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Documentary evidence of urban droughts and their impact in the eastern Netherlands: the cases of Deventer and Zutphen, 1500–1795

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Abstract. Compared to other parts of Europe, very little is known about pre-instrumental drought periods in the Netherlands. Existing reconstructions are based primarily on data from England, France, and Germany, while more local studies on drought and its impact are still absent. This article thus aims to expand our knowledge of droughts in the Netherlands between 1500 and 1795 by focusing specifically on drought in an urban context to provide a more precise and local idea of the impact and severity of drought. The main case studies are cities in the eastern part of the country, Deventer and Zutphen. Both cities lay in relatively close proximity to each other and share similar geological and hydrological conditions, as well as extensive archives that can be used to gather documentary data regarding historical drought periods. The three primary aims of the article are (1) to examine the potential use of documentary data from the city archives of Deventer and Zutphen for historical drought reconstruction; (2) to establish droughts for both cities on the basis of the year and month or season in which they took place, as well as ranking the droughts according to the impact-based Historical Severity Drought Scale (HSDS); and (3) to compare the data from this analysis with those from other indices. In the end, the article strengthens the need to focus on documentary data from local case studies regarding drought, not only to provide more precise local reconstructions of drought severity compared to regional studies, but also to take into account the long-term effects on urban waterscapes and the provisioning of fresh water.

1 Introduction

In recent years, droughts have become a more pressing topic of research. Worldwide, droughts of varying severity affect societies, whether on an agricultural, hydrological, or wider socioeconomic level, which is expected to increase within the current trends of climatic change (Kchouk et al., 2022; Savelli et al., 2022; Spinoni et al., 2018). The study of past droughts for the pre-instrumental period on the basis of documentary evidence and natural proxies, such as dendroclimatology, has displayed the possibility to reconstruct drought events and their societal impact in Europe, which has led to the development of several historical drought reconstructions and indices (Bauch et al., 2020; Brázdil et al., 2016, 2018, 2019, 2020; Camenisch et al., 2020; Garnier, 2019; Kiss, 2017, 2020; Leijonhufvud and Retsö, 2021; Piervitali and Colacino, 2001; Pribyl and Cornes, 2020; Stangl and Foelsche, 2022). However, very little to no historical drought data exist for the Netherlands. The limited data available from the voluminous works of Buisman (1995) are based primarily on reconstructions and sources from England, France, and Germany, as well as sporadic sources from across the Netherlands. A recent study by Camenisch and Salvisberg (2020) has emphasised the need to analyse regional and local aspects of droughts by studying geographically limited source samples, such as municipal data from city archives. Compared with other supra-regional drought indices, this can lead to a more detailed understanding of the extent and severity of certain droughts on a local level, while also providing insights into previously unknown droughts. Even droughts with a larger geographical footprint, such as the infamous 1540 "megadrought" (Wetter et al. 2014), can thus demonstrate a greater temporal diversity if more localised data are included in the analysis (Maughan et al., 2022). As such, the data provided by Buisman cannot suffice to study the local or regional severity and impact of drought for the Netherlands, and, as follows, further research is needed.

This article aims to expand our knowledge of pre-instrumental droughts in the Netherlands between 1500 and 1795, focusing on two cities in the eastern part of the country – Deventer and Zutphen. Both have rich municipal archives, share relatively similar geohydrological, and are located in close proximity to one another. The focus on the eastern Netherlands also has a climatological reason, as a recent study has indicated that the eastern inland parts of the Netherlands could be more prone to future droughts compared to the western coastal regions. While the western parts also receive ample discharge from the rivers Rhine and Meuse, the eastern regions generally depend more on precipitation for drought mitigation, given that their elevation above the level of the two rivers makes it impossible for water to reach these areas without pumping. As such, the possibilities for drought mitigation in the eastern regions are regarded as more limited compared to the west. A comparative analysis has also shown that the differences in precipitation between the east and western parts are accompanied by differences in solar radiation and temperature, which influence potential evapotranspiration. This trend has been visible since the 1950s and is expected to continue with stronger drying trends in the inland regions due to an increase in temperatures as a result of global warming (Philip et al., 2020).

The focus on more specific urban contexts also moves away from the focus on agricultural drought, which is dominant in historiography, shifting the emphasis to the wider hydrological and socioeconomic impact of drought within a city's walls. This implies a focus on sources from city archives that describe the specific effects of droughts on urban water provisioning, the accessibility of canals and harbours, and sanitary issues. Common factors to denominate drought severity according to the Palmer Drought Severity Index, or PDSI, such as temperature, precipitation levels, and soil-moisture deficits, are not enough to determine the impact of droughts on urban environments. Urbanisation, along other large-scale influences of human actions on the distribution and use of water, has often been ignored in many classical drought indices that focused primarily on precipitation and temperature data (Briffa et al., 2009; Savelli et al., 2022). Many previous studies into past droughts worked in relative isolation, without taking into account the complex interactions between natural and human processes in the hydrological sphere (AghaKouchak et al., 2021; Van Loon et al., 2016; Maughan et al., 2022; Mukherjee et al., 2018; Vörösmarty et al., 2004). These factors are more present in another index, the Historical Severity Drought Scale (HSDS). This index allows for a reconstruction of droughts based on a systemic inventory of the different hydrological and socioeconomic impacts to determine levels of drought severity (Garnier, 2014, 2019; Metzger and Jacob-Rousseau, 2020). Urban documentary data provide more precise local reconstructions of drought severity, as they describe the variety of responses to droughts, allowing for the creation of indices along the HSDS. As such, urban droughts refer to specific effects of drought on the urban environment, which can be reconstructed with the use of urban archives to provide a long-term perspective on the effects of droughts on urban water systems. This is primarily relevant given the rising interest in the effects of drought on urban environments for the present as well as the future (Machairas and Van de Ven, 2022; Szalinska et al., 2021).

This article has three primary aims: (1) examining the potential use of documentary data from the city archives of Deventer and Zutphen for historical drought reconstruction; (2) establishing droughts for both cities on the basis of the year and month or season in which they took place, as well as ranking the droughts according to the impact-based Historical Drought Severity Scale; and (3) comparing the data from this analysis with that of other indices, such as the Van Engelen, Buisman, and IJnsen temperature series for the Netherlands; the supra-regional drought index (SDI), which comprises data from Switzerland, France, the Netherlands, and Germany, (Camenisch and Salvisberg, 2020); and the Old World Drought Atlas (OWDA), which provides an overview of dendrochronological drought data on a regional scale (Cook et al., 2015).

