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Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 35th PIANC World Congres 2024

Citation (APA)
Ligtenberg, J., & Vinke, F. R. S. (2024). Comparing Navigability Of The Dutch Rivers Meuse And Waal Following The Pardé-Coefficient. In J. S. Schoonees (Ed.), *Proceedings of the 35th PIANC World Congres 2024* (pp. 1432-1436). PIANC.

Important note
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35th PIANC World Congress, 29 April – 23 May 2024, Cape Town, South Africa
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COMPARING NAVIGABILITY OF THE DUTCH RIVERS MEUSE AND WAAL FOLLOWING THE PARDÉ-COEFFICIENT

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Prolonged droughts induced by climate change are a significant threat to inland shipping on Dutch rivers, particularly on the river Waal, a branch of the river Rhine. The anticipated shift to a more rain-dominated river, due to reduced meltwater from Alpine glaciers, may aggravate extreme low flow conditions, threatening the Waal's navigability. To improve the navigability in a rain-dominated river system, the Dutch government decided the transformation of the river Meuse into a confined river with seven weir-lock complexes. This study aims to compare the discharge regimes of both rivers to examine whether the river Waal turns into a rain-dominated system similar to the river Meuse, which may justify weir-lock complexes in the Waal as a potential solution. Analyzing 100 years of discharge data at Lobith, using the Pardé coefficient, shows that the characteristics of the Waal's runoff regime are shifting from a mixed-river towards a more rain-dominated river. Future climate projections indicate more pronounced extremes in runoff regimes, emphasizing the changing nature of the river Waal. While becoming more rain-dominated, the Waal's discharge regime is not expected to match the Meuse's before 2085.

Keywords: Pardé coefficient, river Rhine, river Meuse, inland navigation, weir-lock complexes

Introduction

Climate change has a huge effect on discharge extremes on rivers all over the world [1]. A climate change related event that aggravates low water events, is the disappearance of the contribution of long-term snowfall and the retreat of glaciers [2] [3]. This leads to discharges becoming more rain dominated. This is the case for the river Rhine. As opposed to the river Meuse which is yet a fully rain-dominated river. Both rivers are shown in Figure 1.

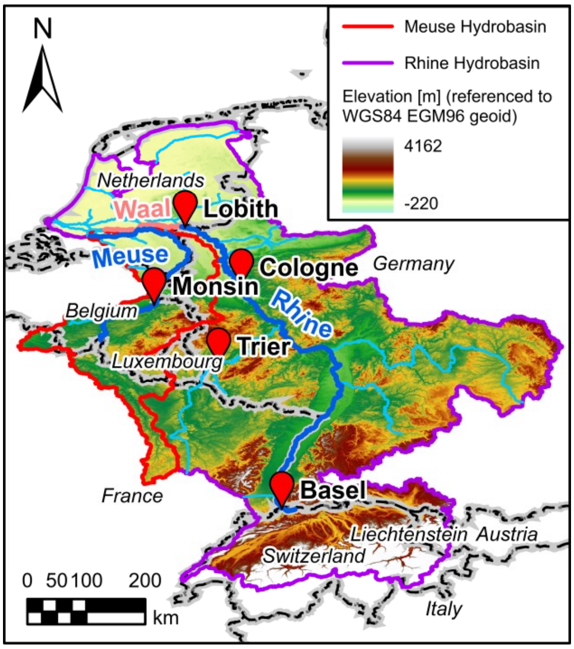

Figure 1 Study area; Rhine and Meuse river basins including relevant locations along the rivers.

Rain-dominated rivers are predominantly influenced by rainfall. This means that the discharge of a rain-dominated river strongly varies with the seasons, leading to relatively high discharges in the wet season and low discharges in the dry season. The low base flow during the dry season makes this type of river vulnerable to droughts.

Droughts affect inland shipping and cause disruptions in supply of materials and freight [4] at the Rhine, which is an important corridor between the seaports of Antwerp, Rotterdam and Amsterdam to the hinterland in the Netherlands, Germany and Belgium.

The drought of 2018 in Northwestern Europe led to large economic losses in Germany and The Netherlands. Erasmus UPT estimates a direct financial loss of 2400 million EUR for Germany and 300 million EUR for the Netherlands due to inland navigation restrictions as result of low discharges [5]. In order to prevent deterioration of the navigability of the Dutch river Waal and prevent large economic impacts, measures are required to facilitate inland shipping in the future.

Several (local) measures to improve navigability on the river Waal are proposed within the program Climate Resilient Networks [6] [7]. Among these measures are infrastructural measures, fleet adaptation, measures for the logistic sector and measures associated to information management. All of these measures are in accordance with the philosophy of free flowing rivers. This philosophy excludes the construction of weir-lock complexes to improve navigability. This option is considered very effective in improving navigability, as it provides constant water levels and sufficient water depth.

