identified two statistically significant change points: the year 1818, with a test statistic value of 26.4, and the year 1915, with a value of 18.42. 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, b~~. B~~oth change points can be considered statistically significant. 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. This division is further supported by Welch's *t*-tests, which confirmed significant differences between periods in both UDV and DWC indicators.

~~For both indicators, we calculated linear trends using linear regression.~~ The average number of UDV was significantly higher in the period 1916~~2000~~–2023 (M = 162~~9~~, SD = 18~~6~~) compared to 1800–1915~~830~~ (M = 103, SD = 22~~1~~). Welch's *t*-test confirmed that the difference between these periods is statistically significant (t = -21.87~~13.36~~, p < 0.001, df = 220.28~~52.99~~). In the case of DWC, we observed a marked decline in the number of days without change: 1916~~2000~~–2023 (M = 30~~1~~, SD = 15~~0~~) versus 1800–1915~~830~~ (M = 74~~90~~, SD = 33). Again, Welch's *t*-test indicated a statistically significant difference (t = 13.26~~9.31~~, p < 0.001, df = 160.59~~37.129~~).

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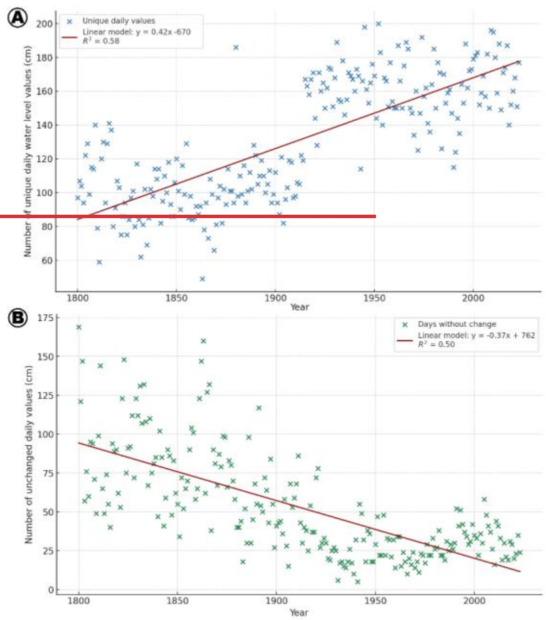
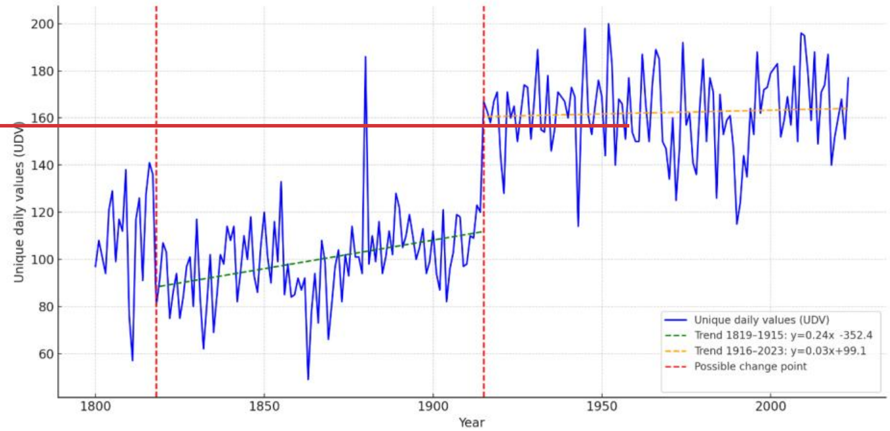

A
Unique daily values
Linear model: y = 0.42x -670
R^2 = 0.58
unique daily water level values (cm)
200
180
160
140
120
100
80
60
1800
1850
1900
1950
2000
Year
B
Days without change
Linear model: y = -0.37x + 762
R^2 = 0.50
Number of unchanged daily values (cm)
175
150
125
100
75
50
25
0
1800
1850
1900
1950
2000
Year

Figure 34: Annual number of Unique Daily Values (A) and Days Without Change (B) in water level observations, 1800–2023.

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, and~~;~~ 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.

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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 in Fig~~.~~ure 4~~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.

