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Master thesis

Influence of inland shipping on sediment transport in the Waal river

UNIVERSITY OF TWENTE.

Rijkswaterstaat

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Master Thesis

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Author:	Bastiaan Spoolder (S1720082)
Supervisors University:	Dr. J.J. (Jord) Warmink
	Ir. L.R. (Lieke) Lokin
Supervisors Rijkswaterstaat:	Ir. M (Michiel) Reneerkens
	Dr. M. (Merel) Verbeek

Preface

As I approach the culmination of my Master's degree in Civil Engineering, I reflect upon an enriching and transformative period as a student. The path leading to this point has been both demanding and fulfilling, affording me the invaluable opportunity to explore my interests within the field of civil engineering. Choosing to pursue the Master's track in River Coastal Engineering and Management has equipped me with a comprehensive understanding of captivating subjects.

This thesis is the result of months of work and dedication. It delves into a specific domain of water engineering and management, focusing on inland shipping and sediment transport specifically in the Waal river. Through this extensive research endeavour, I have acquired a profound comprehension of the subject matter and its associated challenges. The discoveries and recommendations presented herein contribute supplementary insights to the existing body of research, aiming to provide significant value to fellow scholars and interested parties alike.

Throughout my journey, I have been fortunate to receive invaluable support and guidance from my esteemed supervisors, Jord Warmink and Lieke Lokin, from the University of Twente. Additionally, I gratefully acknowledge the daily assistance of Merel Verbeek and Michiel Reneerkens from Rijkswaterstaat. Within the organizational framework of Rijkswaterstaat, I have also received generous help from numerous individuals within the Department of River Engineering. Their pleasant and instructive mentorship has been instrumental in my progress, and I extend my appreciation to them. Furthermore, I would like to express my profound gratitude to my friends and family, whose unwavering support has been a constant source of strength and assistance throughout various occasions. Especially my parents and sister supported me throughout my whole school career and pushed me to continue to follow my goals. I eagerly anticipate the prospect of applying the knowledge I have gained in the professional work field.

Delden, 2023

Executive summary

The objective of this Master thesis was to investigate the effects of inland shipping on sediment transport in the Waal river. Inland shipping plays a crucial role in the transportation of goods, particularly in regions with extensive river networks. The Waal river, situated in the Netherlands, serves as a vital waterway for transporting cargo between major cities and industrial middle points. Rijkswaterstaat, the Dutch governmental body responsible for managing waterways, currently maintains daily communication with shippers to ensure navigable depths in the Waal river. As vessels navigate the river, their cargo capacity is directly influenced by the water depth and width, which can vary considerably. When the load of a vessel exceeds the capacity of the river, leading to insufficient keel clearance, the riverbed is directly affected.

The study aimed to achieve a better understanding of the processes involved in sediment transport resulting from inland shipping activities. Specifically, the focus was on investigating the magnitude of the return flow velocity caused by propeller jets and backflow from inland shipping near the riverbed. This was examined through utilizing the data obtained from CoVadem between Deest and Druten. CoVadem is a platform that monitors the under-keel clearance of a vessel to predict the navigable depth based on real time data, ensuring a comprehensive and reliable dataset. With the found jet velocity and return currents, the study analysed and evaluated the relation between inland shipping activities and sediment transport by using the values from the propeller jets and backflow. For the determination of the sediment transport, several formulas were used. Eventually, the formula by van Rijn (1993) has been picked as the most suitable one.

To show the results, a Python model has been used. The Python model included a script with formulas and parameters for the calculations of the propeller jets and backflow. The results of the propeller jets and backflow led to return current velocities near the riverbed. These velocities were used to calculate the sediment transport for a vessel. The sediment transport has been calculated for three selected vessel types which represented the annual bulk transport in the Waal river. Furthermore, a sensitivity analysis was conducted to examine the effects of various variable parameters on sediment transport in the Waal river. The sensitivity analyses examined the power efficiency rate, keel clearance, vessel width, and vessel velocity. Reducing the power efficiency rate, vessel width, and vessel velocity all have a significant impact on reducing sediment transport in the Waal river. Increasing the keel clearance also led to a reduced sediment transport. Within the sensitivity analyses also the effect of an extreme dry event was tested with regards to the sediment transport. As a result of a lower water depth in dry periods the sediment transport increased significantly due to inland shipping. Eventually, feasible measures were proposed for Rijkswaterstaat and the users of the Waal to manage sediment-related issues in the future.

Since determining the influence of inland shipping on sediment transport is a relatively new subject a few limitations and assumptions are included in this research. One key limitation lies in how the sediment transport is calculated according to return flow velocities near the bed. Specifically for propeller jets and the backflow of a vessel, turbulent accelerations also must be considered. Incorporating these turbulent accelerations requires the use of complex models and significant amount of time.

The effect of the annual bulk transport on sediment transport within the Waal river is determined by classifying all shipping categories into three main groups. For each group, a reference vessel was selected as a simplification for the calculations. The resulting total sediment transport caused by the entire bulk transport was quantified to be $1.23*10^5$ m^2/year.

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1. Introduction

Inland shipping plays a crucial role in the transportation of goods, particularly in regions with extensive river networks. The Waal river, situated in the Netherlands, serves as a vital waterway for transporting cargo between major cities and industrial middle points (Verheij et al., 2008). However, the continuous variation in the dimensions of the river, particularly the water depth, poses significant challenges for vessel navigation. Rijkswaterstaat, the Dutch governmental body responsible for managing waterways, currently maintains daily communication with shippers to ensure the correct and actual navigable depths in the Waal river. As vessels navigate through the river, their cargo capacity is directly influenced by the water depth, which varies considerably. When the load of a vessel exceeds the capacity of the river, leading to insufficient keel clearance, the riverbed is directly affected (Bu et al., 2020). Therefore, it is useful to get an understanding of the interaction between vessels and sediment transport in the Waal river.

Inland vessels disrupt the natural flow of rivers near the riverbed through various mechanisms, including propeller jets and backflow (Guarnieri et al., 2021; (Sloff, 2022). According to the sediment transport formulas of Englund and Hansen (1967), the velocity (u) plays an important role in sediment transport ($q_s = m * u^n$). The exponent (n) is usually equal to 5. Therefore, even small changes in the velocity near the bed lead to significant changes in sediment transport at the riverbed. The flow disruptions like propeller jets and backflow, induced by inland shipping, have the potential to stir up sediment present at the riverbed, thereby affecting sediment transport dynamics, (Bu et al. 2020). The significance of this phenomenon is further magnified by the rapid erosion observed in the riverbed of the Waal river over the past century (Yla Arbós et al., 2021). The potential implications of this erosion on the stability of infrastructure along the river could be a cause for concern in the future.

To gain a better understanding of the effects of inland shipping on sediment transport in the Waal river, this study utilized CoVadem data. Covadem's data is recorded by inland vessels during their travels at several location in the Waal river. CoVadem provides valuable information from several pilot boats, including keel clearance measurements. The keel clearance, which represents the minimum water depth between the keel of the ship and the riverbed, served as critical parameter for assessing the impact of vessel depth on the propeller jets and backflow generated by vessels. These wave jets have the potential to stir up sediment above the riverbed and initiate sediment transport (Guarnieri et al., 2020). By calculating the effects, the relation between inland shipping, flow disruptions, and sediment transport, this study contributes to the understanding of sediment dynamics in the Waal river.

1.1 Knowledge gap

In the Waal river the water depths are varying constantly. For this reason, Rijkswaterstaat informs shippers daily about the varying navigable dimensions of the Waal river to reduce riverbed damages. Despite the significant role of inland shipping in the Waal river and its potential influence on sediment transport, there is currently limited understanding of the specific effects and implications of inland shipping activities on sediment transport within the Waal river. This study area is reasonably new and little literature is available about this subject, (Sloff, 2022; Kitsikoudis, 2023). Rijkswaterstaat lacks comprehensive knowledge regarding the relationship between inland shipping and sediment transport in the Waal river.

This thesis addresses this knowledge gap by investigating the effects of inland shipping on sediment transport within the Waal river. The thesis utilizes data collected by CoVadem at two locations along the Waal river, focusing on parameters that affect sediment transport and employing existing sediment transport formulas to analyse the data. The research examined the impact of a single vessel on the flow within the river and subsequently explore the implications of this flow on sediment transport. By determining the effects of individual vessels, the study will extend its findings to assess the cumulative impact of bulk transport on sediment transport within the Waal river.

This research provides insights into the relationship between inland shipping and sediment dynamics in the Waal river, enabling Rijkswaterstaat and the users of the Waal river to better understand and manage sediment transport within the river. This thesis advices Rijkswaterstaat with measures to manage sediment transport, thereby safeguarding the protection of the riverbed and optimizing navigational conditions for inland shipping while considering the broader implications for the Waal river ecosystem.

1.2 Research objective

The study aims to achieve a comprehensive understanding of the diverse processes and parameters involved in sediment transport resulting from inland shipping activities. Using the data obtained from CoVadem, this research will play a crucial role in assessing the direct effects of inland shipping on sediment transport within the Waal river on the section between Deest and Druten. The study utilized this CoVadem data to analyse and evaluate the relationships between inland shipping activities and sediment transport, considering the influence of propeller jets and the backflow of a vessel. Eventually, the amount of sediment transport caused by the annual bulk transport is calculated. Ultimately, this research provides valuable insights and recommendations for the managers (Rijkswaterstaat) of the Waal river and its users. By gaining an understanding of the main impacts of propeller jets and backflow on sediment transport, stakeholders will be better prepared to make decisions concerning sediment-related matters, navigational depths, and the overall preservation of the river ecosystem.

The four research questions that guide this Master thesis are:

1. *What parameters, induced by inland shipping, influence sediment transport in the Waal river?*
2. *What is the effect of the movement a single vessel on sediment transport using the CoVadem data in the Waal river?*
3. *What is the effect of the movements of the entire bulk transport on sediment transport using the CoVadem data in the Waal river?*
4. *What measures could Rijkswaterstaat and shippers apply to effectively reduce the negative effects sediment transport in the Waal river?*

1.3 Scope

This thesis focuses on the Waal river, which is in the Netherlands and is the largest branch of the Rhine river. The Waal river serves as a critical waterway with 108,800 vessel movements for transportation, connecting the Rotterdam harbour with North Rhine-Westphalia in Germany (Van de Ven, 2021). With a total length of 82 kilometers, it carries approximately 65% of the water discharge in the Netherlands, making it the most water-rich branch of the Rhine in the country (Rijkswaterstaat 2023). Figure 1 illustrates the Waal river, providing a visual representation of its location and flow.

The scope of this thesis relates to examining the impact of inland shipping on sediment transport specifically in the Waal river. By focusing on the Waal river, the study aims to provide insights and recommendations that are relevant to the specific environmental and navigational conditions of this waterway.

The data of CoVadem is collected at two locations in the Waal. These two locations, Druten and Deest, are illustrated in blue in Figure 1. The distance between the two places is 5 kilometers. These locations were selected due to the abundance of valuable data points available along the trajectory between them.

