Water Resources and Industry 33 (2025) 100279

Contents lists available at ScienceDirect

Water Resources and Industry

journal homepage: www.elsevier.com/locate/wri

Assessing water dependencies and risks in Dutch industries: Distribution, consumption and future challenges

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A B S T R A C T

This research examined the water dependencies and associated risks in Dutch industries by focusing on three main aspects: the geographical distribution of industrial clusters relative to water sources, water consumption and its economic value across different sectors, and future water stress scenarios with their regional implications. The study uncovered a complex relationship between industrial facility location and water use. It revealed a strong correlation between facilities and nearby water sources, with a tendency for industries to cluster around water sources, peaking at a proximity of about 0–5 km for both surface water and groundwater sources. However, it also pointed out that this relationship is influenced by several other factors including water quality, extraction rights, historical development, and competition for water resources. Additionally, the analysis underlined the importance of considering both water consumption and proximity to water sources to accurately assess dependency. It advocated a more sophisticated approach that moves beyond mere water usage per unit of output to encompass the production complexities that significantly affect water dependency in particular industries. The future projection showed baseline water stress impacts the security of water supply of industries at different magnitude. Particularly, North Brabant and Limburg stood out as particularly vulnerable. These regions hold a significant portion of the studied industrial facilities (21.7 %) and dominate the nation's mineral industry (75 %). The study acknowledged the drawbacks of depending solely on average sectoral data and stresses the urgency for proactive water management strategies. These insights laid a solid groundwork for further research and the implementation of targeted water conservation and sustainable production measures within the Dutch manufacturing sector and beyond as water management issues have global relevance. This study suggested areas for further exploration such as exploring different circular water strategies, industrial symbiosis, leveraging digital technology for optimising water management, and utilising alternative water sources.

Abbreviations Table

Abbreviations	Acronym
European Pollutant Release and Transfer Register	EPRTR
The Standard Industrial Classification	SIC
European Union's classification	NACE
United Nations classification	ISIC
European Environmental Agency	EEA
OpenStreetMap	OSM
Public Services on the Map	PDOK
Basic Registration of the Subsurface	BRO
Dutch Statistics Centre	CBS

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https://doi.org/10.1016/j.wri.2025.100279
Received 5 July 2024; Received in revised form 10 December 2024; Accepted 6 January 2025
Available online 8 January 2025

(*continued*)

Abbreviations	Acronym
compound annual growth rate	CAGR
Socioeconomic Shared Pathways	SSPs
Representative Concentration Pathways	RCPs

1. Introduction

Throughout history, the Earth's water cycle has seemingly provided an abundant supply of freshwater and has a pivotal role to sustain the functioning of the ecosystem and human society. Water has been utilised by virtually all the processes in the cycle, but its distribution changes over time despite the overall amount of water is relatively steady [1]. Despite its abundance, scientific evidence has shown that accessible freshwater is, indeed, a finite resource, making its sustainable management a pressing global issue. The process industry is one of the main pillars of the European economy and its intertwined relationship with its intensive water consumption is widely acknowledged [2–4]. Industries consume significant volumes of water accounting for 22 % of worldwide water consumption, impacting local water resources and stress levels, yet the economic value derived from this water use varies significantly across sectors [5–8]. Based on the OECD Environmental Outlook to 2050, manufacturing and industrial production are projected to undergo the most substantial growth among all sectors, expanding by a combined 400 % and drive a 55 % increase in global water consumption from 2012 to 2050 [9,10]. Industrial water use finds significant applications in various processes and applications in thermoelectric power plants, manufacturing plants, ore and oil refineries, where it serves e.g. as a cooling agent, solvent, for steam generation and as chemical reagent. Thus, making it an indispensable resource for economic activities and production processes. Inefficient water practices, driven by various factors, lead to excessive water consumption, wasteful discharges, and a strain on freshwater resources. Efficient water management is essential for sustainable industrial practices and environmental preservation as water resources become increasingly limited. By mitigating water inefficiencies, industries can contribute significantly to global water conservation efforts and build a more resilient and water-secure future.

The Netherlands has a significant portion (26 %) of land below sea level and has been fighting a historic battle against water throughout centuries. It has thus developed unparalleled expertise in water management [11,12]. This expertise extends into the industrial sector including its national regulatory frameworks such as Water Act (Waterwet), Activities Decree (Activiteitenbesluit milieubeheer) and Environmental Management Act (Wet Milieubeheer) [13–15], as well as the incentive for collaborative water management [16,17]. The country relies heavily on controlled water systems, making efficient use crucial to ensure sufficient supplies for all users, including agriculture, industry, and domestic consumption [18]. In a recent television program, the former CEO of the largest drinking water supplier in the Netherlands Vitens Jelle Hannema, stated that sometimes the water company has to say 'no' to new connections and cannot accommodate more demand from companies, considering factors like dropping groundwater levels and increasingly frequent periods of low flow in rivers due to climate change are putting pressure on traditional water supplies [19]. In the Netherlands, water use by the manufacturing industry accounts for around 18–24 % (2013–2021) of the water use by all economic activities and is expected to rise steadily with its industrial development [20,21].

The industrial sector is a major consumer of water resources, with increasing demand driven by industrial growth, technological advancements, and energy transitions. Nonetheless, a thorough understanding of industrial water usage trends, including the geographic distribution of industrial water demand, sector-specific consumption rates, and the related economic consequences is still absent in the Netherlands. This lack of knowledge is especially crucial as industries encounter increasing challenges from various sources. Climate change is worsening water shortages in numerous areas, leading to extended drought durations and decreased dependability of freshwater supplies. At the same time, competing needs from farming, residential consumption, and environmental conservation are intensifying pressure on resources that are already scarce. For industries, this changing environment not only jeopardises operational efficiency but also heightens economic and environmental risks, especially for sectors that rely heavily on water. Tackling this gap is crucial for promoting sustainable industrial growth, securing water availability, improving resource management, and facilitating long-term water resilience in the Netherlands.

To address these challenges, this study investigates industrial water use in the Netherlands, focusing on the intersection of geography, economic output, and water risk. Specifically, the research seeks to answer the following questions.

1. What are the industrial clusters in the Netherlands, and what is their geographical proximity to water sources?
2. How does water consumption per unit of economic output vary across industries in the Netherlands? How does the incremental change in value added, resulting from a small change in water consumption, differ across sectors?
3. How will projected water risks (e.g., baseline water stress) impact specific industries in different regions of the Netherlands?

This paper aims for the first time to develop a better understanding of the dynamics of industrial water use and its economic implications. In section 2 we describe the data sources and methodology used in this paper to answer the above questions. Section 3 will then present and discuss the results with focus on the spatial distribution of the industries, how they use water as production factor in their processes and ending with an assessment of future risks. This research not only highlights the critical areas and industries in need of immediate attention but also provides a forward-looking perspective on the challenges and opportunities under different climate scenarios. Furthermore, the findings of this study can provide knowledge, insights, or evidence that can influence or guide the development of effective industrial water management strategies, such as the implementation of industrial symbiosis practices, to mitigate water stress and enhance resource efficiency within industrial ecosystems. The overall conclusions are presented in section 4.

2. Data and methodology

In order to address the research questions posed, this study adopts a multifaceted methodology that integrates spatial and economic data analysis techniques. For the first question regarding industrial clusters and their proximity to water sources, a spatial data analysis approach was employed. This involves the utilisation of geospatial datasets on industrial locations and water resources within the Netherlands. To investigate the relationship between water consumption and value added across different sectors (question two), economic data specific to these sectors in the Netherlands was collected and analysed with econometric modelling. Finally, to explore the potential impacts of projected water risks on industries in various regions (question three), the study integrated projected regional