The article is divided in six sections. The first provides a detailed overview of the sources used in the reconstruction of drought for Deventer and Zutphen. Section 2 presents outcomes from the study of these sources, by which the drought years are presented via a chronological HSDS. Section 3 discusses a specific set of examples from the sources, providing a more detailed analysis of the data and their respective values. Sections 4, 5, and 6 compare the data gathered in this study with other indices, followed by a final discussion and conclusion.

2 The data

To reconstruct past weather and climatic phenomena, historical climatologists draw from a large number of documentary sources that provide either direct or indirect (proxy) data about changes in weather or abnormal patterns of precipitation and temperatures (Brázdil et al., 2010; Pfister, 2018). As for drought reconstructions, the documentary evidence often consists of annals, chronicles, and diaries, in which people recorded daily or extraordinary weather situations, or more institutional sources, such as tax and harvest records, and religious data with regard to rogation ceremonies (Brázdil et al., 2013, 2019, 2020; Domínguez-Castro et al., 2012; Kiss and Nikolić, 2015). Throughout most parts of Europe, municipal records, from cities, towns, and villages, became more systematised from the end of the fifteenth century onward, often containing deliberations and resolutions that indicate means by which local or state governments aimed to alleviate the effects of drought or other weather extremes (Garnier, 2019; Gorostiza et al., 2021; Grau Satorras et al., 2021). Therefore, municipal archives qualify as a reliable *fundgrube* (source) for (proxy) evidence of urban droughts during the pre-instrumental period.

For this study, the municipal archives of two cities in the eastern Netherlands, Deventer and Zutphen, have been studied extensively in search of references to drought-related phenomena. Deventer and Zutphen are both situated along the IJssel river on sandy river dunes from the Holocene and relied on surface water from the rivers and clean groundwater for everyday use (Vogelzang, 1956). The primary sources studied were primarily official municipal records, such as daily resolutions from the city government, ordinance books, and petitions. For Deventer, long-running series of sources, including daily resolutions, decrees from the magistracy (*burspraken*), and citizen petitions, are available from 1459 until 1795. Both the daily resolutions and books of concordances come with alphabetical reference books from eighteenth and nineteenth century authors, which provide a useful, yet also limited tool to find certain relevant entries regarding drought. In the case of Zutphen, the extensive series of daily resolutions can be studied from 1573 until the start of the nineteenth century. These series, including digitised reference books, provided the primary source for Zutphen. In this regard, it must be noted that for certain periods, particularly the seventeenth century, the number of sources regarding Zutphen was generally less extensive compared to Deventer.

3 Methodology

In this section, I discuss several indices and explain the choice for the HSDS as the preferred method to rank the severity of the droughts for Deventer and Zutphen. Many historical drought reconstructions have been done on the basis of natural proxy data from dendroclimatological reconstructions. These focus on tree-ring analysis to reconstruct tree growth that provides insights into precipitation and temperature levels. This can be expressed along the PDSI as an estimate of relative dryness based on reconstructions of temperature and precipitation (Brázdil et al., 2018). Certain long-term dendroclimatological reconstructions, such as the OWDA for Europe and parts of North Africa, use a self-calibrating PDSI (scPDSI) to create year-by-year maps of reconstructed summer droughts on a 5414-point half-degree longitude-by-latitude grid. The scPDSI has a high degree of spatial comparability across a broad range of climatological regions, which allows for comparisons with other pre-instrumental droughts, for example in North America (Cook et al., 2015).

One of the most commonly used indices to categorise drought severity in Europe is based on the seven-point ordinal index devised by Pfister during the 1980s, also named "Pfister indices" (Brázdil et al., 2020; Nash et al., 2021; Pfister et al., 2018). These indices can indicate both temperature differences and variations in precipitation. In the seven-point index for precipitation, values ranging from rather wet to extremely wet ($+1$ to $+3$) and rather dry to extremely dry (-1 to -3) are used to typify periods on the basis of direct or proxy-based information regarding precipitation within a certain area. Such an index cannot be built on descriptive documentary evidence alone and should also include proxy data, such as evidence from plant phenology and dendroclimatological analysis. A merely descriptive index would only be able to use a three-point scale, only taking into account the extraordinary (-1 or $+1$) as a deviation from the average (0). Every seven-point index also requires a reference period to denote the deviations from the average, which often consists of a series of instrumental measurements from the period prior to the full onset of global warming, most commonly 1906 to 1960 (Pfister et al., 2018).

Several studies into historical droughts within Europe have applied the seven-point index as a means to indicate the severity of past droughts (Bauch et al., 2020; Brázdil et al., 2013; Camenisch and Salvisberg, 2020; Leijonhufvud and Retsö, 2021). However, there are also certain limits to the seven-point index. Kiss and Nikolić (2015), for example, remarked that the requirements for the index can hardly be met for the European Middle Ages, for which the amount of available documentary evidence is often insufficient to estimate the severity of drought on a month-by-month basis. In their attempt to create a 400-year-long drought index for the cities of Bern and Rouen, Camenisch and Salvisberg (2020) similarly argue that the available data from both cities – primarily chronicles and municipal records from the fourteenth to the early eighteenth century – did not allow for all three index values (-1 to -3) to be used. The sources from both cities only provide instances of extreme drought events, which left a significant mark on inhabitant memory and prompted city governments to take action. Therefore, instead of using all three values, only extremely dry (-3) and very dry (-2) were used in their analysis, considering that the more frequent and less impactful droughts (-1) were usually not recorded. For both cities, most droughts during the 400-year period were characterised as very dry (-2), and only a few instances were classified as extremely dry (-3). The survey also led to the identification of specific accumulations of droughts, for instance at the end of the fourteenth century, in the second half of the sixteenth century, and in the 1670s, as seasonal difference was discovered as the droughts in Bern often occurred during the summer, while those in Rouen were more prevalent during the spring season.