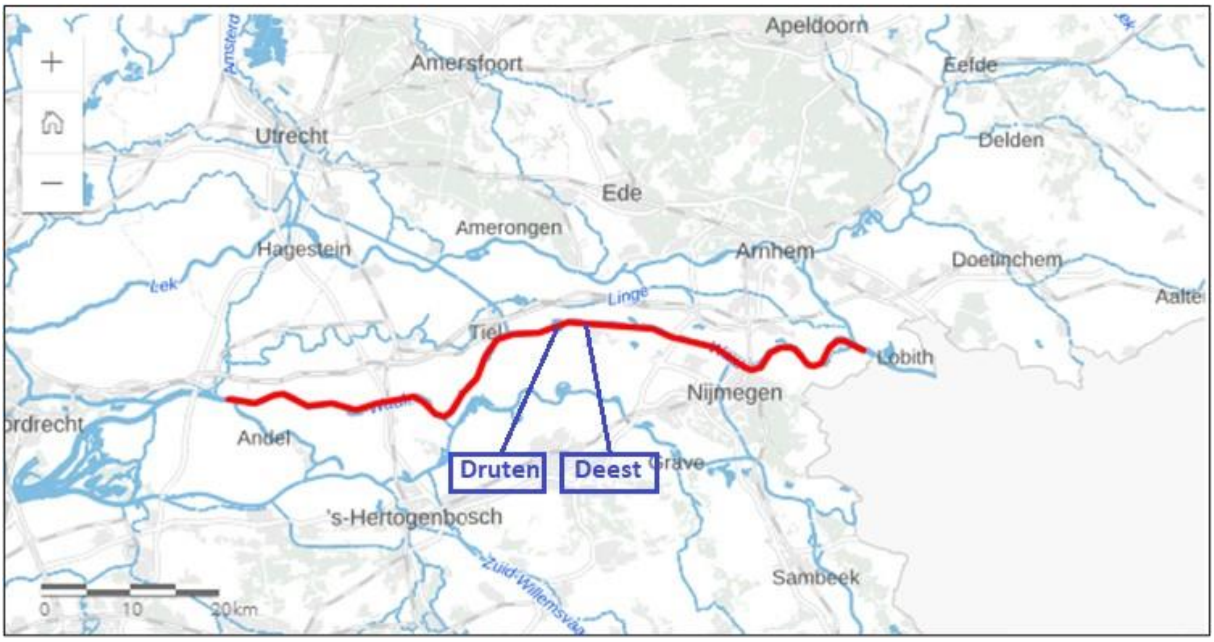

Figure 1 Location of the Waal river (Rijkswaterstaat, 2023)

While the scope of this thesis is limited to the Waal river, the findings and recommendations may give broader insights for other waterways facing similar challenges related to sediment transport and inland shipping. The knowledge gained from this study can contribute to the development of strategies and measures to manage sediment transport effectively, ensuring the preservation of the riverbed and the safety of inland shipping operations in the Waal river and beyond.

1.4 Method

To assess the contribution of inland shipping with regards to sediment transport in the Waal river, a specific methodology was employed. The study focused on distinguishing flow disruptions between two effects: the influence of vessels on the river's flow and the impact of the flow on the riverbed, which can lead to sediment transport. Among the various vessel-induced flow influences, the research specifically investigated the primary effects of the propeller jets and the backflow. To quantify these effects, crucial parameters such as vessel velocities and keel clearances were obtained from the CoVadem data and processed with a Python model. The Python model included a script with formulas and parameters for the calculations of the propeller jets and backflow. The outcomes of this analysis yielded return current velocities, which were then used to calculate the impact on sediment transport at the riverbed. Prior to this, different sediment transport formulas were considered, with Van Rijn's formula (1993) being deemed as the most suitable. Subsequently, sediment transport for individual vessels was determined, leading to an assessment of the overall impact of the annual total bulk transport on sediment transport in the river. Furthermore, a sensitivity analysis was conducted to identify the most influential parameter affecting sediment transport. This involved varying individual parameters by adding and subtracting 10 percent. An extreme dry event as result of climate change was also examined in the sensitivity analyses. As a result of the study, recommendations were provided to control sediment transport in the Waal River for Rijkswaterstaat (the Dutch government agency for water management) and the users of the river.

1.5 Thesis outline

In chapter 2, the focus has been laid on examining the parameters that have a significant impact on sediment transport within the Waal river. Chapter 3 involved the calculation of the effects of inland shipping on the flow patterns in the river. Additionally, the sediment transport caused by inland shipping is quantified, specifically for an average-sized vessel. Chapter 4 extended the analysis to estimate the overall annual bulk sediment transport resulting from inland shipping activities. In chapter 5 a sensitivity analysis was conducted of the involved parameters from chapter 2, aiming to assess their influence on sediment transport in the Waal river. Chapter 6 engaged in a comprehensive discussion to elaborate on the assumptions made in the thesis, providing a deeper understanding of their implications. A comparison with the literature has been included. In the final chapter 7, the conclusions derived from the research were presented, summarizing the key findings and their significance. A reflection on the objective is presented and recommendations for further research is given.

2. Influence of parameters on sediment transport in the Waal river

This chapter provided an in-depth examination of the various parameters influencing sediment transport in the Waal river. The focus is on understanding the relationship between inland shipping and sediment transport, exploring the impact of inland shipping activities on the flow patterns within the river, and investigating how these flow disruptions affect sediment transport. Additionally, the chapter presents the formulas and its parameters that are used in Python.

2.1 Relation inland shipping and sediment transport

The recent developments in the shipping industry have mainly been characterised by an in increase in capacity (Verheij et al., 2008). Vessels are becoming larger and deeper, with higher freight capacity. Besides, the vessel propellors are more powerful. This influences the demands of both harbours, channels and rivers. Guarnieri et al. (2021) found that high flow velocities lead to shear stresses on the river bottom. Bu et al. (2020) investigated with field measurements that shear stresses at the bottom of a river get increased when the load of a vessel increases. The shear stress is one of the key factors that determine the sediment transport capacity of a fluid. In general, as the shear stress exerted by a fluid on a sediment bed increases, the sediment transport rate also increases. This is because the fluid can overcome the frictional forces that keep the sediment particles in place, allowing them to be picked up and carried along by the fluid (Guarnieri et al., 2021).

To investigate the influence of the difference parameters, first the effect of inland shipping on the flow was determined in Section 2.2.

2.2 Influence of inland shipping on the flow

As stated in Section 2.1, the developments of the shipping industry led to larger and deeper loaded vessels (Verheij et al., 2008). Thereby, engines had to be more powerful to transport the increasing load. There are several ways in which inland shipping can affect the flow in a river. For example, when a vessel navigates through a river, several waves occur because of the backflow at the bow and stern side of the vessel (Luo, 2022). In Figure 2 this has been illustrated.

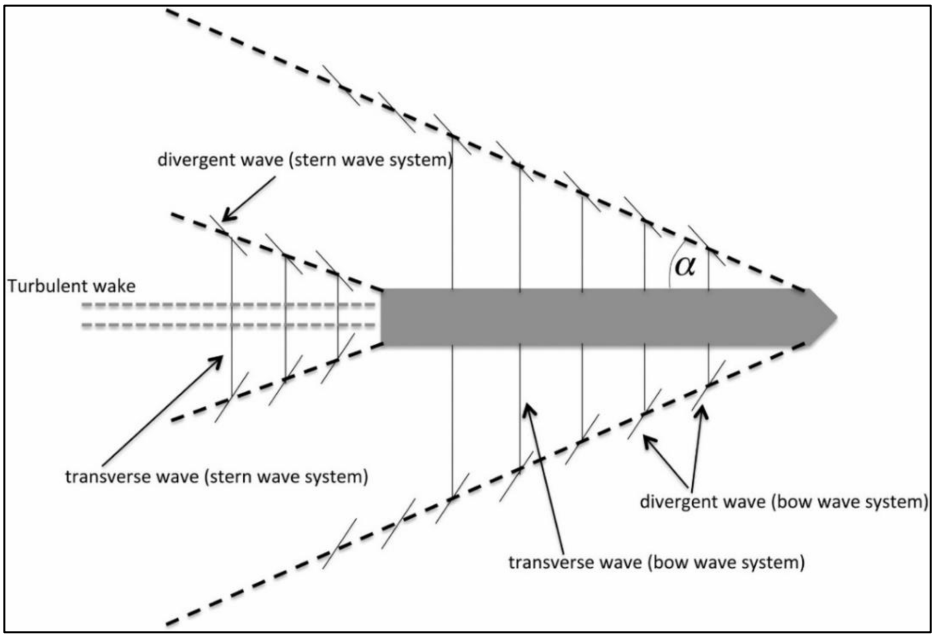

Figure 2 Waves caused by inland shipping on the flow in a river (Luo, 2022)

In vessel-induced water movement, there are various effects which lead to sediment transport, (Sloff, 2022). The primary effects are propellor jets behind and the vessel and backflow caused around the vessel. The aim of this Master thesis is to investigate the effects of inland shipping on sediment transport in the Waal river. Propellors have a big impact on flow disruptions, (Guarnieri et al., 2021). The jets, caused by the propellors, can cause erosion and deposition of sediment. In this Master thesis only the effects of propellors jets are considered regarding sediment transport in the Waal river. The calculations of the effects of the propellor jets are elaborated in Section 2.2.1. The calculation of the backflow is given in Section 2.2.2.

2.2.1 Propellor jets

There are two types of propellors on vessels, see Figure 3. On the left a main propellor is illustrated and on the right a thruster is given. The main propellors are responsible for the forward motion of the vessel. Thrusters are located at the side of vessel. A thruster is a transversal propulsion device that makes manoeuvring around tight areas like harbours possible without the use of towboats. These thrusters are needed on the bigger cargo vessels. In this thesis, only the effects of the main propellors on the flow were calculated since there is mainly forward motion in the observed river part between Deest and Druten. Besides, the influence of the propeller jets is at its biggest at the stern side where the main propellers are located.

Figure 3 Main propellor (left) vs. Thruster (right) (Marine Insight, 2020)

To calculate the effects of the propellor jets the method of Verheij et al., (2008) is used. First the outflow rate (V_0) at the propellor is estimated according to equation [1]:

$$V_0 = 1.15(\frac{\eta P}{\rho {D_0}^2})^{1/3} \qquad [1]$$

In equation [1], P represents the installed power of the propellor. η stands for the power efficiency rate. ρ represents the density of water, and D_0 represents the effective diameter of the propellor. In general, larger propellors can transfer more power at low speeds, utilizing more of the flow stream.

Behind the propellor, a velocity field will start to evolve once the propellors are turned on. The velocity V_{axis}, as a function of the horizontal distance from the axis of the propellor and parallel to the propellor axis, x, can be determined with equation [2]:

$$V_{axis} = 2.8 V_0 \frac{D_0}{x} \quad [2]$$

As the distance from the propellor axis increases, the velocity decreases. The velocity V_{still} at any point, as a function of the horizontal distance from the propellor axis, x, and as a function of the distance perpendicular to the x-axis, r, can be determined with equation [3]:

$$V_{still} = V_{axis} \exp\left(\frac{-15.4 r^2}{x^2}\right) \quad [3]$$

In equation [3], V_{still} represents at which a stationary vessel moves relative to the bottom. The maximum velocity at the riverbed, caused by the vessel propellor, is equal to $x_{max} = h_p/0.18$. In this formula represents h_p the vertical distance from the propellor axis to the riverbed. The maximum velocity at the riverbed behind the vessel can be calculated with equation [4]:

$$V_{b,max,0} = 0.3 V_0 \frac{D_0}{h_p} \quad [4]$$

Figure 4 below shows a visualization of the propeller jets and its parameters.

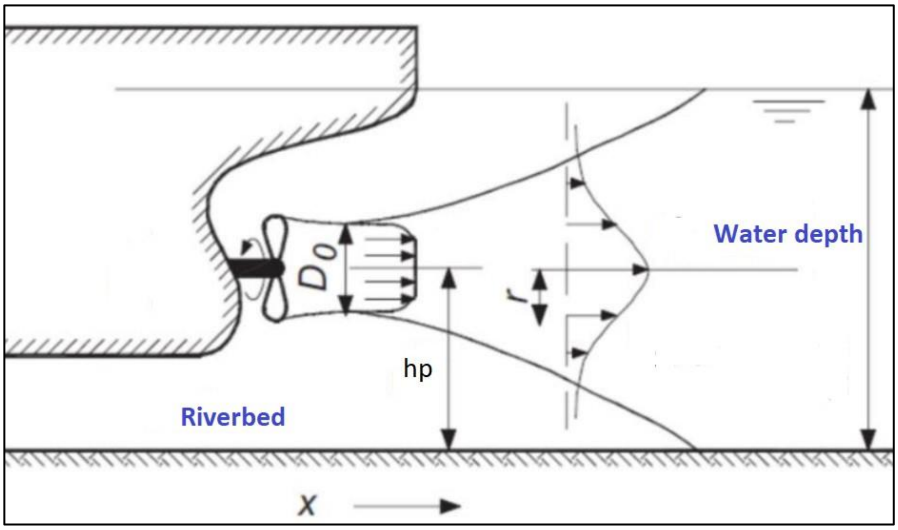

Figure 4 Visualization of propeller jets (Hoffmans, 2011)

Table 1 below gives an overview of the symbols used for the equations [1-4].