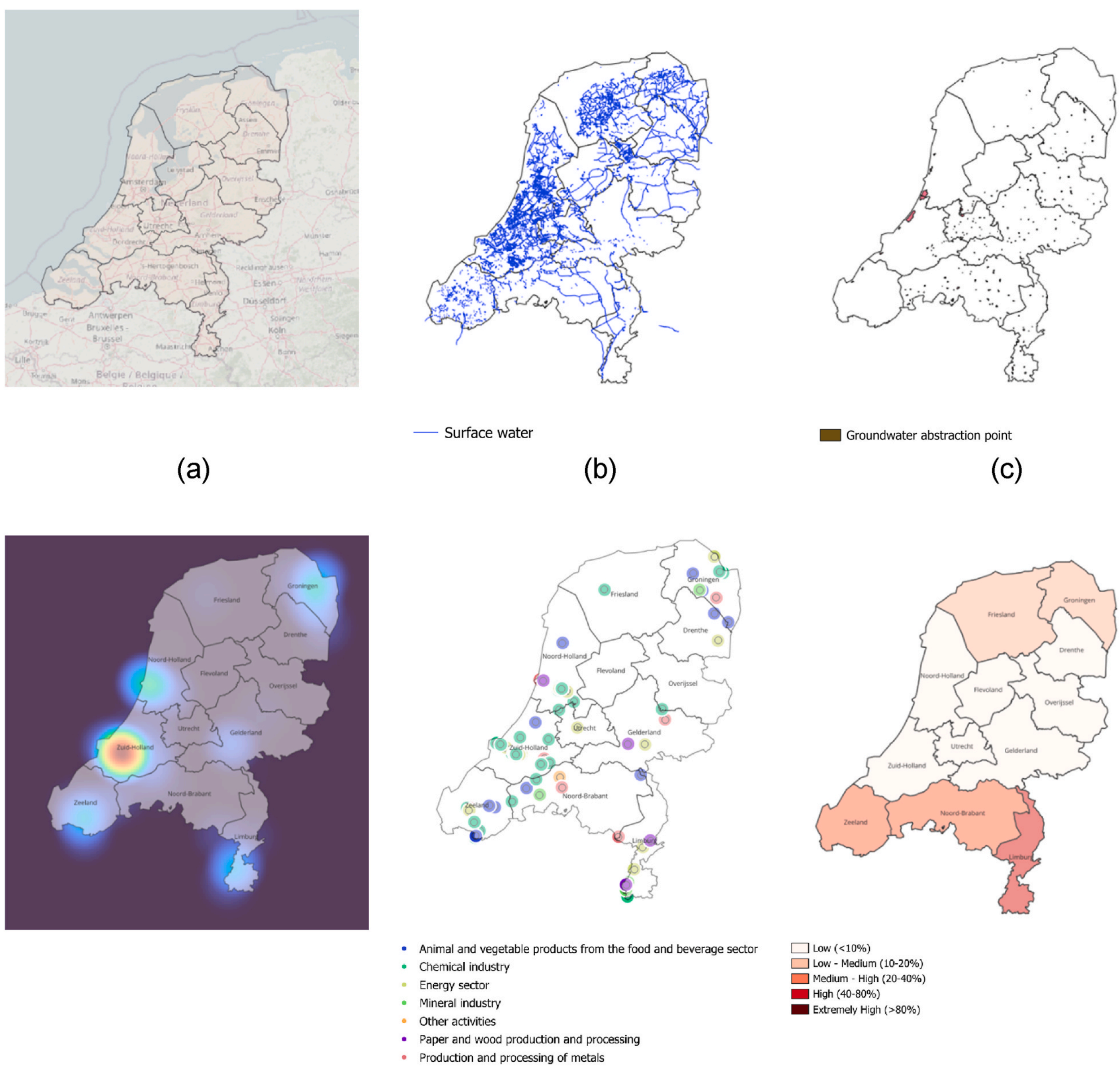

Fig. 1. Different facets of industry water dynamics in the study scope. (a) Map of the Netherlands, scope of study (shaded region); (b), Surface water occurrence (2024); (c) Groundwater abstraction points that needs a permit or notification and geothermal systems under 500 m (2020); (d) Density of industries in the study area, with warmer colours indicating higher density [50]; (e) Distribution of type of industries [50]; (f) Regional baseline water stress level (2024) abstracted from Aqueduct 4.0, areas in red indicate high stress.

water stress with data on regional industrial distribution and assessed the impacts across regions. A more detailed explanation of the specific methods and data employed is provided throughout this section.

2.1. Description of study area

The Netherlands has an extensive network of rivers and canals. It has an estimated 7650 m^2 of surface water, which is about 18 % of its total area. This distribution varies significantly across different regions of the country where major rivers, such as the Rhine, Meuse (Maas), and Scheldt, play a crucial role in the hydrology of the country. These rivers enter the Netherlands from Germany and Belgium and fan out into a vast delta before flowing into the North Sea [22]. This extensive network of surface water distribution has also dictated the placement of industries, particularly those requiring significant water for processing, cooling, and waste disposal. Major industrial zones such as Rotterdam, Amsterdam, and areas along the Rhine, Maas (Meuse), and Scheldt rivers are strategically located to leverage these waterways as shown in Fig. 1(d). These areas have developed robust economies around shipping, logistics, petrochemical manufacturing, and other water-dependent industries. Groundwater in the Netherlands is predominantly replenished by precipitation, infiltrating through the soil into deeper layers where it accumulates in aquifers. These aquifers are not uniformly distributed across the country, leading to regional variations in groundwater availability and quality. The Pleistocenic sandy soils in the Eastern and Southern parts of the Netherlands are particularly permeable, facilitating significant groundwater recharge. These regions, therefore, boast more substantial groundwater reserves compared to the Western and Northern parts, where clayey and peaty soils dominate [23,24]. The latter areas exhibit lower permeability, reducing natural recharge rates and making groundwater extraction more challenging. As described previously, the process industry clusters in the Netherlands significantly contribute to the nation's economic growth. The Netherlands is distinguished by several process industry clusters that strategically leverage geographical and infrastructural advantages, enhancing economic growth, innovation, and sustainability. For instance, as shown in Fig. 1(d), the Rotterdam-Moerdijk Cluster, in the Southwest comprises approximately 60 companies, including 5 oil refineries, 36 chemical companies, 4 waste processing companies and 14 other industrial companies producing goods and materials for the international and European markets [25]. It also stands out as one of the largest chemical clusters globally, with its extensive refineries, petrochemical plants, and logistics infrastructure essential for European manufacturing and global exports. In the Southern province of Limburg, the Brightlands Circular Space, in collaboration with the Brightlands Chemelot Campus and Chemelot Circular Hub in Geleen, focuses on accelerating the energy transition and fostering circular economy initiatives [26]. Similar industrial clusters can also be identified in the Smart Delta Resources in Zeeland, the Noord Nederland Cluster in the North and the Noordzeekanaalgebied Cluster around the North Sea Canal, including Amsterdam and IJmuiden. Of the European Pollutant Release and Transfer Register (EPRTR) sectors studied in this paper, the number of chemical industries is the most prominent in the Netherlands, accounting to 43 % of the total number of facilities (165) reported in the registry. This is also reflected in Fig. 1(e) in green. The remarkable advancement of the Netherlands' chemical sector is largely due to targeted investments in innovation and specialised public funding, coupled with a robust emphasis on research and development to integrate international technologies [27,28]. Additionally, the sector's evolution has been significantly influenced by a tradition of collaborative agreements and an expanding workforce, notably underscored by a significant upturn in chemical manufacturing from 1850, the year marked by the establishment of key chemical factories at that time, namely several garancine (dye), sulphuric acid, alkali, and stearic candle factories [29–33]. Fig. 1(f) shows the baseline water stress level of provinces in the Netherlands extracted from Aqueduct 4.0. The Aqueduct 4.0 baseline water stress measures the ratio of total annual water withdrawals to available renewable surface and groundwater supplies [34]. The legend in Fig. 1(f) incorporates the entire range of water stress levels for a comprehensive view. It is important to note that based on the current baseline data, none of the provinces fall within the "extremely high" water stress category. Nationally, the country has a low to moderate baseline water stress. Noticeably, the Limburg province has a higher baseline water stress than the remaining of the Netherlands, this could be influenced by a combination of its geographical features, less intense rainfall, and the vulnerability of its river valleys [35,36].

This research is confined to the Netherlands, thereby furnishing a detailed representation of national industrial water use and contributing to the broader understanding of the environmental and economic aspects of water resource management.

As demonstrated above, the Netherlands offers a unique opportunity for studying industrial water management. Its high concentration of industries intensifies competition for water resources, making it a prime example of managing water stress in densely populated regions. The Netherlands faces projected water scarcity, providing a real-world testing ground for proactive water management strategies and possibly valuable lessons for regions facing similar challenges, while also fostering the development of innovative and sustainable solutions for the future.

2.2. Terminology

The terminologies for the industrial type and data sources in this study are explained below.

Classification of industry: The Standard Industrial Classification (SIC) system is used for categorising industries as it is highly beneficial for economic research, offering a structured way to categorise industries for comparative analysis. Its uniform grouping denoted by a maximum of five digits, with the four-digit level aligning with the European Union's classification (NACE) and the first two digits corresponding to the United Nations classification (ISIC) allows for easier sector-specific trend analysis and policy impact evaluation, enhancing the coherence and validity of economic studies [37–39]. The widespread use of the SIC system also ensures broad data availability, facilitating cross-study comparisons and contributing to a more nuanced understanding of the economy. However, the reporting system does come with its limitations such as temporal inconsistencies due to system updates, categorisation challenges for multifaceted industries, and obsolescence in the face of technological advancements. Discrepancies in international classification standards can complicate comparative analyses, while subjectivity and potential human error in code assignment may affect data reliability as described in Jacobs (2003) [40]. In the dataset, it was also observed that duplicate entries for facilities arose from the use of varying names or acronyms across different years when reported to the registry. The dataset underwent thorough validation to identify and resolve errors during the analysis, the entries flagged as unreliable were not formally recorded during the process. However, all inconsistencies encountered were addressed immediately, through cross-referencing with external data sources. The entries that could not be verified were excluded from the final analysis. For future studies, tracking the percentage of unreliable entries could provide additional insights into data quality.