The previous conclusions can also be applied for the corpus of municipal sources that have been investigated for Deventer and Zutphen. However, the documentary data from Deventer and Zutphen do not allow for a precise month-by-month reconstruction, as the duration of the droughts cannot be accurately reconstructed from the primarily descriptive data. Monthly records of precipitation are required to categorise such droughts into a seven-point index. In this case, a drought can only be denoted as very dry (−2) after at least a 1.5 months of reduced precipitation, while the value of extremely dry (−3) is reserved for 2 or more months without rainfall (Camenisch and Salvisberg, 2020). As the data from Deventer and Zutphen do not provide insights into the length of certain droughts, only referring to "long" or "prolonged" periods of drought without indicating a specific time frame, the seven-point index cannot be applied. The primary references to drought concern descriptions of its human and economic impact on a societal level, which are also more accurate representations of past perceptions of drought than modern conceptions of precipitation and evaporation (Garnier, 2015). These data can be used according to the HSDS to delineate droughts on an impact-centred scale. The HSDS distinguishes droughts on the basis of societal reactions that can be found in various sources, which are classified in categories on a 1 to 5 scale (see Table 1) from an absence of precipitation to full-scale social crisis. An additional category, −1, denotes instances where both qualitative and quantitative data are considered insufficient, but a drought reference is kept solely for the purpose of chronological reconstruction (Garnier, 2014). This additional category does not apply to any of the cases discussed in this article.

In order to identify periods of drought, an extensive study of the abovementioned sources was carried out. When available, reference books were used as an additional tool for finding entries connected to drought-related issues. These concerned aspects like water provisioning, fires, watermills, and other matters related to waterworks and shipping, as well as a dearth of foodstuffs and other items as a result of drought. Firstly, the sources for Deventer were studied on a year-by-year basis, in which all entries were searched for direct or indirect references to drought. This yielded a steady base of results that formed the foundation of the following archival research. Second in line were petition books, which were also studied on a year-by-year basis. The daily resolutions were not studied on a year-by-year basis because of the density of the source material, as this would render an extensive page-by-page study too time-consuming. Instead, the daily resolutions were studied primarily on the basis of reference books and findings from other sources. In all instances, not only the drought years found in the other sources were consulted in the daily resolutions, but also 2 years before and after a reference to drought. This was deemed relevant given the insidious nature of drought and possibility that the source might display certain developments of a drought on an earlier basis. After the study for Deventer was completed, the study of Zutphen began with an analysis of the largely digitised reference works regarding the daily resolutions. The earlier discovered drought years for Deventer were used as reference points and were used to study specific years, including the years before and after.

For each city, the rough data were first copied into separate databases, after which the data were filtered by setting aside references that did not directly relate to drought. These included references to future measures to be taken when severe droughts occurred or measures for which the relation to a drought event was less obvious. Secondly, the remaining drought events were filtered for each city according to drought type (meteorological, agricultural, hydrological, socioeconomic) and season. Thereafter, a chronological database was created combining the data from Deventer and Zutphen in a chronological overview of the specific drought events for each year. This specific overview was also used for the next step: ranking the severity of each drought per year according to the HSDS.

4 Outcomes

The most common types of drought mentioned in documentary sources refer to instances of meteorological drought, referring to a deficiency of precipitation over a specific period of time. This is usually followed by agricultural drought, which refers to the effects of meteorological drought on agricultural production. Hydrological drought takes into account the consequences of water shortages in rivers, streams, lakes, and underground water tables, while socioeconomic drought describes the effects of drought when the former causes widespread economic and societal disruption, most commonly in the form of subsistence crises (Brázdil et al., 2018; Wilhite and Pulwarty, 2017). As municipal records usually only contain references to extreme weather events, the descriptions of drought in the sources refer almost exclusively to extremities (Camenisch and Salvisberg, 2020; Garnier, 2019).

Based on the indicators of drought and its severity in the studied sources, an HSDS index has been constructed including the data from Deventer and Zutphen (see Fig. 1). The index ranks droughts on an annual basis using the five-point scale, although instances of purely meteorological droughts (scale 1) and its effects (rogation ceremonies and public prayer) have not been found. In total, 33 years with drought have been reconstructed. This includes 26 drought years for Deventer, 16 for Zutphen, and only 9 coinciding years for both cities. Hydrological droughts with a significant impact on the city's waterways and the availability of water (scale 3) are amongst the most common forms of drought described in the sources, occurring 24 times. More extreme hydrological conditions, those within scale 4, are less common but still make up a significant part of the recorded droughts, namely

Table 1. Historical Severity Drought Scale (for the sixteenth to nineteenth centuries) based on Garnier (2014).

Index	Description
5	exceptional drought: no possible supply, shortage, sanitary problems, very high prices of wheat, forest fires
4	severe low-water mark: navigation impossible, shutdown of wheat mills, search for new springs, forest fires, death of cattle
3	general low water (difficulties for navigation) and water reserves
2	local low water in rivers, first effects on vegetation
1	absence of rainfall: rogation, evidence in texts
−1	insufficient qualitative and quantitative information but the event is kept in the chronological reconstruction

nine instances. Scale 5, denoting full-scale societal crisis and critical shortages of food and water, has not been identified.

With regard to both Deventer and Zutphen (see Fig. 2), hydrological drought is by far the most common type of drought described in the sources. These refer to low water levels or a complete lack of water in certain rivers and canals, as well as a shortage of water in wells and pumps. Meteorological drought is more prevalent in sources from Deventer, although in general the descriptions refer exclusively to "excessive", "strong", "prolonged", or "long-lasting" periods of drought, often accompanied by a reference to the hydrological effects. Agricultural drought is mentioned very rarely in the sources. There is only one reference from Deventer that explicitly mentions negative agricultural yields in the city's hinterlands as a result of a drought and the fact that this led to increased prices for certain foodstuffs. Last but not least, socioeconomic drought only occurs during very strong droughts, usually the result of an accumulation of events leading to a severe lack of water and a shortage of food and other goods. This specific factor seems to be absent in the sources from Deventer and Zutphen.

While there are a number of different drought years for both cities (see Fig. 2), there are several coinciding years, although this does not always occur in terms of severity. The year 1615, for example, is ranked 3 for Deventer but 2 for Zutphen. The sources for Deventer for 1615 indicate both a period of drought and a lack of water, while Zutphen did not seem to suffer from the low water levels on the IJssel river. Explanations for such differences in hydrological drought can be found in the geohydrological differences between the two cities. Apart from the IJssel river, the groundwater tables of Deventer and Zutphen were also influenced by the influx of water from two other streams coming in from the east: the Schipbeek for Deventer and the Berkel for Zutphen (see Fig. 3). These streams fed the surrounding moats and canals of the cities, which determined the availability of water for milling or the water level in the wells and pumps. The Schipbeek was a human-made stream, which from its creation in the fifteenth century often suffered from silting due to increased amounts of sediment, human pollution, and poor management. Hence, the Schipbeek was considered an unreliable source of water, in particular during periods of drought (Schutten, 1981). As a natural river, the Berkel suffered less from such problems, and it was known as a relatively reliable supplier of water to the groundwater tables below Zutphen. This could explain different impacts of hydrological drought between the two cities. Nevertheless, many coinciding drought years, such as 1733, 1753, 1772, 1779, 1781, and 1783, indicate similar levels of hydrological drought for both cities, which points out similar effects of the rivers.