Table 1 Parameters regarding propeller jets equations [1-4]

Symbol	Definition	Unit
V_0	Outflow rate	m/s
η	Power efficiency rate	%
P	Power	W
ρ	Density water	kg/m^3
D_0	Effective diameter propellor	m
x	Variable horizontal distance	m
V_{still}	Velocity at the bottom of a stationary vessel	m/s
V_{axis}	Velocity horizontal behind the propellor axis	m/s
r	Variable vertical distance	m
$V_{b,max,0}$	Maximum velocity behind the vessel at riverbed	m/s
h_p	Vertical distance propellor axis and riverbed	m
V_m	Velocity at the bottom of a moving vessel	m/s
V_s	Vessel velocity	m/s

2.2.2 Backflow

When a vessel moves forward, it displaces water at the front of the vessel which then flows along the sides and beneath the hull before filling up the space behind the vessel. In a river or canal with limited depth, a backflow is created underneath and beside the vessel which flows in the opposite direction to the vessel's movement. The water flowing around the vessel needs to be accelerated from a standstill, which requires an increase in pressure. The vessel generates this pressure increase, resulting in a local increase in water level at the bow of the vessel. This is regarded as the bow wave which includes potential energy, see Figure 2. In conjunction with the flowing water, a drop in water level (potential energy converted into kinetic energy) occurs next to the vessel. Behind the vessel, the water level rises back up to above the still-water level. This is regarded as the stern wave which recovers the potential energy, see Figure 2. All these phenomena are referred to as the primary wave, (Sloff, 2022).

Analytical and empirical relationships are available for calculating the flow under a vessel. For the determination of the backflow in the Netherlands, a one-dimensional analytical approach has been widely used. The assumption of one-dimensionality is only valid if the width of the waterway is not more than 1.5 times the length of the vessel, or in practice, if the ratio of the width of the waterway to the width of the vessel is between 2 and 12. Furthermore, the vessel must travel on the river axis. Therefore, one-dimensional models are suitable for canals such as the Amsterdam-Rhine Canal and the Juliana Canal but are less suitable for wide rivers such as the Waal, where the flow around the vessel has more space to deviate laterally (Sloff, 2022). As stated, the one-dimensional analytical approach is possibly not fully suitable for the Waal. However, this approach uses more parameters than the empirical relationships. Besides, a large amount of the parameters could be retrieved from the CoVadem data which would improve the accuracy of the results. Hence, both the analytical and empirical approach will be used.

Empirical Approach

The empirical approach to calculate the backflow is based on empirical relationships typically derived from laboratory experiments. Various relationships are available in literature but are often specific to a particular combination of flow conditions and vessel properties. These formulas tend to perform poorly under different circumstances. For research in Dutch rivers, it is advised to use Maynords's relationship and its adaptations by Stolker and Verheij (2008). In this method, the ratio of the maximum return flow velocity $U_{rb,max}$ (at the bottom, right behind the bow) to the vessel velocity V_s is calculated as a function of the ratio of the vessel beam to the water depth (B_s/h) and the ratio of draught of the vessel to water depth (D/h).

The method is presented in equation [5] below:

$$\frac{U_{rb,max}}{V_s} = 1.07(\frac{B_s}{h})^{0.08} * (\frac{D}{h})^{1.82} \quad [5]$$

Table 2 below gives an overview of the symbols used for equation [5].

Table 2 Parameters regrading backflow empirical approach [5]

Symbol	Definition	Unit
$U_{rb,max}$	Maximum return current velocity along vessel at midships section	m/s
V_s	Vessel velocity	m/s
B_s	Vessel's beam at midships section	m
h	Water depth	m
D	Draught of vessel at midships section	m

One-dimensional analytical approach

The method for calculating the return flow velocity (U_r), developed by Schijf (1949), is based on the principle of energy conservation (using Bernoulli's principle). To achieve this, the 3D flow is first simplified into a one-dimensional flow.

Further simplifications are made that lead to the conclusion that this should only be considered as an approximation (for example, constant vessel speed, uniform return flow, neglecting energy losses due to inertia and friction, etc.). Using the principle of energy conservation, Schijf (1949) determined that there is a maximum velocity or critical velocity at which the flow next to the vessel transitions into a supercritical condition. This transition can be expressed with a Froude number equal to 1. In this situation, water is pushed up at the bow, which cannot be overcome by propeller-driven vessels (but can be by sailboats, for example). Therefore, this velocity is physically the maximum speed that can be achieved for a propeller-driven vessel. In practice, a speed of about 80% of the critical velocity is used because going faster than 80% of the critical velocity results in too little increase in speed compared to the extra amount of fuel required, (Sloff, 2022).

The calculation of the critical velocity is expressed in equation [6]:

$$1 - \frac{A_s}{A_c} + \frac{1}{2}\left(\frac{V'_{lim}}{\sqrt{g*h}}\right)^2 - \frac{3}{2}\left(\frac{V'_{lim}}{\sqrt{g*h}}\right)^{\frac{2}{3}} = 0 \quad [6]$$

If there is no width restriction of the river cross-section, then it follows that the maximum vessel speed is approximately equal to the theoretical long-wave speed ($\sqrt{g*h}$), which in practice means that the Froude number can be expressed as 1.

Furthermore, the above relationships can be simplified further for the situation with $\frac{A_s}{A_c}$ between 0.1 and 0.3, which is often found in inland waters, where the critical velocity is then given by equation [7]:

$$\left(\frac{V'_{lim}}{\sqrt{g*h}}\right) = 0.78\left(1-\frac{A_s}{A_c}\right)^{2.25} \quad [7]$$

Using the approach, the maximum return flow velocity U'_{lim} for this critical situation can be derived according to equation [8]:

$$U'_{lim} = \sqrt{\frac{2}{3}*g*h\left(1-\frac{A_s}{A_c}+\frac{1}{2}\left(\frac{V'_{lim}}{\sqrt{g*h}}\right)^2\right)} - V'_{lim} \quad [8]$$

The corresponding sinkage z_{lim} can then be derived according to equation [9]:

$$\frac{z_{lim}}{h} = \frac{1}{3}(1-\frac{A_s}{A_c}+\left(\frac{V'_{lim}}{\sqrt{g*h}}\right)^2) \quad [9]$$

This theory thus provides the maximum speed at which the vessel can sail, as well as the corresponding return flow velocity and sinkage. In practice, the sailing speed will be lower. In that case, i.e., when $V'_s < V'_{lim}$, the return flow velocity U'_r can be calculated according to equation [10]:

$$\frac{\alpha_{schijf}*(V'_s+U'_r)^2 - V'^2_s}{2*g*h} - \frac{U'_r}{V'_s+U'_r} + \frac{A_s}{A_c} = 0 \quad [10]$$

In equation [11] is α_{schijf} a correction factor for the non-uniform distribution of the return velocity and is usually taken as α_{schijf} =1.1. It should also be noted that $U_r = U'_r - U_c$, where U_r is the return flow velocity relative to the bottom. The sinkage z for this approach can be calculated according to equation [12]:

$$z = \alpha_{schijf}\frac{(V'_s+U'_r)^2}{2*g} - \frac{V'^2_s}{2*g} \quad [11]$$

The maximum flow under the keel occurs directly behind the bow and is higher than the average return flow Ur calculated above (due to local detachment and contraction). Based on a study by (Van der Wal, 1989), the maximum return flow velocity near the bottom (under the bow) $U_{rb,max}$ is related to the cross-sectional average return flow velocity U_r, which can be calculated using the one-dimensional method according to Schijf (formulas 4.167 - 4.174 from the Rock Manual, CUR), through the coefficient α:

$$U_{rb,max} = \alpha * U_r \quad [12]$$

Stolker and Verheij (2006) suggest that the coefficient α is approximately 1.5 to 2. (Lenselink, 2011) determined through experiments that α is approximately 1.46 and (Robijns, 2014) found that α is approximately 1.53 for standard inland vessels and α is approximately 2.88 for a push barge unit. Schoevers et al. (2015) showed based on measurements of vessels in the Julianakanaal that on average α is approximately 1.3 for motor vessels, but for push barge combinations, the average value of α is approximately 1.6 for draft depth of 3 meter and 1.8 meter for draft depth of 3.5 meter (varying between 1.4 and 2.3) due to the well streamlined bow (Sloff, 2022).

It should be noted that the above formulas apply to a rectangular cross-section of the river, but in situations with a more trapezoidal profile, this leads to an error of only a few percent (Sloff, 2022).

Table 3 below gives an overview of the symbols used for the equations [6-12].

Table 3 Parameters regarding backflow analytical approach [6-12]

Symbol	Definition	Unit
A_s	Midship underwater cross-section (B_s*T)	m^2
A_c	Undisturbed wet cross-section	m^2
V'_{lim}	Limit speed	m/s
g	Gravitational acceleration	m/s^2
h	Water depth undisturbed cross-section	m
U'_{lim}	Maximum return current velocity	m/s
z_{lim}	Sinkage	m
α_{schijf}	Correction factor Schijf	[-]
V'_s	Relative vessel speed compared to the water velocity	m/s
U'_r	Return current velocity compared to the water velocity	m/s
$U_{rb,max}$	Maximum return current velocity along vessel at midships section	m/s
α	Correction factor average return current	[-]
U_r	Return current velocity	m/s

2.3 Influence of affected flow on sediment transport

The formulas for sediment transport that were employed to determine the amount of sediment that is being moved in a specific hydraulic environment. There is a vast array of formulas available, each with unique features. Most of these formulas were derived from laboratory observations.

2.3.1 Meyer-Peter and Müller (1948)

The formula of Meyer-Peter and Müller (1948) is experimental and computes only the bed load transport. The formula is developed for the following conditions:

- $\mu_r \tau^* < 0.2$
- $D > 0.4$ mm
- $w_s/u_* > 1$

If all the conditions are applicable, then equation [13] determines the bed load transport as follows:

$$\phi = 8(\psi - 0.047)^{3/2} \quad [13]$$

With the following ripple factor:

$$\mu_r = \left(\frac{C}{C_{90}}\right)^{3/2} \quad [14]$$

Equation [15] gives the sediment transport formula for Meyer-Peter and Müller (1948):

$$q_s = \frac{\phi}{\sqrt{gRD_{50}{}^3}} \qquad [15]$$

Table 4 below shows the parameter for the sediment transport formula of Meyer-Peter and Müller (1948).

Table 4 Parameters regarding Meyer-Peter and Müller (1948) [13-15]

Symbol	Definition	Unit
μ_r	Ripple factor	[-]
τ^*	Shear stress/Shields parameter	[-]
D	Sediment diameter	mm
w_s	Settling velocity	m/s
u_*	Shear velocity	m/s
ξ_k	Correction factor hiding-exposure	[-]
ϕ	Sediment transport parameter	[-]
ψ	Flow parameter	[-]
C	Chézy coefficient	$m^{1/2}/s$
C_{90}	Chézy coefficient related to D_{90}	$m^{1/2}/s$
q_s	Volumetric sediment transport rate per unit width	m^2/s
g	Gravitational acceleration	m/s^2
R	Hydraulic radius	m
D_{50}	Median sediment particle diameter	m

2.3.2 Engelund and Hansen (1967)

Although originally developed to compute bed load, the formula of Engelund and Hansen (1967) is proven to be particularly suited for the computation of bed material load of relatively fine sandy material, where a major part of it is transported as suspended load. The formula is developed for the following conditions:

- $w_s/u_* < 1$
- $0.07 < \tau^* < 6$
- $0.19 < D_{50} < 0.93$ mm

If all the conditions are applicable, then equation [16] determines the bed load transport as follows:

$$\phi = 0.05\psi^{5/2} \qquad [16]$$

With the following ripple factor:

$$\mu_r = \left(\frac{C}{g}\right)^{5/2} \qquad [17]$$

Equation [18] gives the sediment transport formula for Engelund and Hansen (1967):

$$q_s = \frac{\phi}{\sqrt{gRD_{50}{}^3}} \qquad [18]$$

Table 5 below shows the parameter for the sediment transport formula of Engelund and Hansen (1967).