2.3. Data source

The primary data for this research were collected by deploying a structured questionnaire designed to capture qualitative insights into the water usage practices of individual industrial entities. A structured questionnaire was deployed to five industrial entities in the Netherlands, encompassing a cross-sectoral group including representatives from the chemical, basic metals, food and beverage, and chemical, rubber and plastics industries, as well as a utility company. This questionnaire delved into key areas critical to water resource management, including security of water supply, internal water use efficiency, and the identification of water-intensive processes within their operations. This qualitative approach aimed to complement the quantitative data (explained below) by providing insights into the factors that influence and motivate water use improvement initiatives within these diverse industries.

The qualitative data gathered from the questionnaire responses provide a crucial complement to the data obtained from open sources, enriching the study's findings with on-the-ground perspectives of water resource management within industrial settings. The secondary data for the analysis of this study have been gathered through various open data sources, for instance, the location of the industries was gathered through EPRTR, focusing only on the Netherlands. While it came with limitations such as errors in the location of emitting facilities (address of headquarters vs. facilities) as reported in Garcia-Perez (2008) or the inherent nature of reporting where the European Environmental Agency (EEA) cannot change the value of any reported data, even in case of clear outliers as detailed in the database information manual of the registry, the registry still provides comprehensive data for benchmarking corporate environmental performance [41,42]. Furthermore, the registry has been utilised in scholars' articles due to its comprehensive database which enables researchers to understand the release of pollutants from various industries, facilitating detailed environmental impact assessments [43–45]. For a major part of the study, the waste and wastewater management sector is excluded in the analysis due to the inherent nature of such companies in the EPRTR registry.

Data for surface water locations were collected via OpenStreetMap (OSM), a crowdsourced geographic database providing geospatial topographical information, including a fully mapped street network for more than 40 % of the countries. The reliability of the data sourced has been studied by Barrington-Leigh & Millard-Ball (2017) and the result shows that the completeness of OSM can be relied on and was used by researchers and policymakers [46]. OSM is used to delineate canals, rivers, lakes, and reservoirs within a study area involving extracting relevant data tagged with specific keys like "waterway" and "natural" for linear and areal water features, respectively. Data for groundwater abstraction locations was abstracted from Public Services on the Map (PDOK), a platform established by the Dutch's Land Registry, the Ministries of Infrastructure and Water Management, the Interior and Kingdom Relations and Economic Affairs and Climate, Rijkswaterstaat and Geonovum under the INSPIRE Directive to enable access to European geospatial data for the Green Deal, also part of the Basic Registration of the Subsurface (BRO). It provides geographical access to the geo-basic registers and other core geo datasets such as the National Roads Database [47]. The groundwater abstraction data point is submitted by well owners as part of the application process for a groundwater extraction permit, that includes any groundwater use, withdrawal and abstraction that needs a permit or notification and geothermal systems under 500 m.

This study also utilises open data from the Dutch Statistics Centre (CBS) for acquiring data on industrial water consumption and individual industry performance. The CBS serves as a reliable source, offering a comprehensive and standardised data repository perfectly suited for empirical analysis. Furthermore, the open access nature of this data fosters transparency within the research process, allowing for independent verification of findings. The data were first used to study water as a production factor where the water consumption by the industries are correlated with the turnover of the industry (business returns, excluding VAT (value added taxes) from the selling of goods and services to customers). These data are also used to investigate the influence of water as an input on production output within the manufacturing sector using an econometric production function.

A typical production function can be constructed as $V = f(K, L, W)$, where V, the total value-added is a function of capital (K), labour (L) and water consumption (W). Many functional forms have been used to relate production to other variables [48–51]. This study deploys the *translog* function because of its flexibility in capturing both linear and non-linear relationships between production and these variables, as it is a second-order Taylor expansion of the Cobb-Douglas function (The latter is a linear mathematical formula used in economics to estimate how changes in variables impact the total output of a production process) [52]. It captures interaction effects between inputs, providing a more comprehensive analysis. Data from 2009 to 2021 CBS across 17 industrial sectors were analysed. These data were first processed statistically using Ordinary Least Squares to capture the overall trend of the data and indicates how each independent variable influences the dependent variable in that *translog* cost function. The statistical analysis provides a good overall fit for explaining the factors influencing output. The R^2 value of 0.858 indicates that 85.8 % of the variation in the dependent variable [total value-added, V] can be explained by the independent variables in the model. This is a good fit, suggesting the model explains a substantial portion of the data's variation. Furthermore, the model shows a high F-statistic (183.4) and very low p-value ($1.64e^{-110}$) indicating that the model is statistically significant, meaning the relationship between the independent variables and the dependent variable is unlikely due to chance.

The *translog* function applied to each industry sector in this study is presented in Equation (1). If data for a particular year is unavailable, a mean value will be substituted. The elasticity of production with respect to the water input ($\varepsilon_{TL\text{-}W}$) is represented by dividing the percentage change in the water demanded by the percentage change output, essentially the partial derivative of Equation (1) with respect to water consumption as represented in Equation (2).

The marginal value of water is then calculated using the estimated output elasticity Equation (2), the partial differentiation of *translog* function with respect to water consumption Equation (3).

$$\ln V = \ln A + a_1 \ln L + a_2 \ln W + a_3 \ln K + a_4 \ln L \ln W + +a_5 \ln L \ln K + a_6 \ln W \ln K + a_7(\ln L)^2 + a_8(\ln W)^2 + a_9(\ln K)^2 \quad \text{Equation 1}$$

$$\epsilon_{(TL-W)} = \frac{\partial V}{\partial W} \times \frac{\mathrm{W}}{\mathrm{V}} = a_2 + a_4 \ln L + a_6 \ln K + 2a_8 \ln W \quad \text{Equation 2}$$

$$r_{(TL-W)} = \frac{\partial V}{\partial W} = \epsilon_{(TL-W)} \times \left(\frac{V}{W}\right) = (a_2 + a_4 \ln L + a_6 \ln K + 2a_8 \ln W) \times \left(\frac{V}{W}\right) \quad \text{Equation 3}$$

Where Labour L [number of employees]; capital K [M€]; water consumption W [Mm3]; total value-added V [M€]; Elasticity $\epsilon[-]$; *Marginal value, r* $\left[\frac{m^3}{€}\right]$.

This study integrates spatial analysis to assess the future impacts of water risks on industries [32,33]. By leveraging Aqueduct 4.0's