A notable level of difference between the two cities is that of seasonality (see Fig. 4). Deventer seems to have a much higher rate of spring droughts – recorded between March and May – and summer droughts – recorded between June and August, while Zutphen displays a larger number of winter droughts – recorded between December and February. It must be noted that this difference is also due to the higher density of data for Deventer. However, both cities seem to have witnessed an equal number of autumn droughts – recorded between September and November, which, together with summer droughts, constitute the most common category of droughts based on seasonality.

Similar to the research by Camenisch and Salvisberg, the results for Deventer and Zutphen also display specific clusters or accumulations of drought years that took place within a span of several sometimes subsequent years. Droughts with a moderate to severe impact, ranking 3 or 4 on the HSDS, occurred during the years 1630–1640, 1650–1652, 1662–1669, 1731–1733, 1781–1783, and 1790–1794. This does not include years in which references are made to the damaging effects of previous droughts, often a year or even multiple years after a severe drought occurred. Most of the severe droughts ranking 4 on the HSDS occurred during the second half of the eighteenth century, between 1753 and 1783.

5 Examples from the sources

It would go beyond the scope of this article to dive into the details of each specific drought year discovered for both cities. A brief overview of these can be found in Table S1 in Moerman (2024, https://doi.org/10.5281/zenodo.13133348), attached to the article. Nevertheless, to make sense of the otherwise rather abstract notions mentioned in the HSDS, it is necessary to provide a number of detailed examples. The number of examples has been restricted to the most extreme

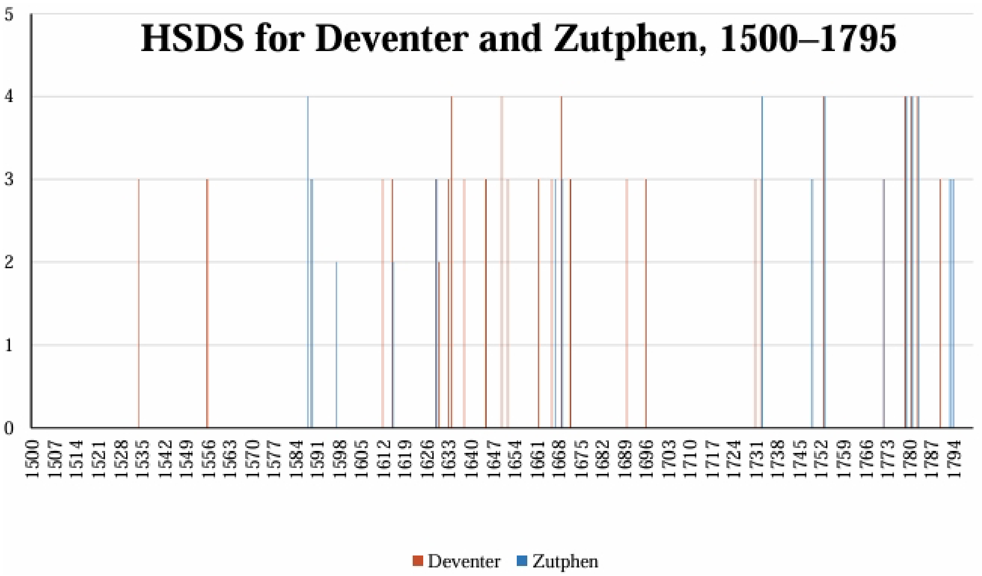

Figure 1. Chronology and severity levels of droughts within Deventer and Zutphen according to the Historical Severity Drought Scale (HSDS), 1500–1795.

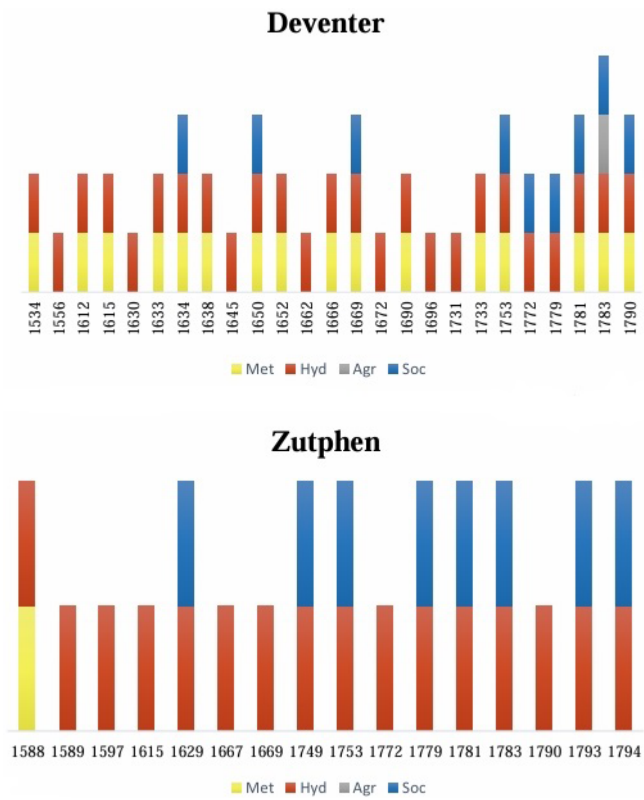

Figure 2. Difference in drought types per year for Deventer and Zutphen in terms of meteorological (Met), hydrological (Hyd), agricultural (Agr), and socioeconomic (Soc) factors during the period 1500–1795.

Figure 3. The locations of Deventer and Zutphen on a modern map of the Netherlands, indicating the IJssel river and the Schipbeek and Berkel sub-streams (map by Bert Brouwenstijn, VU Amsterdam).

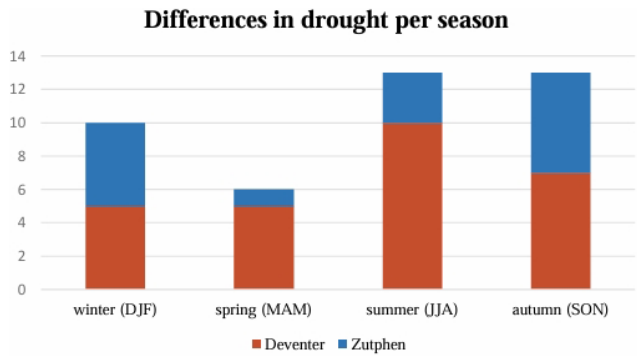

Figure 4. The number of droughts according to season for Deventer and Zutphen, 1500–1795.

and detailed examples, some of which coincide for both Deventer and Zutphen. These are 1669, 1753, and 1783.