Table 5 Parameters regarding Engelund and Hansen (1967) [16-18]

Symbol	Definition	Unit
μ_r	Ripple factor	[-]
τ^*	Shear stress/Shields parameter	[-]
D_{50}	Mean sediment particle diameter	mm
w_s	Settling velocity	m/s
u_*	Shear velocity	m/s
ϕ	Sediment transport parameter	[-]
ξ_k	Correction factor hiding-exposure	[-]
ψ	Flow parameter	[-]
C	Chézy coefficient	$m^{1/2}/s$
g	Gravitational acceleration	m/s^2
q_s	Volumetric sediment transport rate per unit width	m^2/s
R	Hydraulic radius	m
D_{50}	Median sediment particle diameter	m

2.3.3 Van Rijn (1993)

The method of Rijn (1993) is an approach that relies on both flume experiments and field data. For the method of Van Rijn it is assumed that the bed-load transport rate can be described sufficiently accurately by expressing the calculated velocities caused by inland shipping as critical depth-averaged velocities for the movement course gravel and stone, Van Rijn (1984) and Van Rijn (1993).

The particle parameter is defined as follows in equation [19]:

$$D_* = D_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{1/3} \qquad [19]$$

With Figure 5, it can be checked whether the particles are in motion according to the Shields diagram. When there is motion, the depth averaged grain-shear velocity is simplified and calculated as follows in equation [20]:

$$u' = u_{propeller} + u_{backflow} \qquad [20]$$

The depth average critical bed-shear velocity can be calculated as follows in equation [21]:

$$u'_{*,cr} = 1.4[(s-1)gD_{50}]^{0.5}\left(\frac{h}{D_{50}}\right)^{1/6} \qquad [21]$$

The bed-load transport for the particles can be calculated as follows in equation [22]:

$$q_b = 0.005u'h\left(\frac{u' - u'_{*,cr}}{[(s-1)gD_{50}]^{0.5}}\right)^{2.4}\left(\frac{D_{50}}{h}\right)^{1.2} \qquad [22]$$

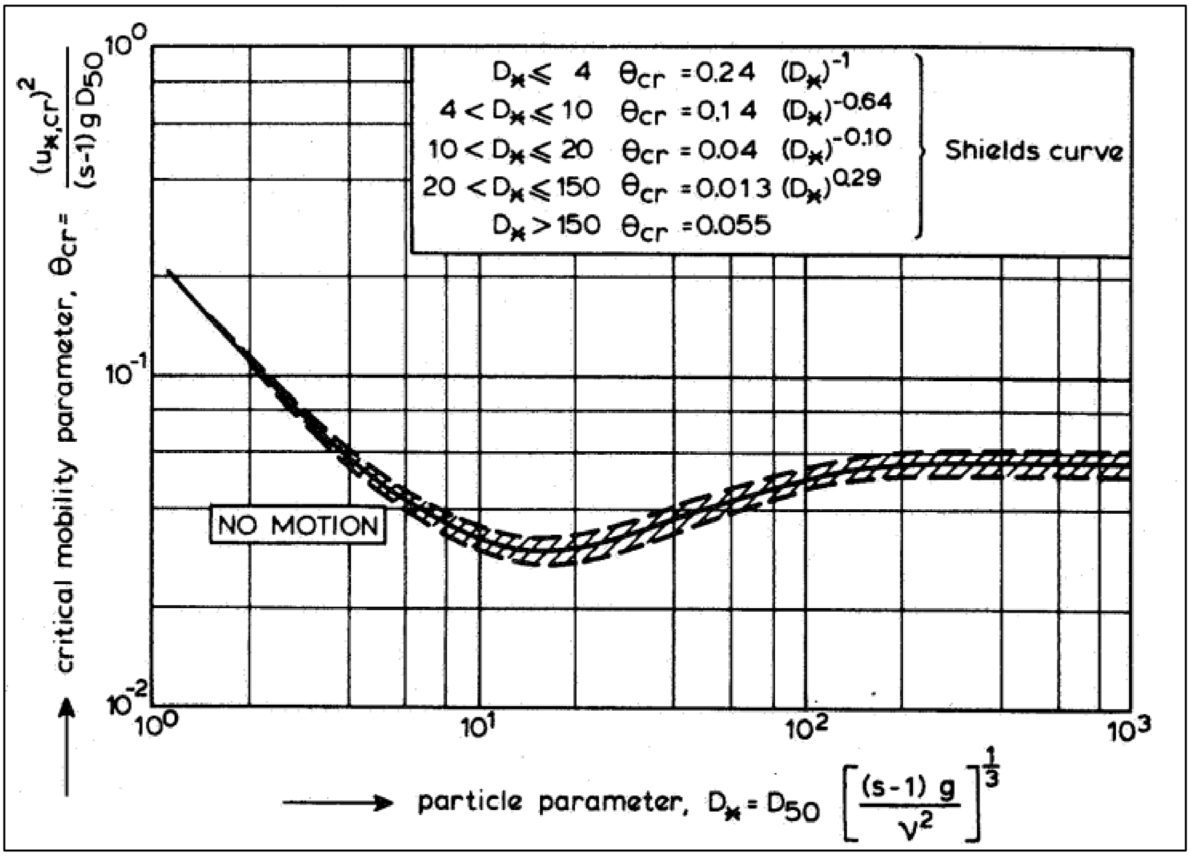

Figure 5 Initiation of motion according to Shields, Van Rijn (1993)

Table 6 below shows the parameters for the sediment transport formula of Van Rijn (1993).

Table 6 Parameters for sediment transport equations Van Rijn (1993) [19-22]

Symbol	Definition	Unit
D_*	Dimensionless particle parameter	[-]
D_{50}	Median sediment particle diameter	m
s	Grain density	[-]
g	Gravitational acceleration	m/s^2
u'_*	Depth average bed-shear velocity	m/s
h	Water depth	m
$u_{*,cr}$	Depth average critical bed-shear velocity	m/s
θ_{cr}	Critical particle mobility parameter according to Shields	[-]
q_b	Bed load transport	m^2/s

2.4 Selected sediment transport formula

As mentioned in Section 2.3, three formulas for sediment transport were considered. It is widely recognized that there exist other formulas for sediment transport, but only these three commonly used formulas are considered in this thesis. The formulas proposed by Meyer-Peter and Müller (1948) and Engelund and Hansen (1967) had certain conditions which had to be met before they could be applied. On the other hand, the formula developed by Van Rijn (1993) did not have any such requirements. Upon examining these formulas, the following findings were made:

- The sediment transport formula of Meyer-Peter and Müller (1948) cannot be used because the following condition was not met:

$$\mu_r \tau^* < 0.2$$

- The sediment transport formula of Engelund and Hansen (1967) cannot be used because the following condition was not met:

$$0.19 < D_{50} < 0.93 \text{ mm}$$

Therefore the selected sediment transport formula is Van Rijn (1993).

2.5 Hiding and exposure effect

Forecasting how the riverbed behaves can be difficult due to the limited precision of sediment transport models and formulas, especially when the riverbed is made up of different sediments. When sediment is of the same size, its movement is dependent on the absolute grain size of the bed material. However, when sediment consists of mixed sizes, the way in which the grains interact with the water flow becomes more complex, leading to selective entrainment, meaning that only certain grains are picked up and moved (McCarron et al., 2018). This phenomenon is called the hiding-exposure effect, which occurs when smaller grains are hidden from the water flow by larger ones. This makes it difficult to accurately calculate the rate at which sediment is transported. Hiding of grains in sediment mixtures leads to an increase in the critical shear stress required to mobilise the smaller sediment particles. Exposure of grains results in a decrease of the critical shear stress required to mobilise the larger sediment particles (Einstein, 1950). It is suggested that as the proportion of coarse material in a mixture increases in relation to the fine material, there is a larger chance that the coarse grains will be exposed to the flow while the fine grains remain hidden. This leads to a stronger hiding-exposure effect. This process is schematized in Figure 6, (McCarron et al., 2018). On the left, fine grains are illustrated with an increasing fraction distribution. On the right, coarse grains are illustrated with an increasing fraction distribution.

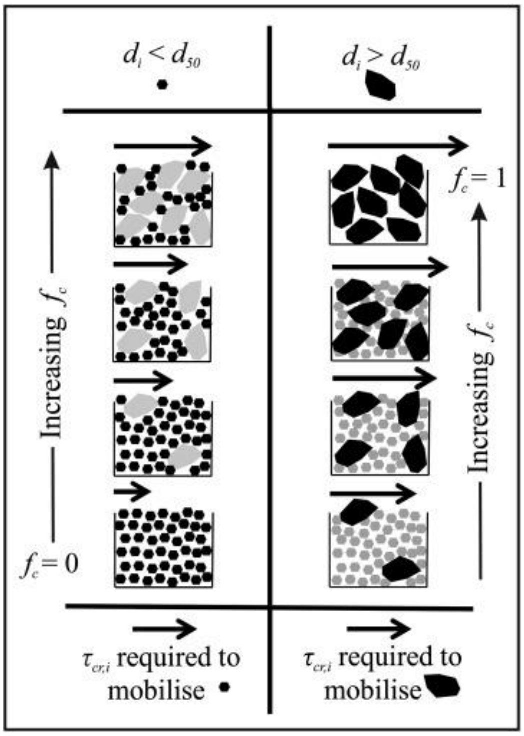

Figure 6 Variation in the hiding-exposure effect (McCarron et al., 2018)

Figure 7 illustrates the depth-averaged distribution of the fractions within the Waal river. The location for Druten is at 903 km along the x-axis. For Druten it can be concluded that there is a wide range of fractions, which means that hiding-exposure effect is present in the Waal river. It must be noted that the level of uncertainty is highest when the riverbed consists of mixed sediment (Wilson et al., 2018).

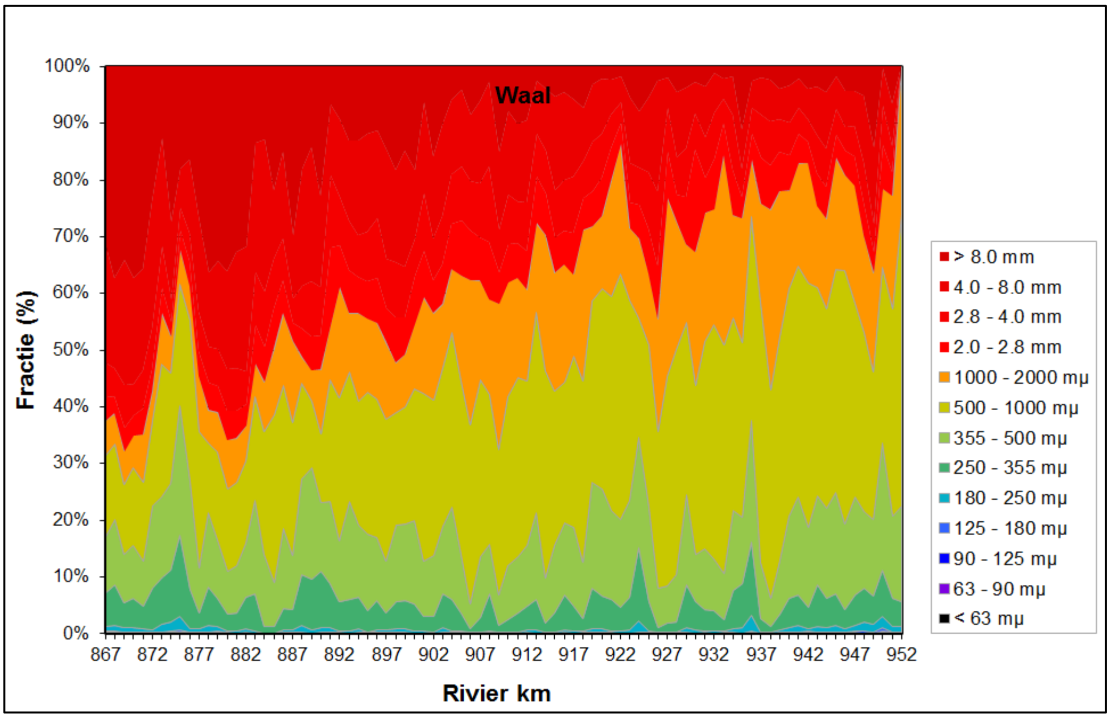

Figure 7 Fraction distribution in the Waal river (Rijkswaterstaat, 2020)

The conclusion that the hiding-exposure effect is present in the Waal river gets supported by Table 7. For the 'centre', 'left' and 'right' side of both locations, the sample sizes (D_{50} and D_{90}) vary heavily which means different sediment sizes are present. These values are used later in the determination of the sediment transport.