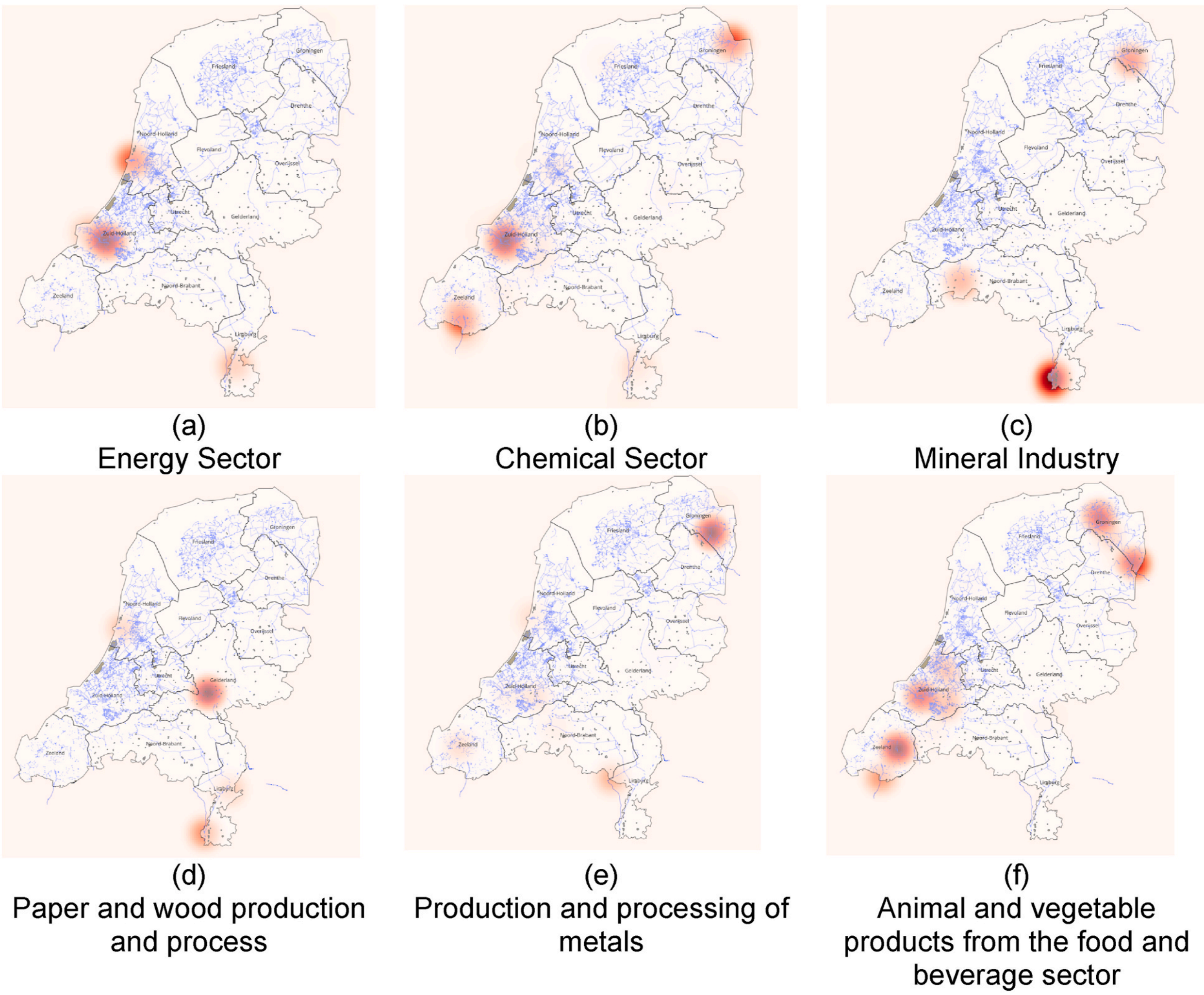

Fig. 2. Spatial Distribution of Surface Water Bodies, Groundwater Abstraction Points, and Industrial Clusters in the Netherlands: (a) Energy Sector; (b) Chemical Sector; (c) Mineral Industry; (d) Paper and wood production and process; (e) Production and processing of metals; (f) Animal and vegetable products from the food and beverage sector. The distribution pattern highlights the historical strategic positioning of industrial types in proximity to water resources, depicted as blue dots, compiled from Fig. 1(b) and (c).

global water risk indicators, particularly baseline water stress, the approach maps industrial vulnerability hotspots. Aqueduct 4.0, developed by the World Resources Institute, provides a comprehensive framework for water risk assessment [34,53]. This study then employs QGIS's Network Analysis tool to assess the spatial relationship between industries and their water sources and baseline water stress. Spatial data containing geographical coordinates of both industrial facilities and freshwater bodies is utilised. Dijkstra's algorithm, implemented within the Network Analysis tool, calculates the shortest network distance between each industry and its closest water source within the defined network [54]. This approach not only generates a new geographic layer but also offers valuable insights into the distribution and spatial connectivity of industries relative to water resources. However, it is crucial to acknowledge a limitation associated with the methodology. While the analysis calculates the shortest network distance, it relies on the closest data point (node) representing the water body within the dataset. This may not always reflect the true shortest distance on the ground, particularly for scenarios involving water sources with complex geometries or when the data resolution is coarse. Conversely, the shortest distance might actually prove to be longer due to restrictions not included in the tool.

3. Results and discussion

3.1. Spatial distribution of industries

Historically, the determination of industrial locations has been a subject of interest for economists and geographers alike, evolving through various phases influenced by a multitude of factors. During the early stages of industrialisation, industries were predominantly located near natural resources, such as coal mines and water bodies, which were essential for powering manufacturing processes and transporting goods [55]. As technology advanced and transportation became more efficient, the significance of proximity to raw materials gradually diminished. The focus shifted towards factors such as labour availability, access to markets, infrastructure, and energy sources [56–58]. The impact of existing railroads infrastructure in the 19th century and the development of highways in the 20th century further transformed industrial location strategies, emphasising the importance of logistical efficiency and distribution networks [59]. This evolution underscores the dynamic nature of industrial location strategies, adapting to changing economic landscapes and technological advancements. Fig. 2(a)-(f) illustrate the geographical correlation between surface water sources, identified groundwater extraction locations, and the aggregation of industrial activities, measured by the number of facilities within the study area [60]. As shown in Fig. 2(a) and (b), the energy sector and chemical sector in the Netherlands is clustered around the port areas, noticeably Rotterdam-Moerdijk Cluster and the Noordzeekanaalgebied Cluster. Such location offers unparalleled access to

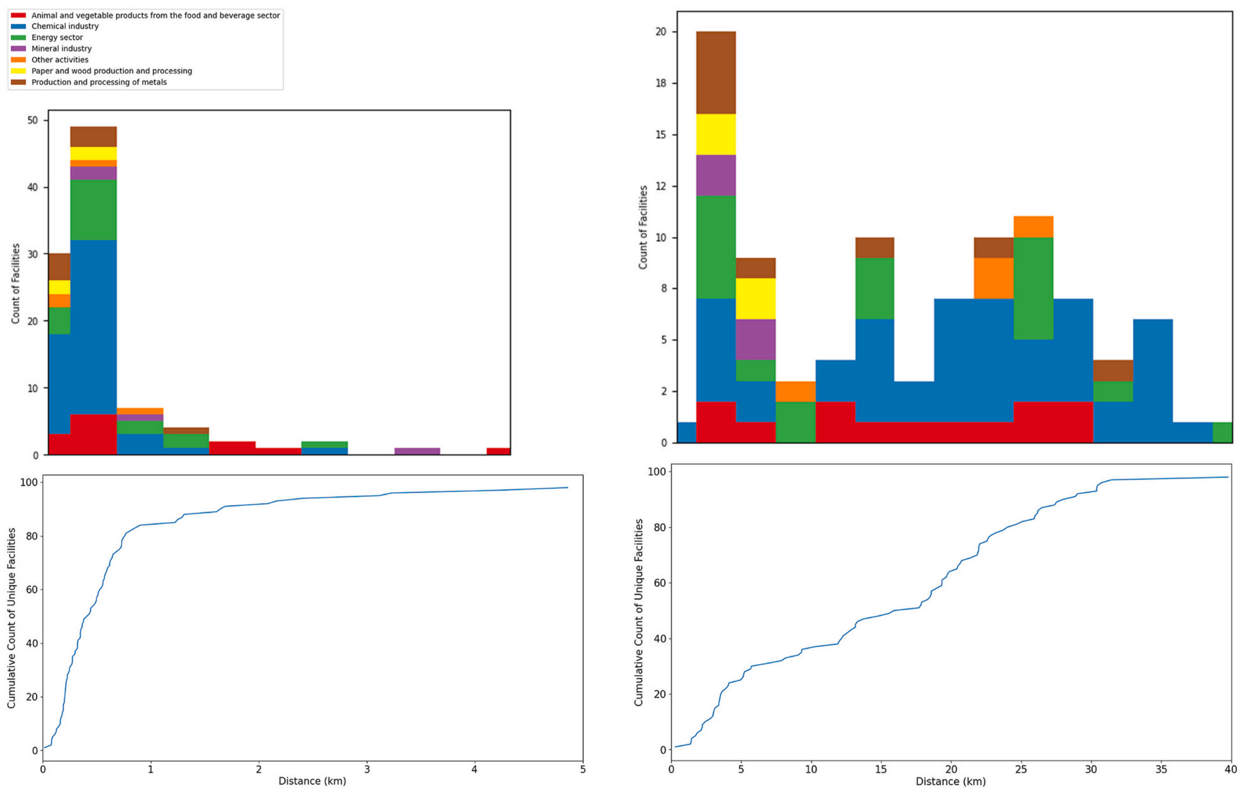

Fig. 3. (a). Distribution stacked bars and cumulative curve showing the distance to the closest surface water source for different industries Fig. 3(b). Cumulative curve and distribution stacked bars showing the distance to the closest groundwater source for different industries.

maritime routes for the import and export of energy commodities like oil, natural gas, and coal, which are crucial for energy production and distribution. Additionally, the proximity to large bodies of water supports the cooling processes essential for the efficient operation of thermal power plants. These industries are often located along rivers, particularly in downstream areas and major tributaries, likely due to the ability of these water bodies to dissipate heat effectively. Furthermore, ports are geographically concentrated with high-energy demand and supply activities due to proximity to power generation facilities, metropolitan regions, and their central hubs in the transport of raw materials[61–63]. Whilst for the mineral industry, the location is primarily determined by the proximity to mineral deposits, as the extraction processes are inherently tied to these resources, rendering the availability of water sources a secondary consideration in their site selection. Fig. 2(c) shows that the most mineral and metal production and processing industries are clustered together. This could be due to their reliance on minerals such as raw materials, metal refineries are often strategically located near significant mineral deposits [64,65]. This proximity minimises transportation costs and logistical challenges. Extracting and transporting large quantities of minerals over long distances can be expensive and time-consuming. By situating themselves close to the source, metal refineries can streamline their operations and ensure a steady supply of essential materials. Similar industrial development can also be seen in the Ruhr Valley in Germany and The Copperbelt of Zambia and the Democratic Republic of Congo [66,67]. Paper and wood production and process cluster around groundwater abstraction points as shown in Fig. 2(d). This may be due to these industries often have specific water quality requirements. Groundwater in The Netherlands is generally known for its good quality, with low mineral content and minimal hardness. Furthermore, the papermaking industry in Gelderland region boasts a rich industrial heritage dating back centuries. Around 1740, the Veluwe region housed a staggering 168 paper mills, making it one of the Netherlands' leading industries at the time [68–70].