5.1 The year 1669

Deventer witnessed a period of severe drought in September 1669, which, according to municipal documents, led to extraordinarily low water levels on the IJssel river. As a result, many of the wells and pumps in the city were rendered dry and unusable. The inhabitants described the lack of water as an inconvenience and public clamour regarding the scarcity of water was heard throughout the city. One of the main concerns was the risk of fire, which was worsened by the shortage of water. As for Zutphen, references to the shortage of water are less explicit for September that year. Here, no explicit mention of water scarcity is made in the city government documentation, but the fear of fire becomes apparent in a resolution that directed the city crier to call upon all inhabitants to store water in case of an uneventful fire. While the impact of the drought is very explicit for Deventer (scale 4), the reference to compulsory storing of water for Zutphen (scale 3) also implicitly links to hydrological drought but less to a direct societal impact or near-crisis situation.

5.2 The year 1753

During the year 1753, equally severe droughts are mentioned for both Deventer and Zutphen in terms of impact. In Deventer, the effects of drought were first felt in June, when an excessive drought (*excessive droogte*) led to a shortage of water in the city's wells. This lack of water led to a general shortage of water that prompted the city government to take action. In Zutphen, the impact of the drought was reported in September, which mentioned the low water levels on both the IJssel and Berkel rivers that led to the "paralysis" (*verlamminge*) of most wells and pumps. This displays a similarity in drought severity (rank 4), which refers to societal setbacks, for example by limiting water use, rather than a full socioeconomic crisis, although the potential for the latter could have been present.

5.3 The year 1783

The most detailed drought year (rank 4) recorded for both cities occurred in 1783. In Deventer, the strong and excessive drought led to a lack of water in most of the wells around the beginning of August. Later that month, a rare instance of agricultural drought is also mentioned as the a great spring drought, which led to a reduced yield in buckwheat. This implies that the prolonged drought probably set in during the spring months, while its effects did not become detrimental until the end of the summer when the prices of cereals increased significantly. In Zutphen, the effects were primarily felt by the drying-up of the Berkel river, which led to a standstill of all watermills at the beginning of August. Another likely effect of the drought of 1783 was an epidemic of dysentery in both Zutphen and Deventer. In Zutphen, the onset of the epidemic in towns and villages around the city was noticed in early August, while the first case within the city walls was recorded on the fourth day of that month. The disease spread rapidly during the following months, and the epidemic must have lasted until the end of October. The spread of waterborne diseases like dysentery can be attributed to a lack of clean, fresh water as a result of drought, which prompted people to use polluted water or to seek water from unsafe sources (Brázdil et al., 2020; Camenisch et al., 2020; Garnier, 2019; Pribyl, 2020).

In general, the source material often refers to similar indicators of hydrological drought, which often hindered socioeconomic life but rarely resulted in a widespread disruption of daily life. Instances of agricultural drought and its effects on food prices or general subsistence are very rare and only account for one particular case: the year 1783, when the prolonged drought led to a shortage of water, shutdown of watermills, dearth of cereals, and an outbreak of dysentery in both cities. However, the sources do not suggest that this led to a moment of crisis. There were also notable differences in the responses to drought, which do not correspond one to one for both cities during most years, despite the relative proximity and similarity of both cities in terms of geological and hydrological circumstances and the systems of water provisioning.

6 Comparison with the Van Engelen, Buisman, and IJnsen Temperature Series

Compared to other countries, very little concrete data with regard to temperature and/or precipitation exist for the Netherlands prior to the instrumental period after 1850. The Royal Netherlands Meteorological Institute (KNMI), founded in 1854, has a collection of "antique data", consisting of early instrumental observations from the eighteenth and early nineteenth century. These datasets are comprised of observations from several weather stations across the Netherlands.

Most of the stations from which eighteenth century records exist are located in the province of Holland – such as Amsterdam, Alkmaar, Bergen (North Holland), Delft, Haarlem, Leiden Rijnsburg, and Zwanenburg – leading to rather regional measurements more typical for the precipitation-rich western provinces along the North Sea coast, not the inland provinces that are more susceptible to strong droughts. The early records for the eighteenth century also contain very few consistent records regarding precipitation (Geurts and Van Engelen, 1992). Most data from this period consist of reconstructions regarding winter and summer temperatures.

The longest list of pre-instrumental, and partially instrumental, estimations of winter and summer temperatures available via the KNMI is compiled by Buisman, in collaboration with Van Engelen, and IJnsen. Despite its incredible length, running from 751 CE until 2000, this dataset is generally not well-known outside of Dutch-speaking academia (Van Engelen et al., 2001a; Pfister et al., 2018). The data series was constructed with the use of various proxy data from the early modern period, such as the weather diary of German pastor David Fabricius for the larger Frisian area in the north of the Netherlands, a set of frost-day notes from the German city of Kassel, and the “tow barge” records from the De Vries (1981) records of monthly temperatures in central England. It also includes data from the aforementioned weather stations (1706–1905). The winter – from November to March – and summer – from May to September – temperatures in this series have been categorised along an annual nine-point scale from 1 (extremely soft/cool) to 9 (extremely harsh/warm) (Van Engelen et al., 2001a). In addition to the categorisation of annual values, the series also contains annual temperature averages in degrees Celsius. This is divided between average summer (JJA), winter (DJF), and annual (November–October) mean temperature.

For the comparison with the HSDS for Deventer and Zutphen, only values from 7 to 9, implying above-average summer and winter temperatures, have been taken into account as relevant for possible correspondence between drought and above- or below-average temperatures. Overall, the result of the comparison was rather meagre. Only a handful of years displayed a correspondence between cases of moderate to strong and very strong droughts – those ranking 3, 4, or 5 on the HSDS – and above- or below-average summer or winter temperatures. Correspondences between droughts and high summer temperatures were found for the years 1534, 1556, 1669, 1733, 1779, 1781, and 1783. Only three years, 1556, 1781, and 1783, were ranked as extremely warm (9). Only for 1672 was there a correspondence between drought and below-average winter temperatures (7). As the data for Deventer and Zutphen are not normally distributed, a Spearman correlation coefficient was used to perform a statistical comparison (see Fig. 5) between the annual average summer temperatures (in °C) for the summer months (JJA). These show a rather weak correlation ($r = 0.14$ with $n = 26$ and a p value of 0.46) for the Deventer and moderate correlation ($r = 0.42$ with $n = 15$ with a p value of 0.12) for Zutphen. Comparing the average annual temperature series with the HSDS led to an even weaker negative correlation ($r = -0.01$ with $n = 26$ with a p value of 0.46) for Deventer and a moderate correlation ($r = 0.58$ with $n = 15$ and a p value of 0.02) for Zutphen. As such, only the comparison with the HSDS of Zutphen led to any statistically significant outcomes.