Table 7 Sample sizes for Druten (Rijkswaterstaat, 2020)

Location	Side	D50 [mm]	D90 [mm]
Druten (Waal-903)	*Centre*	0.988	5.360
	Left	1.247	28.453
	Right	2.735	8.882

To account for the hiding-exposure effect, a correction for the sediment transport must be implemented (Chavarrias, 2021). The correction factor, invented by Parker and Klingeman (1982), is given below in equation [23]:

$$\xi_k = \left(\frac{d_i}{d_{50}}\right)^{-0.982} \quad [23]$$

Table 8 below gives an overview of the symbols used for equation [23].

Table 8 List of symbols hiding-exposure effect [23]

Symbol	Definition	Unit
$\boldsymbol{\xi_k}$	Correction factor hiding-exposure	[-]
$\boldsymbol{d_i}$	Grain size of the i^{th} fraction	m
$\boldsymbol{d_{50}}$	Mean sediment particle diameter	m

As mentioned in Section 2.4, the selected sediment transport formula is Van Rijn (1993). With the inclusion of the hiding-exposure effect, the bed-load transport formula of equation [22] is modified to equation [24] as follows:

$$q_b = \xi_k * 0.005u'h\left(\frac{u' - u'_{*,cr}}{[(s-1)gD_{50}]^{0.5}}\right)^{2.4}\left(\frac{D_{50}}{h}\right)^{1.2} \quad [24]$$

3. Effects of a single vessel on sediment transport in the Waal river

To get an overview of the effects of one single vessel on the sediment transport in the Waal river the CoVadem data is used in combination with Python to show the results. Information about the CoVadem data and its use is elaborated in this section. Furthermore, the sediment transport caused by a single vessel is calculated for the Waal using the Python model. The values for the parameters, that are used in the Python, are substantiated in this section.

3.1 CoVadem data

The utilized vessel data are collected by CoVadem and released by Rijkswaterstaat for this Master thesis. The CoVadem data are available for the vessel movements around the location of Druten. This section elaborates on the company CoVadem, the method of data retrieval, and the contribution of this data to the Master thesis.

3.1.1 CoVadem

CoVadem is a company that uses data from over 250 vessels (such as barges and patrol boats) to create an updated map of the Rhine's dimensions for shippers. As mentioned earlier, Rijkswaterstaat heavily relies on depth data of rivers. Data collected by CoVadem is gathered using field measurements, which are recorded by inland vessels during their travels. Vessels that can join CoVadem's fleet as measurement vessels must at least have a GPS antenna and a single beam echosounder on board. The single beam echosounder's transducer measures the difference between the transducer and the water bottom, which is referred to as draft. This allows vessel captains to determine if they have a safe amount of water under their vessel or if they risk touching the riverbed. The echosounder emits a sound pulse that travels to the riverbed, is reflected, and then returns to the echosounder transducer. The time between transmission and receipt is measured, and using the speed of sound, the distance between the transducer and the bottom can be determined. CoVadem datasets show that the draft and other data are sent to CoVadem every 1 or 2 seconds (CoVadem, 2022).

3.1.2 Data explanation

In Table 9 below, a part of the vessel specifics of the CoVadem data is presented. The first column shows the 'shipid' which gives an identification number to a vessel. In total 129 different vessels were used. In the second, third and fourth column the vessel characteristics of respectively the 'length', 'width' and 'weight' are presented. The 'length' and 'width' is given in meters and the 'weight' is given in tonnes. The fifth column represents the 'count', which is the number of measurements that have been done for the vessel during its travel period. The last two columns present dates for the first and last measurement with a year and month.

Table 9 Vessel specifics CoVadem fleet in Python

	shipid	length	width	weight	count	first	last
0	2	135.0	17.00	1732.44	564918	201901	202012
1	3	110.0	11.45	775.00	161507	201901	202012
2	4	135.0	14.20	1589.00	410763	201901	202007
3	5	90.0	11.45	844.00	35906	201901	202007
4	6	110.0	11.45	886.54	782101	201901	202003

In Table 10 below, the actual CoVadem data is presented. The first column shows the 'index', which are the amount of data points. The second column shows the 'timestamp'. Between two data points there is a time difference of 2 seconds. However due to measurement errors in the keel clearance and the water depth, some the data had to be filtered. Some data points showed keel clearances of 90-100 meters which are not a representative value in the Waal river. The third and fourth column show 'lat' and 'lon' which are respectively the latitude and longitude, so the coordination points of the measurements. 'ukc' indicates the keel clearance of a vessel in meters and 'wd' is the water depth in meters. The seventh column 'speed' is the vessel speed in m/s.

Table 10 CoVadem data via Python

Index	timestamp	lat	lon	ukc	wd	speed
0	2019-01-01 23:57:59	51.8884	5.49433	5.08	6.46	1.83
1	2019-01-01 23:58:13	51.8884	5.49503	5.14	6.52	1.81
2	2019-01-01 23:58:25	51.8884	5.49562	5.05	6.43	1.81
3	2019-01-01 23:58:35	51.8884	5.49611	4.9	6.28	1.81
4	2019-01-01 23:58:51	51.8884	5.4969	5.22	6.6	1.81
5	2019-01-01 23:59:09	51.8884	5.49783	5.08	6.46	1.81

3.1.3 Use of the data

After analysing the data provided by CoVadem, it became evident that the data is not always suitable for accurately determining the water depth and keel clearance. One of the biggest issues is the GPS. The location of the measured depth shows large variations sometimes. This may result in large deviations around the same locations. As stated in Section 3.1.2, there were also some outliers in the water depth and keel clearance.

After filtering the data the keel clearance, water depth and the speed of the vessel, are considered sufficiently accurate from the data, along with the characteristics of the vessel itself. The keel clearance refers to the distance between the vessels lowest point at the stern side and the riverbed. It can be used to assess how the depth of a vessel affects the creation of wave jets generated by the vessel's movement. These wave jets have the potential to disturb the sediment present above the riverbed. Detailed information and calculations regarding the impact of inland shipping on the flow and transport of sediment will be provided in the following two chapters.

The data primarily indicates that the vessels of CoVadem's fleet are predominantly moving towards the North Sea, which can be considered as moving downstream. However, there is a lack of sufficient movements in the opposite direction, away from the North Sea (upstream). As a result, this Master thesis focuses solely on analysing the effects of inland shipping on the Waal river based on the downstream movements.

3.2 Reference vessel

Table 11 shows an overview of the primary shipping classes that contribute to sediment transport in the Waal river in the period 2009-2018, M. Van de Ven (2021). The classification of vessels on rivers is determined according to the Navigation Guidelines 2020. The table contains information on the characteristic lengths (L), width (Bs), loaded draft (T), and average number of passages measured on the middle Waal river section between Maas-Waalkanaal and Druten.

To study the effects on an individual vessel, it is necessary to select a reference vessel. The chosen reference vessel for the study is an M8 Groot Rijnschip, representing the 'Average' single vessel. This vessel is also the most frequently observed type in the Waal river, accounting for 43,800 vessel movements annually, which constitutes to 40% of all primary shipping classes presented in Table 11.

Table 11 List of vessels through the Waal in 2009-2018 (M. Van de Ven, 2021)

RWS Klasse	Naam	CEMT Klasse	L (m)	Bs (m)	T (m) (max)	Aantal/ jaar	Aan-tal %
M2	Kempenaar	II	50-55	6.6	2.6	4500	4
M3	Hagenaar	III	55-70	7.2	2.6	5800	5
M4	Dordtmund-Eems	III	67-73	8.2	2.7	6200	6
M5	Verl. Dordtmund Eems	III	80-85	8.2	2.9	7700	7
M6	Rijn-Herne schip	IVa	80-85	8.2	2.9	1900	2
M7	Verlengd Rijn-Herne	IVa	105	9.5	3	5700	5
M8	Groot Rijnschip	Va	110	11.4	3	43800	40
M9	Verl. Groot Rijnschip	Va	135	11.4	3.5	10300	9
M10	Maatg. Schip 13,5 * 110 m	VIa	110	13.5	4	1500	1
M11	Maatg. Schip 14,2 * 135 m	VIa	135	14.2	4	4400	4
M12	Rijnmax schip	VIa	135	17	4	3900	4
BLL-4	4 baks duwstel		185-190	22.8	3.5-4	2800	3
BLL-6l	6 baks duwstel lang (berg)		270	22.8	3.5-4	1300	1
BLL-6b	6 baks duwstel lang (dal)		170-190	34.2	3.5-4	1300	1
C3l	Koppelv. Va+Eur.II lang		170-190	11.4	3.5-4	5800	5
C4	Koppelv. Va+3 Europa II		185	22.8	3.5-4	1900	2

3.3 Parameter values propeller jets

This section focuses on the parameters related to the propeller jets' impact caused by a single vessel, which are presented in Table 1. Specifically, the values of these parameters are discussed in relation to the Python model representing the M8 Groot Rijnschip operating in the Waal river. The parameter values for the average class are included in Appendix B. Parameter values average vessel.

3.4 Results

This section shows the results of the influence of an M8 Groot Rijnschip on the flow in water regarding the propeller jets and the backflow. Besides, the sediment transport is calculated. The backflow is presented with both the empirical solution and the one-dimensional analytical solution. The travel of the vessel took one hour. This is consciously done to ensure equal conditions for all the vessel types that are tested later within this study. The travel between Deest and Druten was one of the only travels with these equal conditions for the relevant vessel types. An example of these conditions is that travels had to take place within the same year and month, as trips during different years and months tend to exhibit variations in water levels. Moreover, this travel stood out as one of the rare instances in which all relevant ship types were included, facilitating a comparison of the return current velocities caused by different vessels.

3.4.1 Propeller jet

The results are achieved by combining the formulas from Section 2.2.1 with the parameters from Appendix B. Parameter values average vessel. Figure 8 shows the return velocity values ($V_{b,max,0}$) of an M8 Groot Rijnschip through the Waal with Deest as starting location and Druten as end location because of propeller jets. Within the first 10 minutes of the travel there is a lack of data points visible. This lack of data is due to the filtering process applied to remove outliers, particularly those associated with unusually high keel clearances. The reason why the return velocity values deviate between 0.7 and 1.1 m/s is devoted to the fluctuations in the keel clearance during the travel of the vessel. The other parameters regarding the propeller jets remained almost constant.