As demonstrated above, numerous factors influence the historical location of industries. However, proximity to essential resources, such as raw materials and water sources, stands out as one of the key drivers. Traditionally, industrial water management has relied on consumption volume metrics to assess water dependency. This geographically focused analysis offers a valuable insight for evaluating water dependency across various industrial sectors. It is however worth noting that distance alone is an insufficient metric. Analysing proximity to water sources offers a valuable initial assessment of an industry's potential water dependence. Fig. 3 shows a shortest distance between industrial facilities to the closest surface and groundwater source (represented as groundwater abstraction point). Noticeably, industrial facilities are a lot closer to surface water than to groundwater extraction points. This could be attributed to The Netherlands' extensive network of rivers and canals [71,72]. Industries situated near water sources are more likely to be highly water-reliant, particularly those involved in water intensive processes such as food and beverage processing industry. The chemical industry demonstrates a more varied and evenly distributed dataset to the groundwater sources, which can be attributed to the larger sample size. This greater sample representation captures a broader range of processes and operational conditions, leading to a more

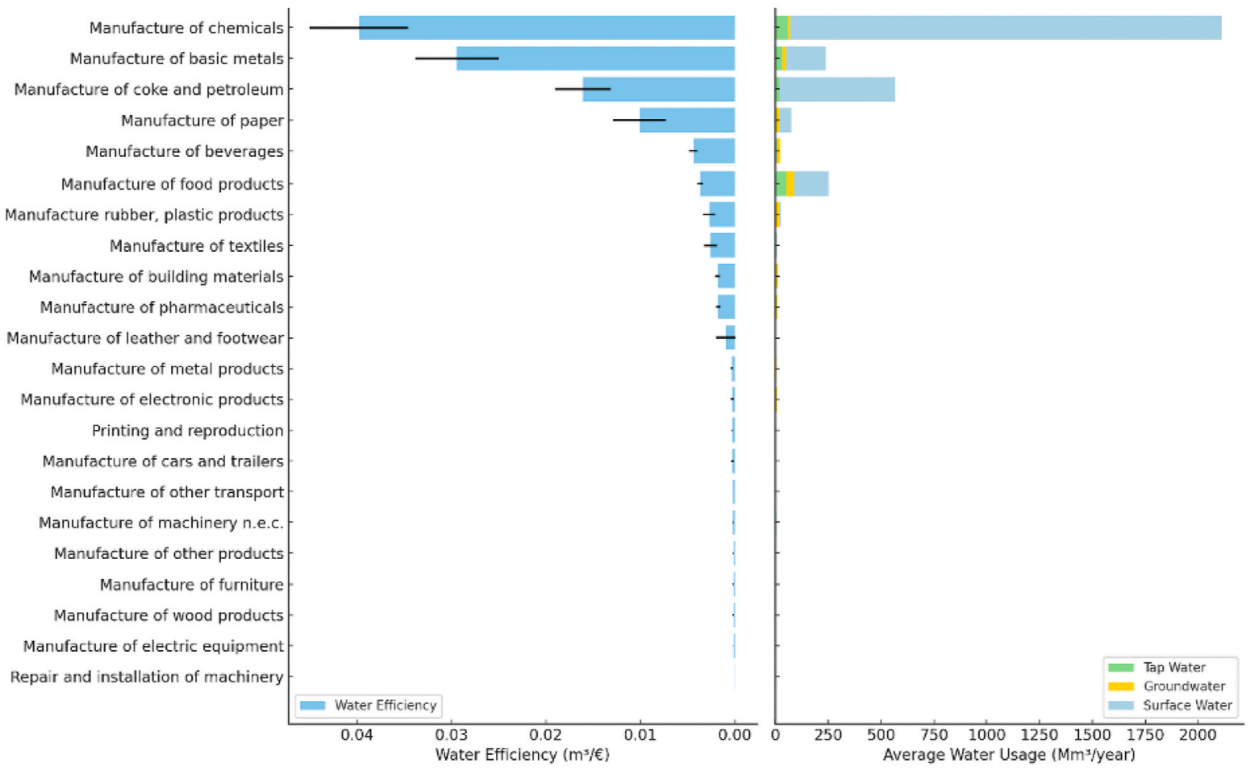

Fig. 4. Average water usage (and source) and efficiency measured by water use per unit turnover by industry sectors from year 2009–2021, error bar shows variation over the years. Calculated based on data from CBS [21].

comprehensive distribution. The paper and wood production and processing industries exhibit a peak clustering near both water sources. This spatial distribution can be attributed to historical development patterns and expansion. Many older mills in these industries were originally powered by hydropower and relied on groundwater for their operations, leading to their establishment close to rivers and aquifers [73].

3.2. Water as a production factor

This section dives into water as a production factor, revealing industrial water consumption patterns and highlighting the dependency of different sectors on specific water resources. Fig. 4 provides insights into industrial water consumption patterns in the Netherlands, enabling an overview on industrial water usage. The right side of the tornado chart details water utilisation by source across various industries. Across most industries, surface water appears to be the preferred source for industrial water consumption. This trend might be due to factors like accessibility or cost, but an exception is observed in the food and beverage industry, that prioritise higher quality water to ensure product safety. This information is crucial to understand the dependency and reliance of different sectors on specific water resources. For instance, industries with high water usage per euro turnover, such as manufacture of chemicals, predominantly utilise surface water abstractions. Furthermore, while the chemical industry and the metal industry have a comparable water efficiency, it is also evident that the chemical industry uses a significantly higher amount of water than the metal industry. This shows that while measuring a water efficiency ratio provides a straightforward efficiency metric and allows for a quick comparison of water efficiency or benchmark across different industries, it does not account for the complexities of production processes. A high $m^3/€$ value might simply indicate a high production volume, not necessarily inefficient water use. This indicates that while this ratio indicates how much water is consumed per unit of turnover, it does not capture the change in value added when water consumption changes.

To complement the analysis, an econometric study of using *translog* cost function was carried out. The function involved a derivative approach directly measuring the incremental change in value added resulting with respect to a small change in water consumption. It provides a more precise measure of the change in value added as water consumption varies. The *translog* cost function is a flexible and widely used tool in econometrics for analysing relationships between multiple inputs [74,75]. Labour (L), capital (K), and water consumption (W) were used as input and a single output (total value-added (V)) in a production process were studied in this paper.

1. Elasticity: Elasticity refers to the responsiveness of output (e.g., production level) to a proportional change in an input (such as water), measured as the percentage change in output resulting from an infinitesimally small percentage change in the input, while holding all other inputs constant.
2. Marginal Value: The marginal value of an input (such as water) represents the additional revenue associated with using one more unit of that input, holding all other inputs constant. It is essentially the derivative of the cost function with respect to the input quantity.

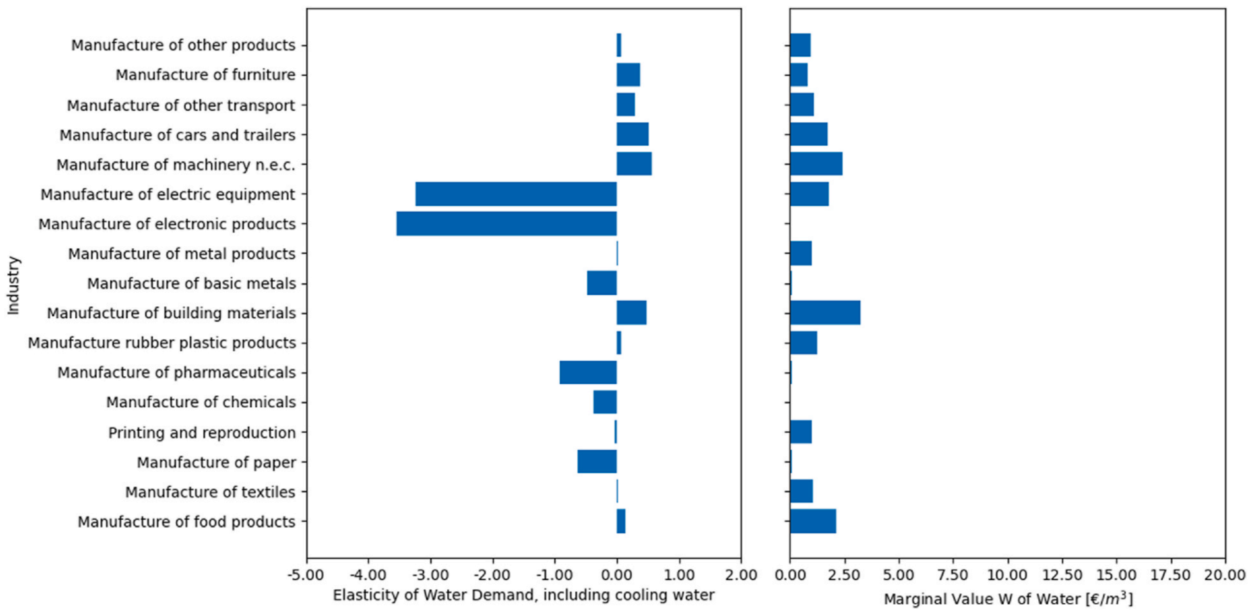

Fig. 5. The average elasticity and marginal value of water for various manufacturing sectors in the Netherlands from year 2014–2021. Calculated based on data from CBS [21].