Associated to the traffic engineering aspect, Ligtenberg [8] showed that two weir-lock complexes would be sufficient to facilitate fully loaded inland shipping at the river Waal and operate current vessel intensities within the present throughput requirements. From a financial perspective Taekema [9] illustrated, based on a rough estimate, that weir-lock complexes can be viable under the most unfavorable climate projections. This suggests that weir-lock complexes are an option to consider. Keeping in mind the large investment costs and potential large impacts on other river functions e.g. ecology, groundwater levels and water distribution.

Although these issues, in the early 20th century the Dutch government decided to canalize the rain-dominated river Meuse to facilitate the transport of coal by large barges as a result of insufficient available draught during long periods of drought [10]. The same weir-lock complexes are still essential for navigability on the river Meuse. Nowadays (2020) approximately 30.000 vessels navigate the Meuse, transporting 18.3 million tons of cargo and 220.000 TEU annually. The annual vessel intensity on the river Waal is approximately 115.000, allowing for transport of 135 million tons of cargo and 2.1 million TEU. Therefore, the construction of weir-lock complexes in the river Waal seems to be a potential measure to overcome the impact of climate change on inland shipping.

Objective

In this paper we examine historical and future discharge patterns of the river Waal and river Meuse, to identify whether the future discharge regime of the Waal will be similar to the river Meuse' at the start of the 20th century. The result could legitimate a change in policy to facilitate the construction of weir-lock complexes on the river Waal.

Methodology

The applied methodology consists of three steps. First, the historical development of the discharge regimes of the rivers Rhine (Lobith) and Meuse (Monsin) are compared based on a discharge-time series (1903-2020) using the Pardé coefficient [11] [12]. The locations mentioned are in Figure 1.

The coefficient (see Equation 1) describes the ratio between the mean monthly discharge ($Q_{i\ (monthly)}$) and the mean annual discharge (Q_{annual}).

$$PC_i = \frac{\bar{Q}_{i\ (month)}}{\bar{Q}_{year}} \tag{1}$$

The outcomes for the individual locations are compared to three locations along multiple Rhine branches, each representing a characteristic and distinct discharge regime. See Figure 1 for the locations and Figure 2 for the corresponding discharge regimes.

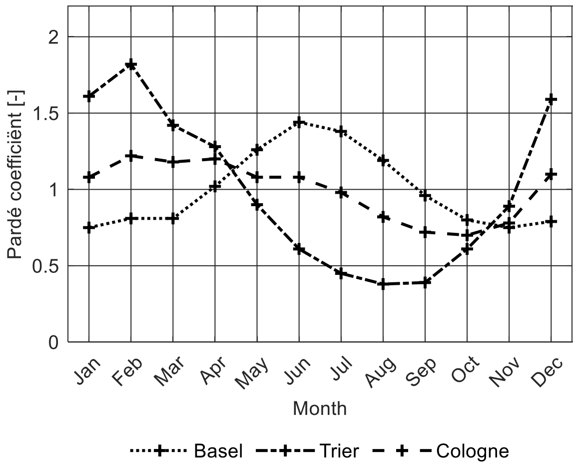

Figure 2 Typical discharge regimes in the Rhine basin; reference period 1961-1990 (adapted from [13])

The discharge regime at Basel, which is situated at the foot of the Alps, is labeled as "nival" and is snowmelt dominated. The regime is characterized by a peak value in June because of a large contribution of melt water. The discharge regime at Trier, located along a branch of the Rhine, is labeled as "pluvial" and is rainfall runoff-dominated. This regime is characterized by a peak value in the wet season (Dec. until Feb.) and low values in the dry season (July until Sept.). At Cologne, located along the main branch of the Rhine, several branches have merged, resulting in a "nival-pluvial" regime. This is a mixed regime due to contributions of melt water and rainfall runoff.

Secondly, the effects of local climate projections [14] on the future development of the Pardé coefficient at Lobith for 2050 and 2085 are investigated. Lastly, the projected discharge regimes for the river Waal are compared to the historic discharge regime of the river Meuse.

A synthetic discharge-time series based on HBV-model output was used to compute future Pardé coefficients [15]. New discharge-time series corresponding to the latest KNMI'23 climate projections appeared in December 2023 [16], however we were not able to include these in this paper due to time limitations.