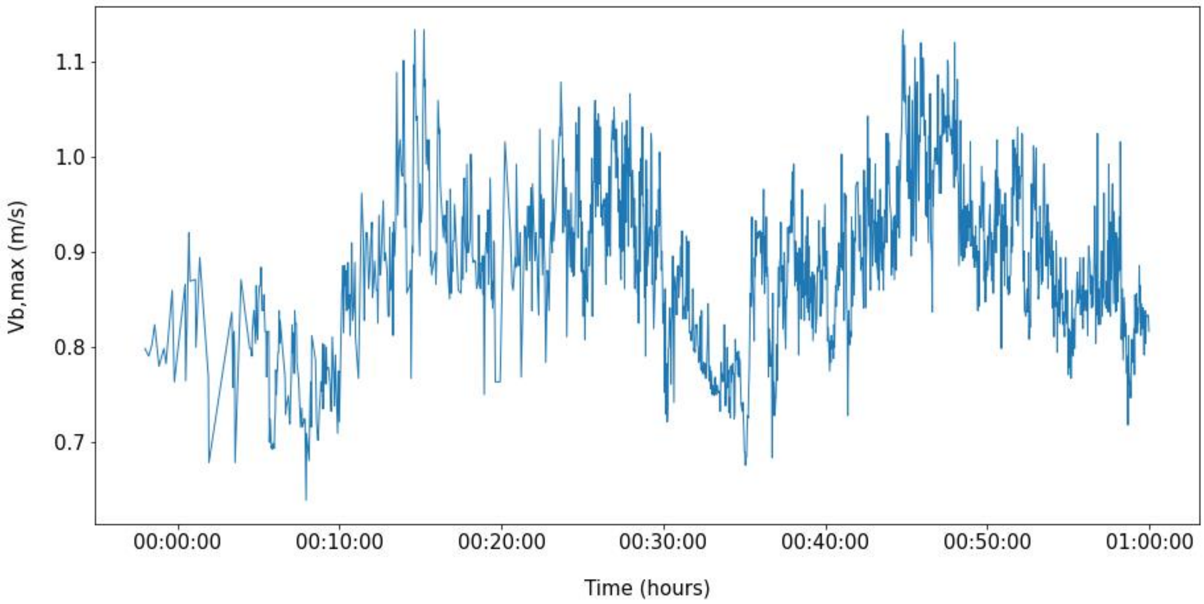

Figure 8 Propeller jet velocity of an M8 Groot Rijnschip

Table 12 shows the values for the maximum velocity behind the vessel at the riverbed ($V_{b,max,0}$)

Table 12 Values propeller jet of an M8 Groot Rijnschip

Description	Value
Shipid CoVadem	14
Vessel class	‘Average’
Start Location	Deest
End Location	Druten
Date	2019-01-01 till 2019-01-02
Time	23:57:59 till 00:59:59
Stream	Downstream
Datapoints	1447
Average $\boldsymbol{V_{b,max,0}}$	0.88 m/s
Minimum $\boldsymbol{V_{b,max,0}}$	0.64 m/s
Maximum $\boldsymbol{V_{b,max,0}}$	1.13 m/s

3.4.2 Backflow

The result for the backflow is presented the both the empirical solution and the one-dimensional analytical solution.

Empirical approach

The results are achieved by combining the formulas from Section 2.2.2 with the parameters from Appendix B. Parameter values average vessel. Figure 9 shows the return velocity values ($U_{rb,max}$) of an M8 Groot Rijnschip through the Waal with Deest as starting location and Druten as end location because of the backflow (empirical approach). Just like the data for the propeller jets, there is a lack of data at the start of the travel due the filtering process of outliers in water depth. The reason why the return velocity values deviate between 1.1 and 1.4 m/s is devoted to the fluctuations in the water depth during the travel of the vessel. The other parameters regarding the backflow (empirical approach) remained almost constant. It is visible that the return velocity of the backflow (empirical approach) is higher than the propeller jets. This is endorsed by a previous study of (Sloff, 2022).

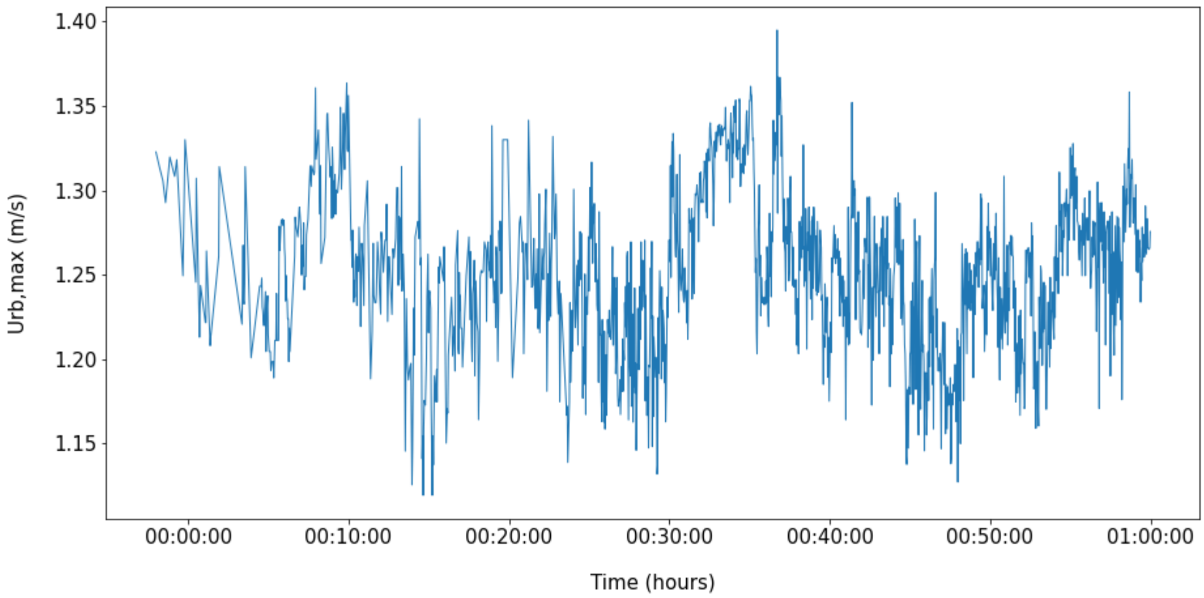

Figure 9 Backflow velocity M8 Groot Rijnschip

Table 13 shows an overview of important values regarding the calculations for the maximum return current velocity along ($U_{rb,max}$) the vessel.

Table 13 Values backflow (empirical solution) for an M8 Groot Rijnschip

Description	Value
Shipid CoVadem	14
Vessel class	'Average'
Start Location	Deest
End Location	Druten
Date	2019-01-01 till 2019-01-02
Time	23:57:59 till 00:59:59
Stream	Downstream
Datapoints	1447
Average $\boldsymbol{U_{rb,max}}$	1.25 m/s
Minimum $\boldsymbol{U_{rb,max}}$	1.12 m/s
Maximum $\boldsymbol{U_{rb,max}}$	1.39 m/s

Analytical approach

The results are achieved by combining the formulas from Section 2.2.2 with the parameters from Appendix B. Parameter values average vessel. Figure 10 shows the return velocity values ($U_{rb,max}$) of an M8 Groot Rijnschip through the Waal with Deest as starting location and Druten as end location because of the backflow (analytical approach). Just like the data for the propeller jets, there is a lack of data at the start of the travel due the filtering process of outliers in water depth. The average values for the return velocity between the empirical and analytical approach deviate with 40 percent. This can be attributed to differences within the two calculation methods. The reason why the return velocity values deviate between 1.4 and 2.4 m/s is devoted to the fluctuations in the water depth during the travel of the vessel. It is also visible that the return velocity of the backflow (analytical approach) is higher than the propeller jets. This is endorsed by a previous study of (Sloff, 2022).

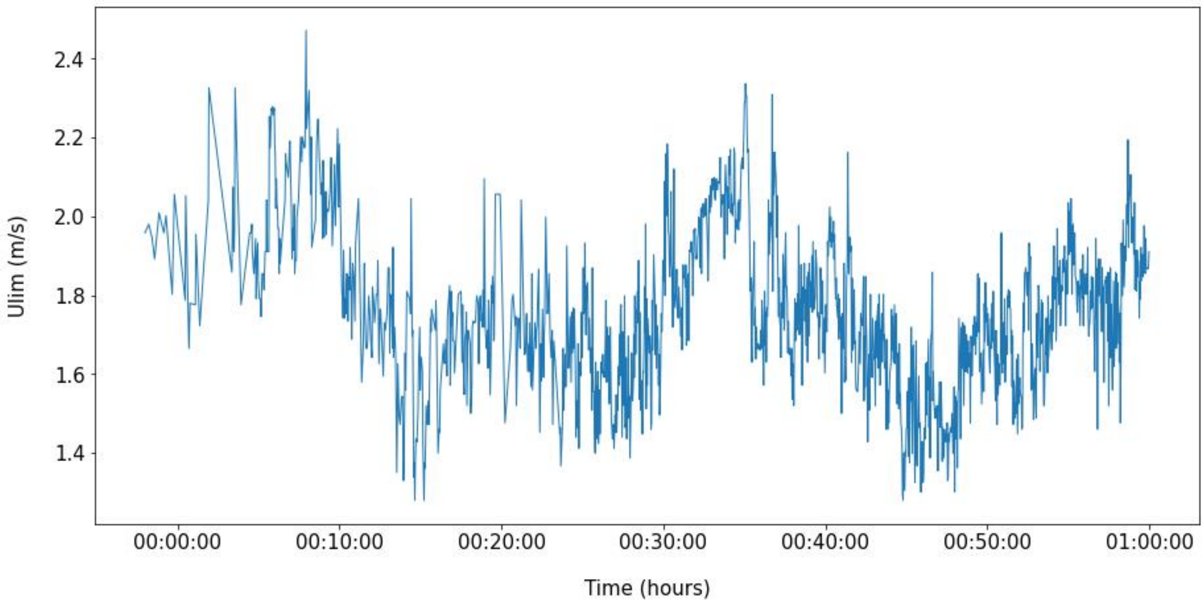

Figure 10 Backflow (Analytical approach) M8 Groot Rijnschip

Table 14 shows an overview of important values regarding the calculations for the maximum return current velocity ($U_{rb,max}$) along the vessel.

Table 14 Values backflow (Analytical approach) for an M8 Groot Rijnschip

Description	Value
Shipid CoVadem	14
Vessel class	'Average'
Start Location	Deest
End Location	Druten
Date	2019-01-01 till 2019-01-02
Time	23:57:59 till 00:59:59
Stream	Downstream
Datapoints	1447
Average $\boldsymbol{U_{rb,max}}$	1.76 m/s
Minimum $\boldsymbol{U_{rb,max}}$	1.28 m/s
Maximum $\boldsymbol{U_{rb,max}}$	2.47 m/s

3.4.3 Choice for backflow

The determination of the effects of a single vessel on sediment transport in the Waal river relies heavily on the impact of that vessel on the flow, specifically considering propeller jets and backflow (Sloff, 2022). In this Master's thesis, both the empirical and analytical approaches have been utilized to calculate the backflow. However, for the calculation of sediment transport, only on approach will be used. The empirical approach is favoured.

The decision to favour the empirical approach is based on the following considerations:

- Waterway width: As mentioned in Section 2.2.2, the analytical approach is applicable when the waterway's width is no more than 1.5 times the length of the vessel or falls within a ratio of 2 to 12 between waterway width and vessel width (Sloff, 2022). Given that the Waal river has a large width of approximately 150 meters, the empirical approach appears to be more suitable.
- River profile: It should be noted that the formulas mentioned earlier for the one-dimensional analytical approach are applicable to a rectangular cross-section of the river. However, in situations with a more trapezoidal profile, such as the Waal river, the resulting error is only a few percent (Sloff, 2022).

Considering these factors, the empirical approach is deemed more appropriate for the present study, as it more applicable for a river like the Waal.