The relatively low correspondence between the HSDS for Deventer and Zutphen and the temperature series by Van Engelen, Buisman, and IJnsen can indicate two possibilities: (1) drought periods did not necessarily coincide with periods of above-average or extreme heat (or winter droughts with extreme cold), and/or (2) the series of temperatures provided by Van Engelen et al. (2001b) also might not provide precise enough information, given the reliance on non-local sources for the reconstruction of pre-instrumental temperature records. While modern data mentioned earlier show a trend of rising temperatures since the 1950s contributing to increased drought risk in the eastern regions of the Netherlands (Phillip et al., 2020), this is not necessarily in line with the data presented in this article. A similar study with regard to northwestern Europe suggested higher correlations between temperature and droughts than for temperature and precipitation, which might indicate that drought indices refer primarily to above-average temperatures and evapotranspiration (Leijonhufvud and Retsö, 2021). Given the relatively low correlation between the temperature series and HSDS for Deventer and moderate outcomes for Zutphen, the latter cannot be easily concluded for both cities. Possibility 1 is supported by the comparison with Deventer but less so for Zutphen. Possibility 2 can be used as proof that the reliance on data from various distant locations is not always useful when studying specific territories and localities. This can also be tested by using a large compiled index of drought years for multiple nearby territories, which is the case with the SDI.

7 Comparison with the SDI

The SDI was created by Camenisch and Salvisberg (2020) with the use of pre-existing precipitation reconstructions from documentary sources for the Netherlands and Belgium, Germany, France, and Switzerland between 1315 and 1715, applying the seven-point scale index. Because the SDI is based on years when a drought was reported across different territories, the number of drought years is significantly higher than in more local indices. When comparing their data from Bern and Rouen with the SDI, the number of corresponding droughts was relatively low, namely a total of 17 corresponding cases out of the 87 drought years in the SDI.

When comparing the data between 1500 and 1715, there were only 8 corresponding drought years out of 52 instances mentioned in the SDI for this period. These concern 10 instances in total: 8 specifically with regard to Deventer (1534, 1556, 1615, 1630, 1634, 1645, 1666, and 1669), 2 con-

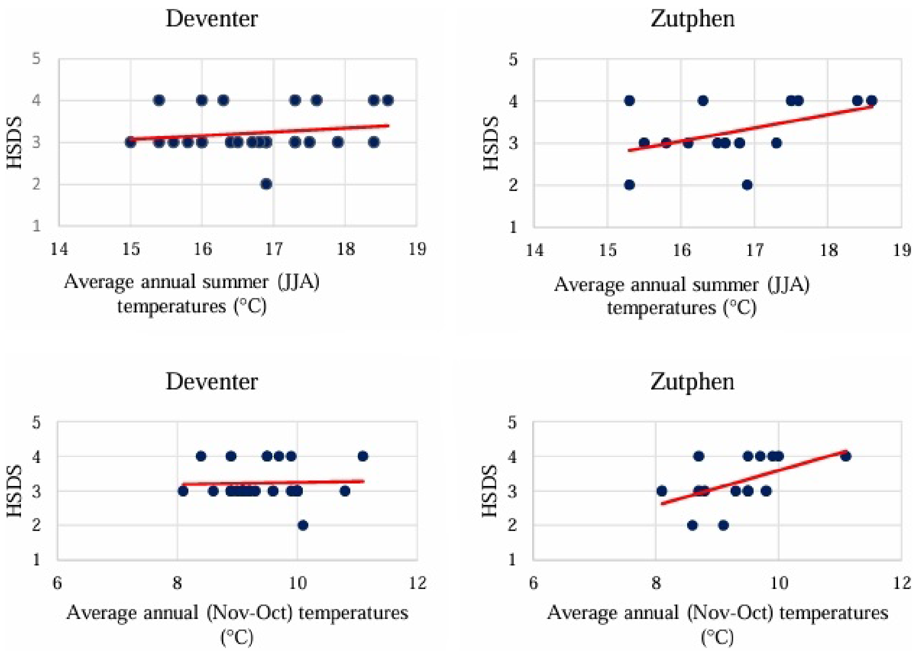

Figure 5. Scatterplots of the comparison between average annual summer and average annual temperatures with the HSDS for Deventer.

cerning both Deventer and Zutphen (1615 and 1669), and none specifically for Zutphen. This indicates that 44 droughts recorded in the SDI were not found for Deventer and Zutphen, while 14 instances of drought (1588, 1589, 1597, 1612, 1629, 1633, 1638, 1650, 1652, 1662, 1667, 1672, 1690, 1696) were documented specifically for Deventer and/or Zutphen during this period but do not occur in the SDI. Comparing the HSDS values for Deventer with the SDI led to a rather weak negative correlation ($r = -0.36$ with $n = 8$ and a p value of 0.19). Such a low degree in correspondence supports the conclusions regarding Bern and Rouen that generalised drought data cannot easily be applied to reconstruct or strengthen knowledge of specific local droughts. In fact, it shows that local sources can provide better insights into droughts that may not appear in compiled datasets. This prompts the need to do more in-depth research for multiple regions and localities to minimise faulty generalisations about the widespread effects of drought on different parts of society.

8 Comparison with the OWDA

Camenisch and Salvisberg (2020) also compared their findings for Bern, Rouen, and the SDI with the OWDA. The OWDA is a freely accessible online database that provides year-by-year data – either via a dataset or an interactive map – of drought severity throughout Europe and certain parts of North Africa and the Middle East on a 0.5° latitude–longitude grid going back as far as 0 CE and coming to a halt in 2012. The OWDA displays drought severity on an scPDSI scale from extremely dry (−6) to extremely wet (6). It is based on a vast amount of dendrochronological data for Europe, completed with additional information from historical data on hydroclimatic extremes, but only with regard to spring and summer drought conditions (Cook et al., 2015). This is also the main setback of the OWDA, as it can only be used to compare drought conditions from June to August. Another pitfall is the scPDSI ranking system, which has to be calibrated to other forms of indices, such as the seven-point Pfister index or the HSDS. Camenisch and Salvisberg tested the OWDA against the data from individual indices of Bern and Rouen, as well as the SDI. They used the censure of −2.5 on the scPDSI scale as the mark of moderate to severe and extreme droughts. As expected, the comparisons with the drought indices for Bern and Rouen showed low similarities between the OWDA ($r = 0.32$ and $r = 0.22$) for the respective indices. The wider SDI yielded a more moderate similarity ($r = 0.42$) with the data from the OWDA, which was also the only statistically significant outcome given the difference in sample size.