Results

The last of seven weir-lock complexes on the river Meuse was completed in 1936 under a pluvial discharge regime (see Figure 3). Figure 3 also shows that the Meuse at Monsin has a very similar character compared to the pluvial Rhine branch at Trier. The discharge regime has not changed significantly over time as illustrated in Figure 3. The

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discharge in the river Meuse is characterized by high discharges in the wet season (Oct.-Apr.) and low discharges in the dry season (May-Sept.). Pardé coefficients generally reach maxima of 1.6-2.1 in December and January and minima of 0.3-0.4 in August and September.

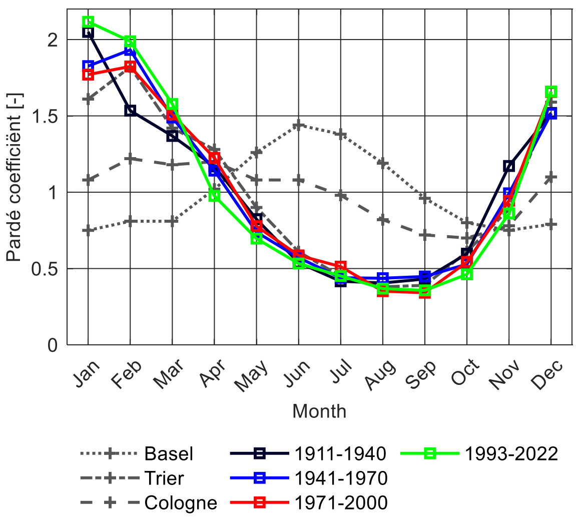

Figure 3 Development of the Pardé coefficient at **Monsin** between 1911 and 2022 averaged over periods of 30 years with a 30-year interval.

The river Waal is a free flowing river and has a very similar runoff regime compared to the Rhine's main branch at Cologne. The nival-pluvial regime is bimodal, fed by both snow- and ice melt runoff from the Alps and rainfall runoff from the Rhine and tributaries. Figure 4 shows that the wintery runoff maximum dominates the summer maximum, leading to largest Pardé coefficients in the wet season (Oct.-Apr.). Pardé coefficients vary from 0.7 in the dry season to 1.4 in the wet season (May-Sept.).

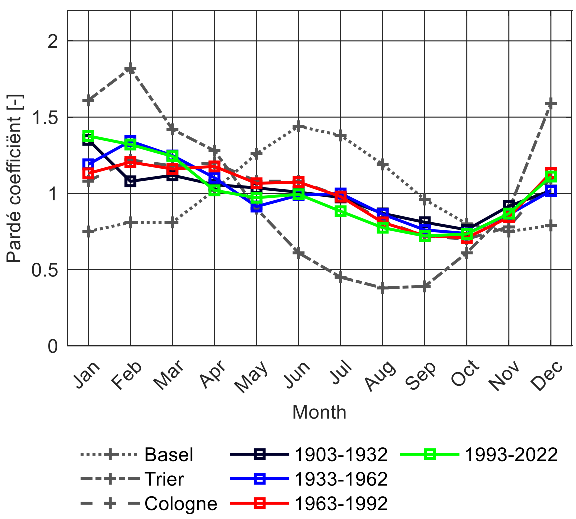

Figure 4 Development of the Pardé coefficient at **Lobith** between 1903 and 2022 averaged over periods of 30 years with a 30-year interval.

Over the past century, the river Waal's discharge regime has shifted slightly towards a more pluvial regime. Pardé coefficients have decreased for the months July until September by approximately 0.1. Meaning that these months have become drier with respect to the annual average discharge over time. As opposed to January, February, March and December, these months show an increase in Pardé coefficient varying from approximately 0.1 to 0.3. Meaning that these months get wetter with respect to the annual average discharge.

Figure 5 illustrates the change in Pardé coefficient on a 10-year interval, also indicating the shift from a nival-pluvial regime to a more pluvial regime. The shift is even more pronounced when introducing climate projection $W_{h,dry}$ for 2050 and 2085 on the discharge regime at Lobith. Note that $W_{h,dry}$ is the driest local climate projection for the Netherlands [17]. Pardé coefficients are decreasing further for the months July, August, September and October. Reaching minima of 0.56 and 0.45 for climate scenario's $W_{h,dry}$ 2050 and $W_{h,dry}$ 2085 respectively. Pardé coefficients are increasing from December until April. This climate projection illustrates, based on the Pardé coefficient, that the wet season gets wetter and the dry season get drier.