3.4.4 Sediment transport

For the calculation of the sediment transport, caused by the propeller jets and backflow, the bed-load method of Van Rijn (1993) is used according to Section 2.3.3. The sediment transport induced by an average vessel through the Waal river equals a value of $3.09*10^{-5}$ m^2/s. A substantiation of the calculation for the sediment transport, caused by an average vessel (M8 Groot Rijnschip), is given in Table 15.

Table 15 Calculations sediment transport average vessel

Variable	Value	Unit
Particle parameter	69.05	[-]
Depth average bed-shear velocity	2.13	m/s
Critical bed-shear velocity	1.07	m/s
Bed-load transport	Pr	m^2/s

4. Effects of the entire bulk transport on the sediment transport in the Waal river

The previous chapter examined the influence of an M8 Groot Rijnschip (average vessel) on sediment transport in the Waal river. The objective was to quantify the sediment transport effects generated by an average vessel, focusing on the two primary impacts of inland shipping on the river's flow: propeller jets and backflow. To achieve this, calculations were conducted using the Python script that integrated the formulas representing these primary effects, along with ship data obtained from CoVadem.

Building upon those findings, this chapter delves further into the consequences of the entire bulk transport for sediment transport in the Waal river. The primary focus is to examine how the transportation of goods in large quantities impacts the movement of sediment within the Waal river. By understanding these effects, valuable insights into the complex dynamics of sediment transport in the Waal river will be gained.

4.1 Distribution annual bulk transport Waal river

Table 16 shows an overview of the annual bulk transport in the Waal river. This table is used to divide the annual bulk transport into three classes, ‘Small’, ‘Average’ and ‘Large’. This distribution is executed to simplify the amount of data. Gathering extensive information on each parameter of every vessel class would be a time-intensive task. This approach reduces the complexity of the dataset while still capturing the essential information needed to analyse and draw meaningful conclusions.

In Table 16 the three classes are shown. The distribution of the classes is based on the length of the vessels.

Table 16 List of 3 vessel classes through the Waal in 2009-2018 (M. Van de Ven, 2021)

RWS Klasse	Naam	CEMT Klasse	L (m)	Bs (m)	T (m) (max)	Aantal/ jaar	Aan-tal %	
M2	Kempenaar	II	50-55	6.6	2.6	4500	4	
M3	Hagenaar	III	55-70	7.2	2.6	5800	5	
M4	Dordtmund-Eems	III	67-73	8.2	2.7	6200	6	Small
M5	Verl. Dordtmund Eems	III	80-85	8.2	2.9	7700	7	
M6	Rijn-Herne schip	IVa	80-85	8.2	2.9	1900	2	
M7	Verlengd Rijn-Herne	IVa	105	9.5	3	5700	5	
M8	Groot Rijnschip	Va	110	11.4	3	43800	40	
M9	Verl. Groot Rijnschip	Va	135	11.4	3.5	10300	9	Average
M10	Maatg. Schip 13,5 * 110 m	VIa	110	13.5	4	1500	1	
M11	Maatg. Schip 14,2 * 135 m	VIa	135	14.2	4	4400	4	
M12	Rijnmax schip	VIa	135	17	4	3900	4	
BLL-4	4 baks duwstel		185-190	22.8	3.5-4	2800	3	
BLL-6l	6 baks duwstel lang (berg)		270	22.8	3.5-4	1300	1	
BLL-6b	6 baks duwstel lang (dal)		170-190	34.2	3.5-4	1300	1	Large
C3l	Koppelv. Va+Eur.II lang		170-190	11.4	3.5-4	5800	5	
C4	Koppelv. Va+3 Europa II		185	22.8	3.5-4	1900	2	

For each of the three classes, a reference vessel is taken to determine the impact of the annual bulk transport in the Waal river. The three classes with their reference vessel are distributed in Table 17. The distribution for the reference vessel for each of the classes is based on the average ‘RWS klasses’ of each class. For the classes ‘Small’ and ‘Large’ the calculations of the propellor jets, backflow (empirical approach) and sediment transport must be done like the calculations of the ‘Average’ class in section 3.

In total, there are approximately 100,000 vessel movements of 16 vessel types (as classified by the ‘RWS klasses’ in Table 16) traveling in both upstream and downstream directions through the Waal. The distribution of traffic in both directions is evenly divide (Sloff, 2022). Since only the downstream traffic (see section 3.1.3 for reasoning) is examined in this Master thesis, only 50% of the total traffic within the Waal river must be calculated.

Table 17 below shows the distribution used within this thesis which will be used to see the influence of sediment transport in the Waal river in downstream direction caused by the annual bulk transport.

Table 17 Distribution of the three classes for downstream movement with their reference vessel

Class	Reference vessel	CEMT Class	L (m)	Bs (m)	T (m)	Vessels/year	%
Small	M4 Dordtmund-Eems	III	73	7.5	2.7	13050	12
Average	M8 Groot Rijnschip	Va	110	11.4	3.0	34800	32
Large	BLL-6b 6 Baks Duwstel lang		190	22.8	3.8	6550	6

4.2 Parameter values

This section examines the parameters associated with propeller jets, backflow (empirical approach), and sediment transport for two categories of vessels: 'Small' and 'Large'. As stated in Section 3, all the parameters relevant to the Python model concerning the 'Average' class (M8 Groot Rijnschip) were gathered. The same process is repeated for the 'Small' and 'Large' vessel classes. The reference vessel for the ‘Small’ class is an M4 Dordtmund-Eems, which is equal to shipid 68 from the CoVadem data. The reference vessel for the ‘Large’ class is a 6 Baks Duwstel lang, which is equal to shipid 2 from the CoVadem data. For the propellor jets of the ‘Large’ class it is important to mention that 2 propellors are included.

The parameter values for the ‘Small’ and ‘Large’ class are included in Appendix C. Parameter values small and large vessel.

4.3 Results

This section shows the results of the influence of an M4 Dordtmund-Eems and a 6 Baks Duwstel lang on the flow in water regarding propeller jets and the backflow calculated by the Python model. Besides, the sediment transport is calculated. The backflow is presented with the empirical approach only.

4.3.1 Propeller jets

The results are achieved by combining the formulas from Section 2.2.1 with the parameters from Appendix C. Parameter values small and large vessel. Figure 11 shows the return velocity values ($V_{b,max,0}$) of an M4 Dordtmund-Eems through the Waal with Deest as starting location and Druten as end location because of propeller jets. The objective of selecting a vessel travel from CoVadem corresponding to the same conditions of the average vessel discussed in Section 3.4 was challenging. Due to limited available data from CoVadem concerning the reference ship of an M4 Dortmund-Eems, it was not possible to find a travel at the exact time and date of the average vessel. The same challenge was encountered for other types that belong to the smaller vessel types. Hence, selecting a different ship type was not a viable solution.

Although the data was taken from the same year, 2019, the specific date and time varied between the two vessel travels. The M4 Dortmund-Eems ship journey occurred in early February, towards the end of the afternoon (16:17), while the average M8 Groot Rijnschip's travel took place at the beginning of January, towards the end of the night (23:57). Such differences in time and date could lead to variations in water depths, potentially influenced by factors like varying rainfall and thus no equal conditions. Like the average vessel, the fluctuations in return velocity values for the M4 Dortmund-Eems ship, ranging between 0.3 and 0.8 m/s, were attributed to the changes in keel clearance during the travel. This because other parameters related to propeller jets remained relatively stable throughout the vessel's travel.

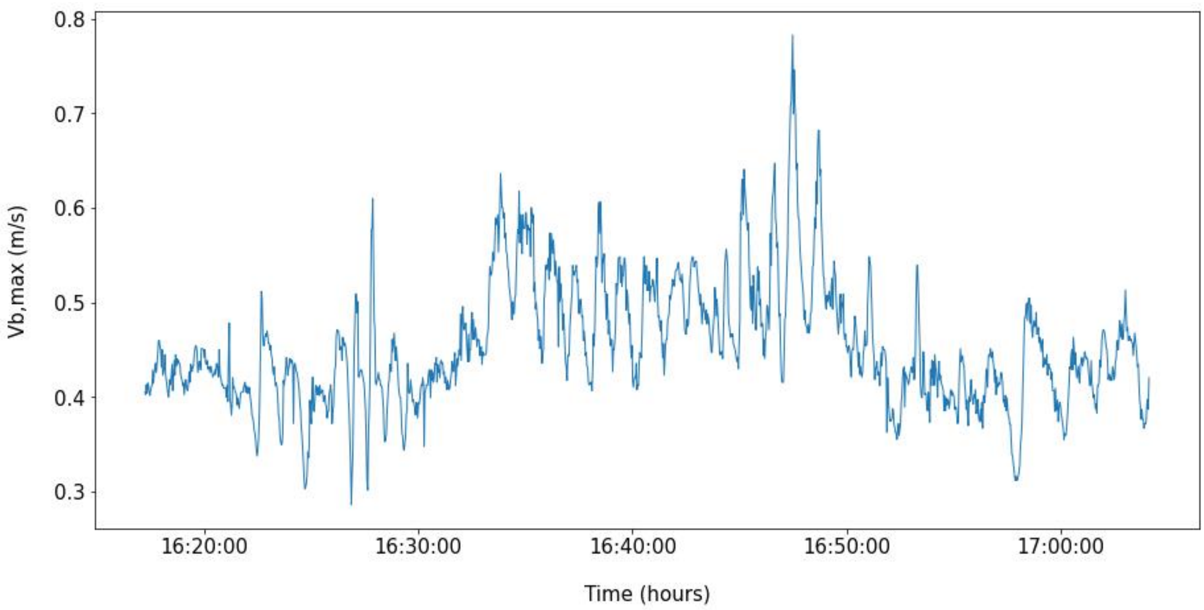

Figure 11 Propeller jet velocity M4 Dordtmund-Eems

Table 18 shows the values for the maximum velocity behind the vessel at the riverbed ($V_{b,max,0}$)

Table 18 Values propeller jet M4 Dordtmund-Eems

Description	Value
Shipid CoVadem	68
Vessel class	'Small'
Start Location	Deest
End Location	Druten
Date	2019-02-03 till 2019-02-03
Time	16:17:15 till 17:04:07
Stream	Downstream
Datapoints	1406
Average $\boldsymbol{V_{b,max,0}}$	0.48 m/s
Minimum $\boldsymbol{V_{b,max,0}}$	0.28 m/s
Maximum $\boldsymbol{V_{b,max,0}}$	0.78 m/s

Figure 12 shows the return velocity values ($V_{b,max,0}$ of a 6 Baks Duwstel lang through the Waal with Deest as starting location and Druten as end location because of propeller jets. The objective of selecting a vessel travel from CoVadem corresponding to the same conditions of the average vessel discussed in Section 3.4 was challenging. For the large class of vessels, finding a comparable travel situation was relatively easier, as the deviation in time was only 1.5 days, and the journey took place in the afternoon. Although there might still have been some differences in weather conditions that could potentially influence the water depth and, consequently, the results, the impact is less likely compared to the small class of vessels. Like the average vessel, the fluctuations in return velocity values for the 6 Baks Duwstel lang, ranging between 0.8 and 1.7 m/s, were attributed to the changes in keel clearance during the travel.