Fig. 5 reveals a significant distribution in elasticity and marginal value across sectors, indicating varying levels of reliance on water resources. For 7 out of 17 industries, elasticity of water is negative, indicating that water demand is generally inelastic. This indicates the changes in water consumption do not have a significant impact on production levels in these industries. This is especially significant in the manufacture of electrical equipment and electronic products. Some industries exhibit moderate elasticity on water. For instance, the manufacture of food products exhibits a moderate elasticity (0.14) and marginal value (2.14€/m^3), suggesting water plays a necessary role but might not be the most critical factor for production. Industries such as manufacture of chemicals, paper and basic metals have a negative elasticity (−0.38, −0.63 and −0.47 respectively), indicating some price sensitivity and water is essential for production, but changes in water availability are unlikely to significantly impact output. However, a low marginal value (0.05€/m^3, 0.06€/m^3 and 0.07€/m^3 respectively) suggesting water might not be a significant cost driver, aligning with the operational reality where energy and raw material inputs dominate production costs. This corresponds to the finding from the questionnaire where industry finds energy is of much more relevance than water.

As mentioned above, cooling towers play a critical and complex role in industrial water consumption. These systems are essential for managing heat generated during industrial processes and add significantly to an industry's overall water consumption, even though the water itself might not be directly involved in production activities. In the *translog* cost calculation, the inclusion or exclusion of water consumed by cooling towers leads to divergent perspectives on water dependency and economic valuation of these industrial sectors, where only 3 out of 17 of the industries, elasticity of water is negative as demonstrated in Fig. 6. The inclusion of cooling tower water can inflate the perceived reliance on water in sectors with heavy cooling needs, potentially neglecting the true water demands of production itself. Fig. 6 shows a focused analysis that excludes cooling tower water consumption which potentially provides a clearer picture of how water used directly in production impacts output. Fig. 6 shows some insights where sectors with high water dependence such as paper manufacturing exhibits relatively high elasticity (0.92) and marginal value (14.13€/m^3). This indicates that water plays a crucial role in various paper production processes, and its efficient use is likely critical for maintaining output levels, while in Fig. 5, it exhibits a negative elasticity and a negligible margin value of water of 0.063 €/m^3 (i.e. rate of change of value added in production does not positively correlates to the rate of change of increased (cooling) water consumption). This indicates that within the processes in an industry, the water consumption in cooling tower appears to be a less water-sensitive process. Combining the information with cooling water data obtained from statistic centre (plotted in supplementary material), it shows paper manufacturing uses only about 1 % of its total water abstraction for cooling purposes. When this 1 % of cooling water is excluded from the analysis, every 1 m^3 changes in the water consumption has led to €14 difference in the value added in the production processes [21]. This shows that the inclusion of cooling water could be having a diluting effect in the elasticity of water and subsequently the marginal value of water, masking the true impact of water dependence for other production processes. This can make it appear as though the industry has a lower dependency on water for production processes than it actually does.

Some industrial sectors exhibit moderate water dependency from the analysis. For example, both food production and building materials exhibit moderate values, with 0.22 elasticity and 2.13 €/m^3 marginal value, and 0.28 elasticity and 1.71 €/m^3 marginal value respectively. While water plays a role in food processing and cleaning, and likely across various stages of building material production, the influence of other factors like raw materials and specific processing techniques could be a more substantial for overall output within these sectors. For discrete manufacturing industries such as manufacture of machineries and car and trailers, whilst their

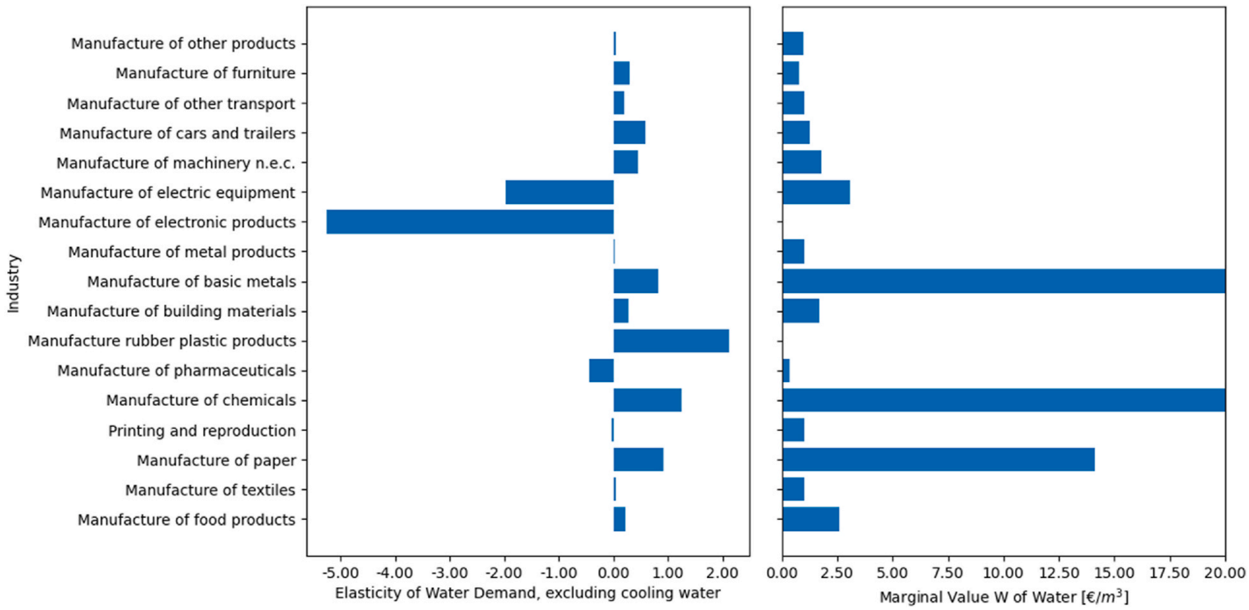

Fig. 6. Average elasticity and marginal value of water for various manufacturing sectors in the Netherlands from year 2014–2021, excluding cooling tower water consumption.

cooling water consumption (relative to total water abstraction) varies (11 % and 3 % respectively), the elasticity of water and marginal value of water remain comparable in both scenarios. This indicates that the changes in water consumption for cooling have minimal contribution towards the value added for both industries, suggesting rooms for water saving measures without disrupting the production efficiency of these industries. The analysis also shows cases with low or negative water dependence in some sectors. Pharmaceutical production exhibits a negative elasticity (−0.45) and low marginal value (0.37€/m^3), suggesting that increased water use might not directly correlate with higher output. This could be due to highly efficient water usage practices, or potentially due to other factors such as highly skilled labour playing a more prominent role in production levels. In both analyses, the production of electronics stands out with a very negative elasticity and negligible marginal value, indicating water consumption is likely not a critical factor in the production processes. This could be due to the inherently low water needs of electronic manufacturing. Fig. 6 sets the axis limit for marginal value at €20/m^3 due to possible outliers in the manufacture of chemicals (2320€/m^3) and manufacture of basic metals (83€/m^3). These sectors have significantly higher marginal values compared to others. There are a few potential explanations. First, there could be data errors inflating the values, necessitating further investigation. In addition, these industries, especially the chemical industry, consist of a diverse range of businesses, including both large integrated chemical plants and smaller, specialised facilities. Larger chemical plants typically require significant quantities of water for tasks such as cooling and producing steam. Water is usually distributed effectively throughout different parts of the facility, lessening the effects of water supply changes on individual operations. Measuring the marginal value of water or the elasticity of production accurately is difficult due to the efficiency and integration involved. On the other hand, smaller chemical manufacturers, operating on a smaller scale, are at higher risk from changes in water availability and usage. These smaller units have a stronger influence on marginal value and production levels because their operational efficiency is directly impacted by changes in water availability. The diversity in the chemical industry highlights the difficulties of consistently measuring elasticity and marginal value among various entities. While Figs. 4–6 give an overview of the water consumption in the manufacturing industries, there is limitation bounded to both the inherent nature of the SIC classification of industry and the EPRTR registry, for instance, certain industries, such as data centres, are substantial consumers of water. Despite their significant water usage, these entities may not be consistently recorded in the registry due to the unique nature of their operations or the nature of their discharge. The consumption will be expected to increase in the future along with the growth of the industry at a compound annual growth rate (CAGR) of 10.9 % by 2030 due to an increase in data generation, technological advancements, and the adoption of cloud-based services and digital transformation across various sectors [76,77]. This oversight underscores the necessity for a more inclusive reporting system that can accommodate the evolving landscape of industry types and their respective resource use. Furthermore, hydrogen technology and its associated cooling needs are progressing as a key factor in the energy transition, with potential for large-scale implementation in the coming times which require more water for hydrogen production to replace natural gas [78–80]. This coupling of the Water-Energy Nexus would likely to reflect in an increase on the elasticity of water and marginal value of the water significantly. This research provides the current status quo of water use and presented an opportunity as a baseline for evaluating future water stress scenarios and industrial water efficiency measures. This approach highlights potential deviations in water dependency and vulnerability across regions and industries under projected stress conditions. Nevertheless, the increasing utilisation of water reuse (methods, technologies, frameworks, etc) in different sectors offers a significant chance to improve water usage effectiveness and reduce the strain on fresh water supplies. Numerous sectors are currently adopting different methods of water reuse, such as onsite recycling and advanced treatment systems, to promote a more circular approach to water management [81–85]. These methods not just enhance water usage but also lessen the need for fresh water sources. Furthermore, recent laws in the EU and Netherlands are pushing for wider use of water recycling technologies and requiring more stringent reporting guidelines [86,87]. With the increasing focus on water reuse, it will be vital in influencing industrial water efficiency in sectors with high water demand, possibly impacting the elasticity and marginal value of water demand in the long run.