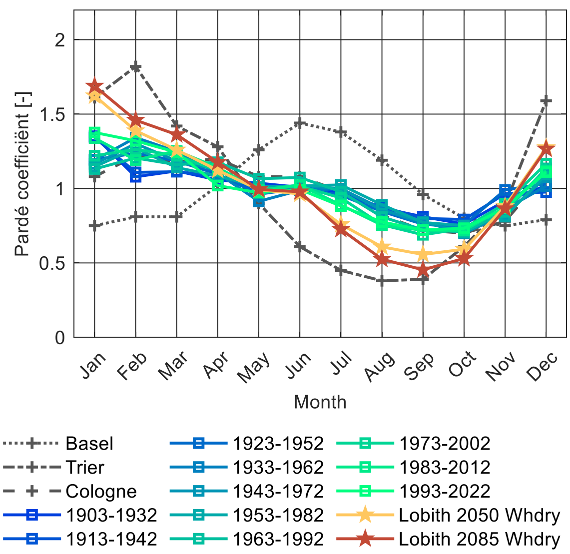

Figure 5 Development of the Pardé coefficient at **Lobith** between 1903 and 2022 averaged over periods of 30 years with a 10-year interval, including climate projections for **Lobith**.

Figure 6 shows the historical development of the discharge regime of the river Meuse at Monsin, including the projected discharge regimes for 2050 and 2085 at Lobith. Again, there are no clear shifts in Pardé coefficients between 1911 and 2022 at Monsin. The discharge regime in 2085 at Lobith (river Waal) in climate scenario $W_{h,dry}$ starts to show similarities with the discharge regime at Monsin, however Pardé coefficients do not overlap (April and October excluded). This process is expected to continue until the Alpine glaciers and vast snow fields have disappeared.

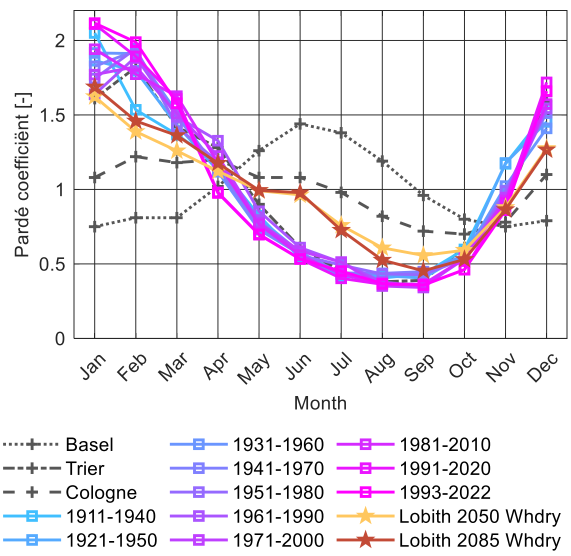

Figure 6 Development of the Pardé coefficient at **Monsin** between 1911 and 2022 averaged over periods of 30 years with a 10-year interval, including climate projections for **Lobith**.

Conclusion

The discharge regime in the river Waal is currently characterized as nival-pluvial. However, our analysis on a discharge-time series at Lobith (1903-2020) using the Pardé coefficient shows that the regime is slowly shifting towards a more pluvial regime.

The projected runoff characteristics in 2085 at Lobith are not as such as the runoff characteristics of the river Meuse in early 20th century (period of construction of weir-lock complexes on the river Meuse). Although, we can conclude that the runoff regime has shifted substantially, from a nival-pluvial regime to a more pluvial regime under the considered climate projections.

A pluvial runoff regime is characterized by the lack of ice- and snowmelt water and a heavy dependence on rainfall runoff. This implies a reduction of base flow (due to the reduction in ice- and snowmelt water) on the river Waal in the future. The absence of base flow aggravates periods of drought, especially in the dry season.

As the dry periods become drier, the navigability of the Waal is anticipated to decrease during those periods. It is expected that future low water periods occur earlier in the year and become more severe.

Discussion

The data used for climate projections is based on output generated by the HBV-model. The HBV-model may not handle the change in glacier volume properly, resulting in an overestimation of the portion of ice melt water [3], especially in May, June and July.

New discharge-time series corresponding to the latest local climate projections appeared in December 2023 [16]. However, these discharge-time series were not used in this paper due to time limitations. The results that could be obtained from the new discharge-time series are not expected to deviate substantially from the results obtained in this paper, because the concluded implications from these projections in [16] are very similar to the conclusions drawn in this paper.

This paper illustrates a worst-case scenario, as only the most severe climate projection is used. Data for a milder climate was available, however the intention was to examine whether the future runoff characteristics of the Waal river could potentially match the runoff characteristics of the Meuse river.

Detailed conclusions on navigability cannot be drawn based on the Pardé coefficient solely. The Pardé coefficient is a dimensionless number, where navigability needs to be expressed in absolute values. However, the Pardé coefficient can be used to assess the (future) discharge characteristics of a river, which can indicate a change in navigability.

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