For the comparison with the HSDS for Deventer and Zutphen, grid snapshots were generated for each reconstructed drought year using the area which includes Deventer and Zutphen (52.34 to 52° N and 6 to 6.48 ° E) (see Fig. 8). Following the example of Camenisch and Salvisberg (2020), only values of −2.5 or lower were taken into account for relevant comparisons. The outcome of the comparison was rather meagre, as from 11 drought years corresponding to relevant outcomes of the OWDA survey (1534, 1615, 1630, 1634, 1652, 1666, 1669, 1753, 1790, 1793, and 1794), only one year, 1666, was relevant as it fell within the range of summer (JJA) drought. No usable data were available for the years 1638 and 1662. Another interesting aspect is that some of the major summer drought years in the HSDS, such as 1783, only received a ranking of −2 in the OWDA. However, the OWDA data for certain years, such as 1615, 1630, 1669, and 1793, indicating autumn and winter droughts, could perhaps indicate that the effects of the summer droughts were still felt during the following seasons. A quantitative comparison between the HSDS for Deventer and the OWDA has shown a weak negative Spearman correlation for Deventer ($r = -0.40$ with $n = 9$ and a p value of 0.29) and a weak positive correlation for Zutphen ($r = 0.42$ with $n = 6$ and a p value of 0.39). Once again, it must be taken into account that the sample size for this comparison remained rather small and the results are not statistically significant.

Perhaps the reconstructions using the OWDA are susceptible to the same criticism as the comparisons to the Van Engelen, Buisman, and IJnsen series, as well as the SDI. Individual comparisons between the HSDS and these datasets sometimes show strong deviations for Deventer and Zutphen. This could indicate the more localised character of most droughts, focusing specifically on their local effects and how these were experienced in society. Yet it also shows the limits of dendroclimatological analysis on the basis of tree rings as a proxy for drought, which highlights the value of using documentary sources as a means to verify the occurrence of historic droughts (Bothe et al., 2019; Maughan et al., 2022; Pribyl, 2020).

9 Discussion and conclusion

This article aimed to provide the first documentary evidence-based look at pre-instrumental droughts in the eastern Netherlands between 1500 and 1795, focusing on two case studies: the cities of Deventer and Zutphen. This was done by (1) examining the possibility of urban municipal archives to reconstruct past droughts, (2) creating drought indices for both cities, and (3) comparing the gathered data with other indices to spot possible correspondence.

The archives of Deventer and Zutphen contain plenty of municipal records that provided impact-based instances of drought from the early sixteenth to the late eighteenth century. As for Deventer, slightly longer-running and more records are available compared to Zutphen, where consistent records, such as daily resolutions, date back to the second half of the sixteenth century. Nevertheless, similar examples of drought-related measures were found that indicate how droughts affected both cities, primarily in terms of hydrological circumstances. The most common issues are related to low water levels in the rivers and canals around the city hampering navigation and low groundwater tables leading to a lack of water in wells and pumps. The main problem with the information from the documentary evidence from both archives is that although it provides a good view of the impact of drought in cities like Deventer and Zutphen, it remains difficult to establish the exact duration of droughts. The extent of droughts is only mentioned in terms of general words like prolonged and extraordinary. As such, the seven-point index, in which drought severity is measured according to monthly thresholds, cannot be applied to the data found for Deventer and Zutphen.

The alternative, creating an index along the HSDS, applies better to the source material, yet it is less precise than the seven-point index, which is also calibrated using an instrumental reference period. Nevertheless, using the HSDS for Deventer and Zutphen has led to an index with a total of 33 droughts of varying severity on the scale of 1 (deficiency of precipitation) to 5 (widespread societal disruption) for the period 1500–1795. As is the case with municipal records, only extreme instances of drought are reported, most of which appeared to fall within the range of scale 3 to 4, primarily denoting hydrological droughts in the form of dried-up waterways, wells, and pumps. Widespread societal disruption in terms of scale 5 was not discovered in the sources, which indicates that the droughts had a disturbing rather than a crippling effect on society. The data from both cities also suggest a difference in seasonality, as there seems to be an unequal distribution between spring and summer droughts. There were also notable differences between similar indexed drought years for both cities, by which the effects of drought were reported differently to indicate similar levels of severity, for example by referring to dried-up wells in Deventer and a shutdown of watermills in Zutphen. Although both instances indicate a scale 4 drought on the HSDS, referring to hydrological circumstances leading to socioeconomic drought, it can be questioned whether both examples were considered equally severe by contemporaries. Was a low-water mark in wells and pumps, for instance, considered just as bad as a period without the ability to employ watermills? The descriptive nature of the HSDS makes it a valuable index for the study of qualitative data from municipal records, although the next step should be to calibrate such data according to a more precise scale. This scale should be based on different conceptions from contemporary records to determine drought severity more precisely. This can be done by extending the categories into different levels of, for example, hydrological drought. For instance, a lack of navigation and shutdown of watermills can be regarded as more critical or disastrous compared to a general shortage of water for domestic purposes like cooking and washing, while the need for stable availability of water for firefighting purposes could be regarded as more important regarding the wide-ranging socioeconomic effects a major fire could have on the city as a whole (Garrioch, 2018).

Comparisons with other indices, such as the Van Engelen, Buisman, and IJnsen temperature series, the SDI, and the OWDA, yielded differing insights. This was the case in terms of both quantitative and direct comparisons between the different datasets. The comparisons with the Van Engelen, Buisman, and IJnsen temperature series yielded weak to moderate results for average annual summer temperatures and average annual temperature, displaying no consistent correlation between droughts and temperature for the HSDS regarding Deventer and Zutphen. The latter could also be influenced by the fact that the dataset compiled with input from multiple areas outside of the Netherlands cannot be used to accurately reconstruct extreme temperatures on a local scale. The comparison with the SDI for the sixteenth and seventeenth centuries led to a similar limited number of corresponding drought years, also indicating that supra-regional indices often have little correspondence with more localised documentary-based drought reconstructions. The same can be said of the comparison with the data gathered from single-year-based snapshots from the OWDA. In this case the correspondence was even lower regarding the sole focus on summer droughts, although the indications for certain years could point towards possible long-lasting effects of summer droughts during consecutive months. For each comparison, however, the limited size of the dataset for the HSDS concerning Deventer and Zutphen made quantitative analysis and comparisons difficult to render with a high degree of statistical significance. To enhance this, more data from several locations could be added to the existing dataset to create a more encompassing series along the HSDS for the eastern Netherlands or the country as a whole.