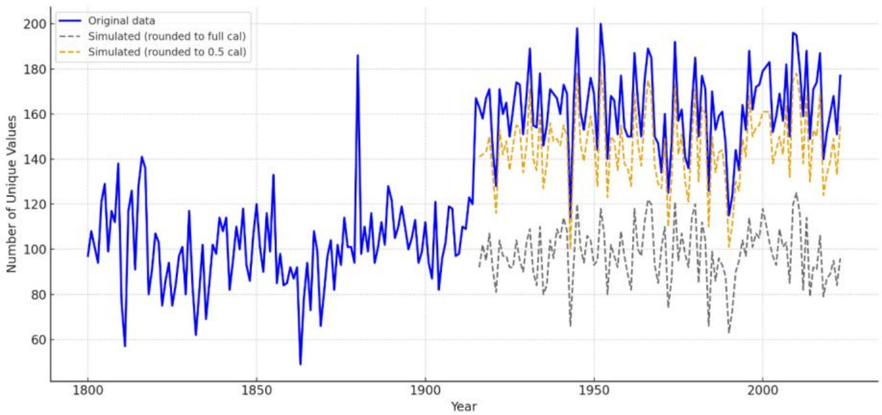

Figure 46: UDV index, based on historical Vistula River measurements and simulations, 1800–2023.

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 2,3743,416 missing days (2.94%) were identified and filled using LSTM models based on inter-gauge relationshipeither 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 (see Figure 5).

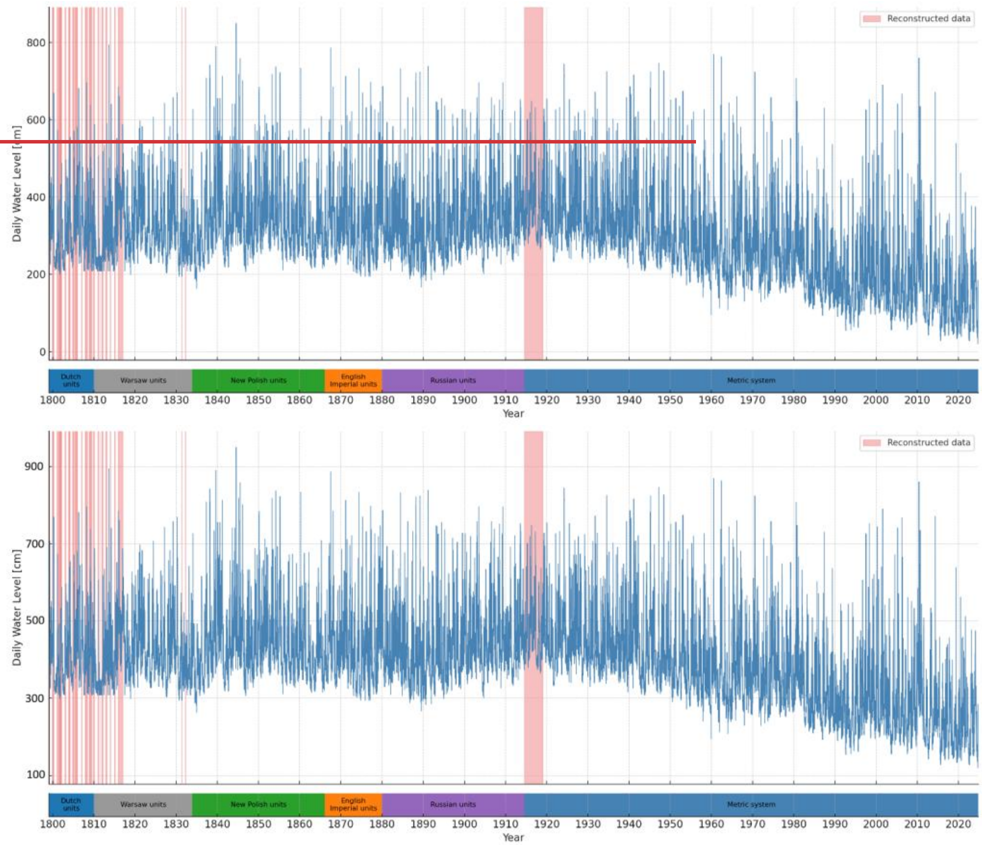

Figure 57: Daily water level in Warsaw since 1 February 1799 to 31 October 2024.

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.

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.

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; t~~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 3~~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 4~~6~~: UDV index, based on historical Vistula River measurements and simulations, 1800–2023.

Figure 5~~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. Hyperparameter search space used for LSTM model tuning~~Parameters of linear regression models used for gauge relationships~~

Table 5. Predictive performance of the LSTM reconstruction models

Table 6~~5~~. Periods of uncertainty in the reconstruction of water levels for the Vistula River in Warsaw

Table 7. Seasonal validation metrics for LSTM-based water-level reconstructions

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