3.3. Future water risks for industries

The following part of the study leverages results from Aqueduct 4.0, developed by WRI to assess the potential future impacts of water risks on Dutch industries. Baseline water stress is a direct measure of the pressure on water resources, which is a key component of water security. High baseline water stress values indicate that water resources are under pressure, which can lead to water scarcity and stress. This pressure can affect water security by making water resources less available, more polluted, or less accessible to users, including the process industry. The process industry, being a major consumer of water resources, is particularly vulnerable to these pressures, as it relies on a continuous supply of water for its operations. Aqueduct 4.0 utilises three Socioeconomic Shared Pathways (SSPs) combined with Representative Concentration Pathways (RCPs) to generate water risk projections. By combining these pathways, Aqueduct 4.0 can generate multiple future scenarios with varying levels of climate change and socio-economic development. This study utilises three default scenarios provided by Aqueduct [88,89], namely,

1. Optimistic (SSP1 RCP2.6) with aggressive emissions reductions and low population growth;
2. Business-as-usual (SSP3 RCP7.0) with moderate emissions reductions and regional competition including slow economic growth;
3. Pessimistic (SSP5 RCP8.5) with high emissions, fossil fuel reliance, and initial population growth

[34,88,89]These scenarios will be projected in three different temporal groups, indicated as 2030, 2050 and 2080 for the years 2015–2045, 2035–2065 and 2065–2095 respectively.

The baseline scenario in Fig. 7 shows that nationally, the country has a low-moderate baseline water stress, the midland of the country including Zuid-Holland, Utrecht, Overijssel, Noord-Holland, Gelderland, Flevoland, and Drenthe has a low water stress.

However, some areas face greater challenges. Noord-Brabant and Zeeland experience medium to high water stress, while Limburg experiences high stress. It is important to note that uncertainties in the future industrial landscape may affect these patterns, and no scholarly articles currently project potential specific industrial growth or decline. An example is the conversion of a coal-fired power station into an energy hub in the province of North Holland, designed to supply and store fossil-free electricity, heat, and sustainable fuels such as green hydrogen. These changes impact the regional dynamics of the water availability. This limitation and uncertainty are acknowledged, but also considered out of scope for this article.

- An optimistic scenario suggests that baseline water stress levels will remain unchanged for all Dutch provinces in 2030. However, by 2050, Drenthe, Gelderland, and Flevoland are projected to experience a slight increase in water stress, transitioning to a low-medium category. This shift might potentially impact industries in these regions, including animal and vegetable product manufacturers (1), energy sector companies (2), a paper and wood production facility, and a metal production and processing plant. North Brabant, as in the baseline scenario, is expected to see a rise in water stress, transitioning from medium-high to high by 2050. This escalation is likely to affect nine industrial facilities, including those involved in animal and vegetable product production (2), chemicals (2), energy (1), minerals (1), other activities (1), and metal production and processing (1). While all other provinces

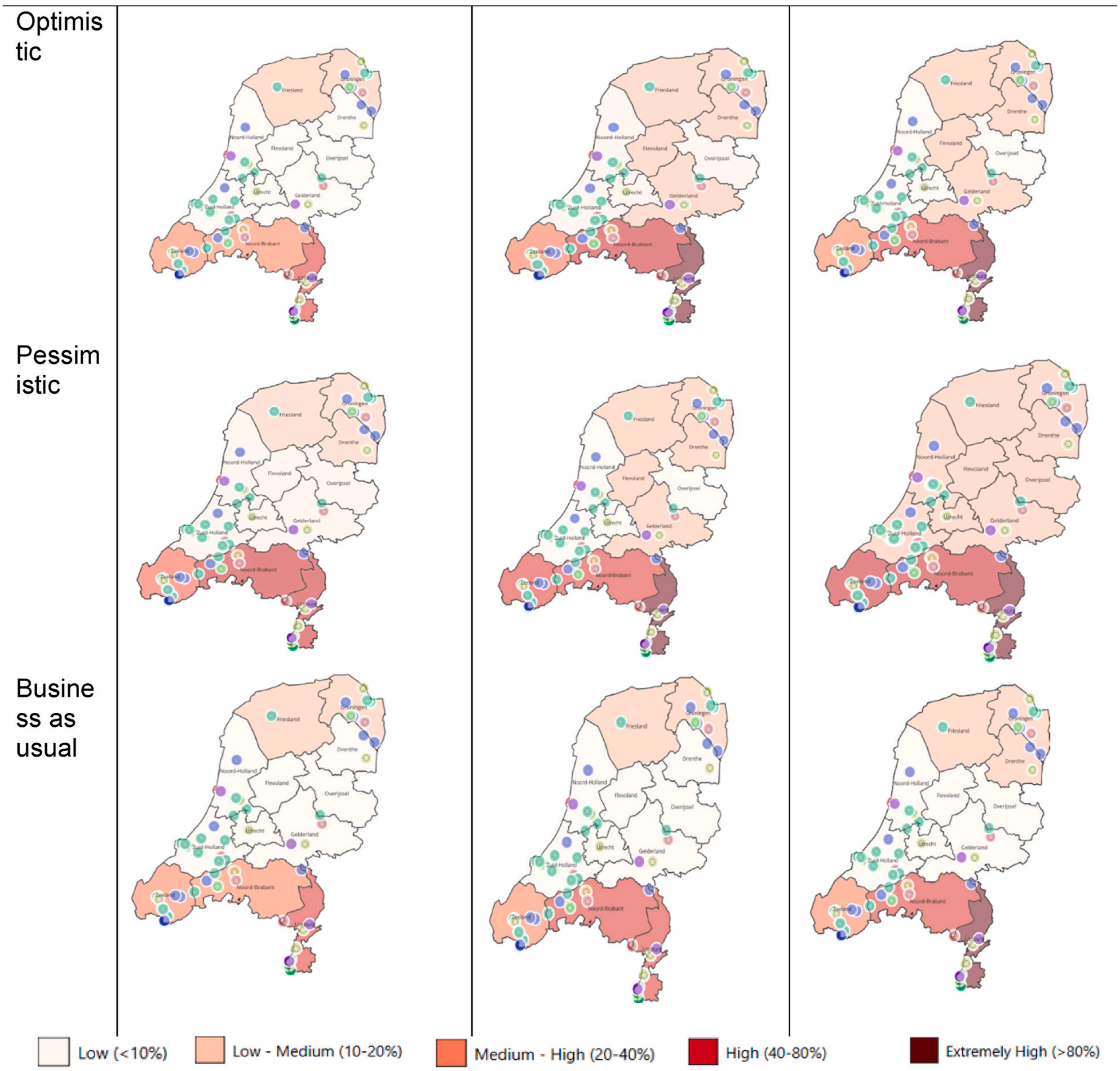

Fig. 7. Distribution of industries and the projected water stress in 3 temporal variations under 3 scenarios (optimistic, pessimistic and business as usual).

maintain their current stress levels, Limburg remains an area of concern. By 2050, it is projected to reach an extremely high water stress level, posing a significant threat to water security for industries such as chemicals (2), energy (2), minerals (2), and paper and wood production (2).