Nevertheless, the data for Deventer and Zutphen display evidence for a small number of supra-regional droughts, but the sources primarily indicate a larger number of local droughts specifically mentioned in the documentary sources for the period under study. These concern moderate to severe instances of drought that impacted society and prompted responses from the city government to avert possible negative outcomes, such as food and water shortages. As such, the sources to reconstruct droughts are closely connected to the societal responses to drought, which indicates that specific instances of drought, primarily hydrological drought, impacted society not necessarily by causing a widespread crisis but by limiting the use of water and waterways. The urban sources also record very few instances of agricultural drought, only one instance of which was found for a 300-year period. It is also remarkable that, at least for Deventer, the megadrought of 1540 is entirely absent in the sources. As Camenisch and Salvisberg (2020) demonstrated, however, this is not rare with regard to more localised reconstructions. Although major European drought events, such as in 1540, feature widely in supra-regional indices comprised of documentary and natural proxy data from across different regions (Wetter et al., 2014), they are less likely to show up in more local urban documentary evidence. Drought reconstructions for specific locations, whether cities or villages with adequate data density, should therefore be taken into account when compiling large-scale drought reconstructions to gain a more accurate picture of the regional and local spread of drought and its severity in terms of societal impact.

However, comparisons between specific localities constitute another aspect that requires more attention. Deventer and Zutphen, for example, despite their similarities and close proximity to one another, yield a number of different drought years. This can be explained, in part, by a difference in source density for specific periods. More and longer-running series of sources were available for Deventer, but considering the relative consistency and duration of the municipal records for both cities it could also be argued that droughts were not always perceived as equally menacing. Explanations for this can be found in the municipal records, which mostly refer only to high-impact drought events that required a governmental response, but also at the local level, for example by studying the hydrological, geological, and socioeconomic aspects of each city. This would include the dependence of specific water sources for a city's economy, such as the need to operate watermills or the general system of water provisioning and how this was impacted across different areas within a city. Differing hydrological or socio-political means that strengthened or helped to alleviate the effects of past drought could thus play an important part in determining the severity of drought on a local level (Metzger and Jacob-Rousseau, 2020). This could provide a better image of droughts through human actions and natural circumstances that have an influence on the local impact and severity of drought and other climatic hazards, which counts not only for the past but also the future (Degroot et al., 2021; Kchouk et al., 2022; Savelli et al., 2022; Van Loon et al., 2016). More research is needed in order to draw broader conclusions on the specific local impacts of urban droughts and how this was influenced by local natural or human factors over time.

Appendix A: Archival sources

- Historisch Centrum Overijssel (HCO) (Regional Archives of Overijssel), Deventer, Stad Deventer, periode Middeleeuwen, 1241–1591 (ID 0690), Edicta magistratus die buyrspraecht genoemptt or Dat boick der buyrspraiken, 1459–1538, 1555–1596, 135.1, 3.

- Historisch Centrum Overijssel, Deventer, Schepenen en Raad van de stad Deventer, periode Republiek 1591–1795 (ID 0691), Prothocoll des Rades van dagelicken resolutien, or Liber quotidianarum resolutionum civitatis Daventriensis, 1591–1795, 4.14.

- Historisch Centrum Overijssel, Deventer, Schepenen en Raad van de stad Deventer, periode Republiek 1591-1795 (ID 0691), Register van resolutien van Schepenen en Raad en Gezworen Gemeente (Concordaten), 1600–1794, 6a-m.

- Historisch Centrum Overijssel, Deventer, Schepenen en Raad van de stad Deventer, periode Republiek 1591–1795 (ID 0691), Register van verordeningen en bekendmakingen van het stedelijk bestuur (Buurspraakboek) or Liber publicationum, 7a–g.

- Erfgoed Centrum Zutphen (ZuRAZ) (Regional Archives of Zutphen and surrounding areas), Zutphen, Oud-Archief van de stad Zutphen, 1206–1815 (ID 0001), Memorien- en resolutieboek van de stad Zutphen, registers van resoluties van de magistraat, 1573–1808, 2, 3, 6, 8, 18, 32, 35, 37, 46, 49, 50, 52.
- Erfgoed Centrum Zutphen, Zutphen, Oud-Archief van de stad Zutphen, 1206–1815 (ID 0001), Repertoria op de resoluties van de magistraat, 1573–1620, 110.
- Erfgoed Centrum Zutphen, Zutphen, Oud-Archief van de stad Zutphen, 1206–1815 (ID 0001), Repertoria op de resoluties van de magistraat, 1620–1660, 111.
- Erfgoed Centrum Zutphen, Zutphen, Oud-Archief van de stad Zutphen, 1206–1815 (ID 0001), Repertoria op de resoluties van de magistraat, 1661–1700, 112.
- Erfgoed Centrum Zutphen, Zutphen, Oud-Archief van de stad Zutphen, 1206–1815 (ID 0001), Repertoria op de resoluties van de magistraat, 1701–1740, 113.
- Erfgoed Centrum Zutphen, Zutphen, Oud-Archief van de stad Zutphen, 1206–1815 (ID 0001), Repertoria op de resoluties van de magistraat, 1741–1780, 114.
- Erfgoed Centrum Zutphen, Zutphen, Oud-Archief van de stad Zutphen, 1206–1815 (ID 0001), Repertoria op de resoluties van de magistraat, 122.

Data availability. The data used in this article are included in two Supplements attached to the article (https://doi.org/10.17026/dans-x3p-camy, Moerman, 2022 and https://doi.org/10.5281/zenodo.13133349, Moerman, 2024). The Van Engelen, Buisman, and IJnsen temperature series are available via the website of the Royal Netherlands Meteorological Institute (https://cdn.knmi.nl/knmi/map/page/klimatologie/gegevens/daggegevens/antieke_wrn/nederland_wi_zo.zip, Van Engelen et al., 2001b). The SDI is available as a Supplement to the article by Camenisch and Salvisberg (2020). The dataset related to this article is available via https://doi.org/10.17026/dans-x3p-camy (Moerman, 2022).

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/cp-20-1721-2024-supplement.

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