- Baseline water stress projections under a business-as-usual scenario indicate no change for most Dutch provinces by 2030. However, North Brabant is projected to experience an escalation in water stress, transitioning from a medium-high to a high-stress category by 2050. This shift is likely to impact twelve industries in the region, including those involved in food and beverage production of animal and vegetable products (2), chemicals (2), energy (1), minerals (1), other activities (1) and metal production and processing (1). Furthermore, by 2080, water stress in Drenthe is projected to be low to medium impacting a food and beverage production of animal and vegetable products and one energy sector. The water stress in Limburg is projected to reach an extremely high level, posing a significant threat to water security for industries such as chemicals (2), energy (2), minerals (2), and paper and wood production (2).
- Under a pessimistic scenario, the baseline water stress in 2030 remains unchanged for most Dutch provinces, with the exception of Drenthe, which is projected to transition from a low to a low-medium stress region. North Brabant, as in the business-as-usual scenario, is expected to experience a significant increase, shifting from medium-high to high water stress. This escalation is likely to impact eleven industries in the region. The situation is projected to worsen by 2050, with Gelderland and Flevoland transitioning to low-medium stress regions, potentially affecting an energy sector company, a paper and wood production facility, and a metal production and processing plant. Notably, Limburg is again projected to reach an extremely highwater stress level by 2050, posing a severe threat to water security for industries including chemicals (2), energy (2), minerals (2), and paper and wood production (2). By 2080, the pessimistic scenario displays a concerning picture, with all provinces experiencing at least low-medium water stress. This widespread increase is likely to put a significant number of industries (at least 50) at equal risk of water scarcity. Additionally, Zeeland is projected to transition from medium-high to high water stress, potentially jeopardizing the water security of companies in the animal and vegetable products (3), chemical (4), energy (1), and metal production and processing (1) sectors.

In essence, across all scenarios, baseline water stress levels remain unchanged for most Dutch provinces in 2030. However, North Brabant faces a significant rise, transitioning from medium-high to high water stress by 2050, impacting various industries. Limburg consistently emerges as an area of concern, with projections indicating it will reach extremely high stress levels by 2050, posing a significant threat to water security for industries like chemicals, energy, minerals, and paper production. As demonstrated in Figs. 4–6, these industries are not only making a significant economic contributions to the country, they also have a positive production elasticity to process water, indicating that in the case of water scarcity, the limitation of water availability will have a direct impact on the production of these industries. While the scenarios differ in how other provinces fare by 2050 and 2080, the potential impact on specific regions and industries underscores the urgency of water management strategies for a sustainable growth for these industries.

The analysis also reveals an intriguing finding whereby for the year 2035–2065 (indicated as 2050), some Dutch provinces (Gelderland and Flevoland) for the optimistic scenario (SSP1 RCP 2.6) exhibit a higher water stress compared to the business-as-usual scenario. This can be attributed to the underlying assumptions employed by Aqueduct's indicators when projecting future water conditions under various climate and economic growth possibilities. The optimistic scenario assumes a rapid decrease in emissions, resulting in moderate increases in global temperature and sea levels. While this scenario is environmentally favourable, it might not necessarily translate to reduced water stress in specific regions.

While this analysis gives an overview of water related risk of industries under different climate scenarios in the Netherlands, it does come with several limitations, the baseline water stress indicator used in this study, while based on validated models, needs improvement. For instance, water stress is subjective and lacks a direct measurement and a universal standard, making validation challenging, nevertheless, the best way to represent water stress is still under debate [34]. From the interview, numerous industries also pointed out that increasing competition, particularly the projected growth of intensive water users like data centres and water electrolysis for hydrogen production compete for resources, impacting the regional availability of process water. This increase in competition is likely not captured by Aqueduct 4.0 when assessing baseline water stress as the model does not measure the impact on water sources due changing patterns of how industries use water [90]. This risk is accompanied by other rising concerns about water quality due to factors like salt intrusion, PFAS contamination, and microplastics that would threaten production efficiency. Furthermore, water availability during droughts or periods of low rainfall could be restricted, potentially leading to production limitations and supply chain disruptions. An industry pointed that a complete water outage, even for a short duration, could cause a cascading effect, halting production for weeks and incurring significant financial losses. Nevertheless, it is also pointed by an industry that while climate change models predict water scarcity, the immediate threat of the physical availability of water within the next decade appears to be less concerning, especially for the industries that relying on surface water with access to the main rivers such as the Meuse River. These findings underscore the urgency of implementing water management strategies to mitigate the escalating water stress in specific regions and safeguard the long-term sustainability of water-dependent industries in the Netherlands.

This research provides a foundation for enhancing water conservation and sustainable practices within the Dutch manufacturing sector, leveraging quantitative metrics and scenario-based projections to provide actionable insights into the relationship between industrial water use, economic output, and water stress. Effective measures are essential for long-term water security and economic prosperity. Recommended research areas include investigating industrial symbiosis within Dutch clusters to unlock resource sharing and wastewater reduction opportunities, analysing the potential of digital advancements and data analytics to optimise water management strategies, and exploring the economic viability and environmental benefits of alternative water sources like treated wastewater effluent. Another crucial scope for future study is the internal recycling of water in industrial settings, like reusing condensate and passing water through processes with decreasing quality demands. These strategies, currently in use in certain sectors, offer great potential for enhancing water efficiency and reducing dependence on outside water supplies. Additional investigation into these strategies, could offer valuable understanding on how industries can attain sustainable and circular water management practices.

The insights from this study, though focused on the Dutch manufacturing sector, offer valuable principles that can be transferred to other regions facing similar water management challenges. By understanding industrial water dependency, analysing water use efficiency, and evaluating future water stress risks, these findings can be used as a status quo and adapted by policymakers and industry leaders worldwide to develop targeted (future) water management strategies. However, potential limitations such as the availability of reliable data on water use and economic output across different sectors may vary by country. Additionally, the economic viability of certain water management strategies might differ based on local circumstances and water sources. By acknowledging these limitations, further research and adaptation of the findings are needed to tailor the approach to specific regional contexts, ensuring both transferability and reproducibility of effective water management strategies and promoting sustainable industrial practices globally.

4. Conclusion

This study addressed three key research questions to gain a comprehensive understanding of water dependency and associated risks for Dutch industries. The following deductions can be made therefrom.

1 Industrial Clusters and Water Source Proximity:

This research revealed significant industrial clusters in the Netherlands, such as the Rotterdam-Moerdijk Cluster, Brightlands Circular Space, Smart Delta Resources, Noord Nederland Cluster, and Noordzeekanaalgebied Cluster. The results emphasised a significant link between industrial sites and their proximity to freshwater and groundwater resources, highlighting the historical importance of water availability in influencing industrial growth. Nonetheless, the results indicated that reliance on water goes beyond mere proximity, with elements like water quality, extraction rights, historical events, and competition for resources being vital factors. These insights emphasised the need for integrated water management strategies tailored to the unique characteristics of industrial clusters and their surrounding water systems.

2 Water Consumption and Value Added Across Sectors:

This study showed that water consumption per unit of economic output ($m^3/€$) varies significantly across industries in the Netherlands, reflecting the complexity of production processes and water dependencies. While this metric enables cross-industry comparisons, it often oversimplifies relationships, as seen in the chemical industry, which uses significantly more water than the metal industry despite similar efficiency ratios, due to higher production volumes rather than inefficiency. Using a translog cost function analysis, this study examined incremental changes in value added from water use, highlighting key metrics: elasticity (responsiveness of output to water input changes) and marginal value (revenue generated per additional unit of water). For example, excluding cooling water, the paper manufacturing industry exhibited positive elasticity (0.92) and a significant marginal value (€14.13/m^3), indicating the essential role of water in its production process. In contrast, pharmaceuticals exhibited negative elasticity and low marginal value, reflecting reliance on other inputs (such as labour or raw material availability).

3 Projected Water Stress and Regional Impacts:

Projected water risks, based on baseline water stress, are expected to affect industries in the Netherlands unevenly, with significant regional variability. Regions such as Noord-Brabant and Limburg face increasing water stress under most scenarios. This could severely impact water-intensive industries, including chemicals, energy, and paper manufacturing, which exhibit high sensitivity to water availability. Conversely, regions with access to surface water, such as the midland provinces, show greater resilience. Addressing these challenges will require tailored, region-specific strategies to ensure water security for industrial operations.

CRediT authorship contribution statement

C.J. Teo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **J. Poinapen:** Writing – review & editing, Supervision, Conceptualization. **J.A.M.H. Hofman:** Writing – review & editing, Supervision, Conceptualization. **T. Wintgens:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study was funded by the H2020-AquaSPICE project (EC, CE-SPIRE-07-2020, Horizon 2020). This project has received funding from the European Union's Horizon-2020 research and innovation program under grant agreement No. 958396. The responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Union, and the European Commission is not responsible for any use that may be made of the information contained herein.

The authors extend their sincere gratitude to Roy Tummers from VEMW for his invaluable assistance in organising and facilitating outreach to industry contacts. Special thanks are also due to our colleagues at KWR, including Nienke Koeman-Stein and Frank Oesterholt, for their valuable expertise and insights, which significantly contributed to the quality and depth of this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wri.2025.100279.

Data availability

Most sources are open data

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