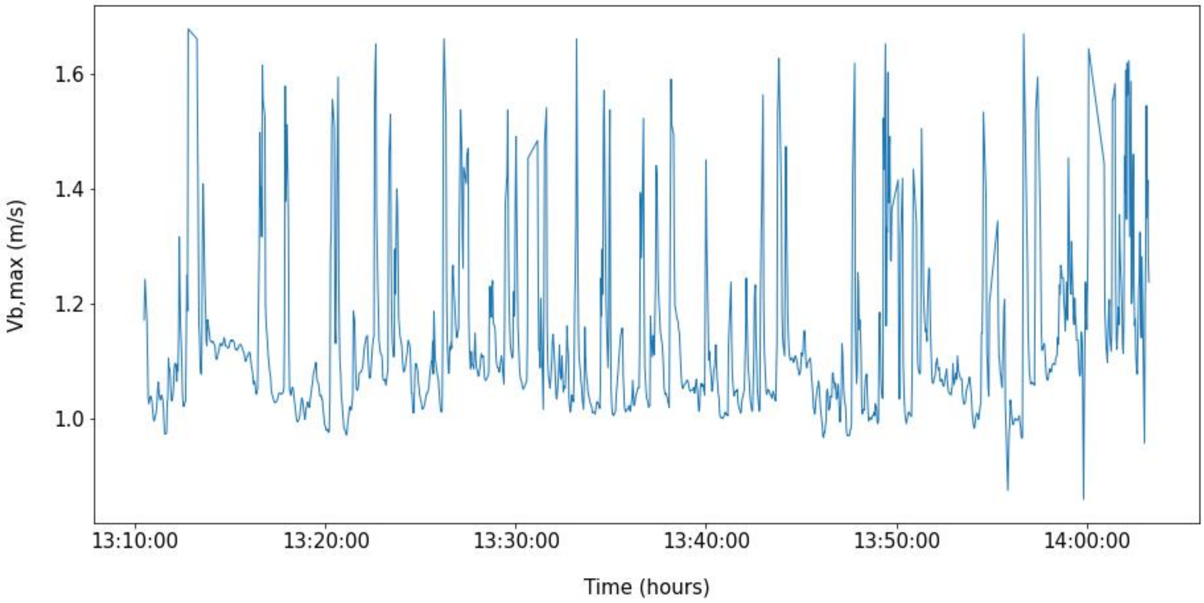

Figure 12 Propeller jet velocity 6 Baks Duwstel lang

Table 19 shows the values for the maximum velocity behind the vessel at the riverbed ($V_{b,max,0}$).

Table 19 Values propeller jet 6 Baks Duwstel lang

Description	Value
Shipid CoVadem	2
Vessel class	'Large'
Start Location	Deest
End Location	Druten
Date	2019-01-02 till 2019-01-02
Time	13:10:28 till 14:03:17
Stream	Downstream
Datapoints	1435
Average $\boldsymbol{V_{b,max,0}}$	1.12 m/s
Minimum $\boldsymbol{V_{b,max,0}}$	0.86 m/s
Maximum $\boldsymbol{V_{b,max,0}}$	1.68 m/s

4.3.2 Backflow

Figure 13 shows the return velocity values ($U_{rb,max}$) of an M4 Dortmund Eems vessel through the Waal with Deest as starting location and Druten as end location because of the backflow (empirical approach). The results are achieved by combining the formulas from Section 2.2.2 with the parameters from Appendix C. Parameter values small and large vessel The reason why the return velocity values deviate between 0.3 and 0.9 m/s is devoted to the fluctuations in the water depth during the travel of the vessel. The other parameters regarding the backflow (empirical approach) remained almost constant.

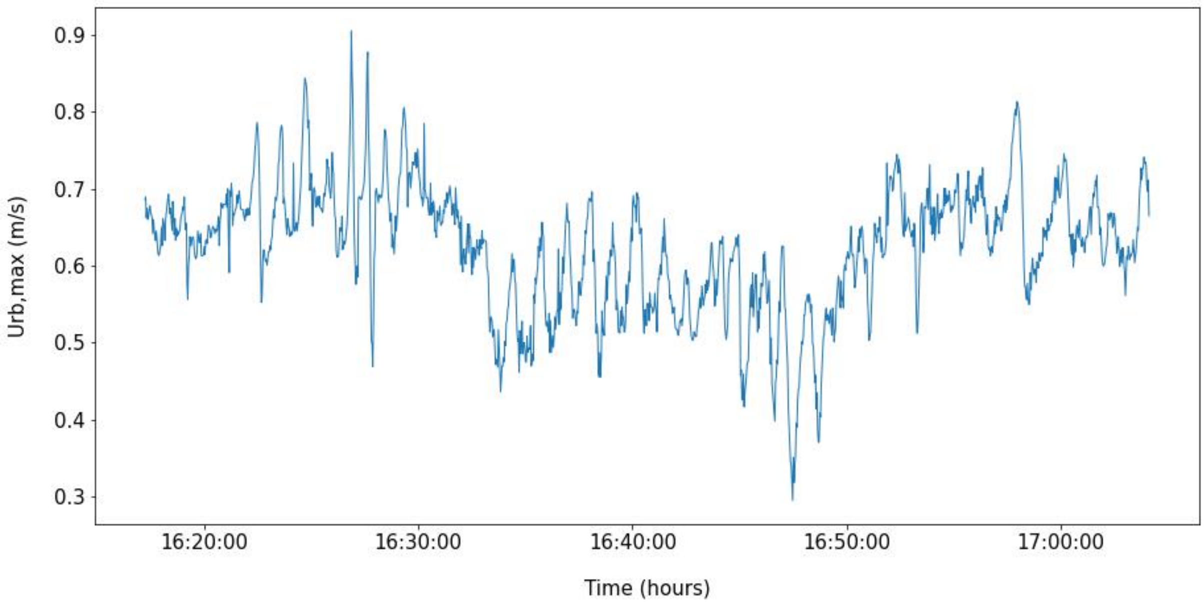

Figure 13 Backflow velocity for an M4 Dordtmund-Eems

Table 20 shows an overview of important values regarding the calculations for the maximum return current velocity ($U_{rb,max}$) along the vessel.

Table 20 Values backflow (empirical solution) for an M4 Dordtmund-Eems

Description	Value
Shipid CoVadem	68
Vessel class	'Small'
Start Location	Deest
End Location	Druten
Date	2019-02-03 till 2019-02-03
Time	16:17:15 till 17:04:07
Stream	Downstream
Datapoints	1406
Average $\boldsymbol{U_{rb,max}}$	0.64 m/s
Minimum $\boldsymbol{U_{rb,max}}$	0.29 m/s
Maximum $\boldsymbol{U_{rb,max}}$	0.90 m/s

Figure 14 shows the return velocity values ($U_{rb,max}$) of a 6 Baks Duwstel lang vessel through the Waal with Deest as starting location and Druten as end location because of the backflow (empirical approach). The results are achieved by combining the formulas from Section 2.2.2 with the parameters from Appendix C. Parameter values small and large vessel. The reason why the return velocity values deviate between 2.5 and 3.0 m/s is devoted to the fluctuations in the water depth during the travel of the vessel. The other parameters regarding the backflow (empirical approach) remained almost constant. However, the fluctuations are much smaller compared to the fluctuations of the average and large vessels. A more constant water depth is probably the reason.

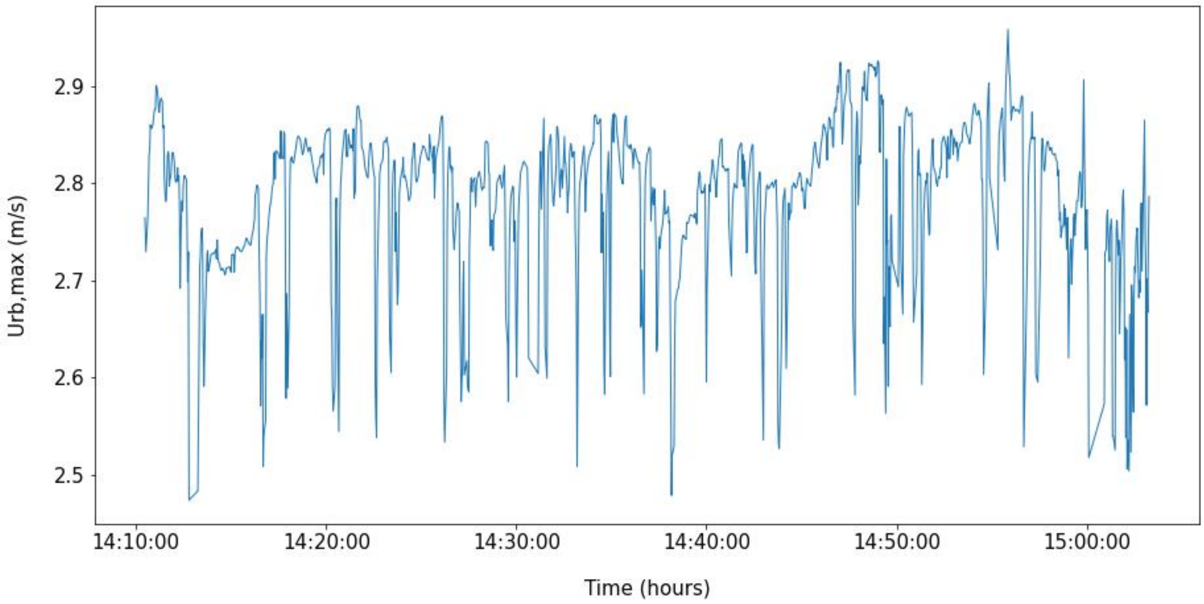

Figure 14 Backflow velocity for a 6 Baks Duwstel lang

Table 21 shows an overview of important values regarding the calculations for the maximum return current velocity ($U_{rb,max}$) along the vessel.

Table 21 Values backflow (empirical solution) for a 6 Baks Duwstel lang

Description	Value
Shipid CoVadem	2
Vessel class	'Large'
Start Location	Deest
End Location	Druten
Date	2019-01-02 till 2019-01-02
Time	13:10:28 till 14:03:17
Stream	Downstream
Datapoints	1435
Average $\boldsymbol{U_{rb,max}}$	2.79 m/s
Minimum $\boldsymbol{U_{rb,max}}$	2.47 m/s
Maximum $\boldsymbol{U_{rb,max}}$	2.96 m/s

In conclusion, the results showed the effects of propeller jets and backflow caused by inland shipping in the Waal river. Both factors impact the riverbed since they cause a return current velocity These return current velocities are $V_{b,max,0}$ for the propeller jets and $U_{rb,max}$ for the backflow. As expected, the 'Small' ship type (M4 Dordtmund-Eems) exhibited the smallest return current velocities, while the 'Large' vessel type (6 Baks Duwstel Lang) showed the largest velocities. This difference can be attributed to the variable values, which were lower for the smaller ship type and higher for the larger ship type, as stated in Appendix C. Parameter values small and large vessel.

The return current velocities for the backflow were smaller compared to those for the propeller jets, as expected based on the literature by (Sloff, 2022). The results revealed that there were fluctuations in the return current velocities for both ship types. The 'Small' vessel type had higher fluctuations compared to the 'Large' vessel type. This difference could be attributed to the position of the ships in the Waal river. Smaller vessel types tended to move closer to the side of the river, while larger vessels gravitated towards the middle. Consequently, both ship types encountered varying water depths and keel clearances during their travels between Deest and Druten.

4.3.3 Sediment transport bulk transport

The bulk transport consists of the all the three vessel types as referred to in Table 17. The sediment transport caused by the 'Average' vessel is elaborated in Section 3.4.4. This section shows the values that were calculated for the sediment transport calculation for both the 'Small' and 'Large' vessel types. The sediment transport, which is caused by the return current velocities of the propeller jets and backflow, is calculated according to the bed-load method of Van Rijn (1993) in Table 22 and Table 23.

Small class

Table 22 Calculations sediment transport small vessel

Variable	Value	Unit
Particle parameter	69.05	[-]
Depth average bed-shear velocity	1.12	m/s
Critical bed-shear velocity	1.07	m/s
Bed-load transport	$7.07*10^{-7}$	m^2/s

Large class

Table 23 Calculations sediment transport large vessel

Variable	Value	Unit
Particle parameter	69.05	[-]
Depth average bed-shear velocity	3.91	m/s
Critical bed-shear velocity	1.07	m/s
Bed-load transport	$1.52*10^{-4}$	m^2/s

With the individual sediment transport for each vessel type being calculated, the total annual sediment transport in the Waal river can be calculated with the information of Table 17. Table 24 shows the total annual sediment transport by the bulk transport in the Waal river.

Table 24 Total annual sediment transport (downstream) by bulk transport in the Waal river

Class	Sediment transport [m^2/s]	Sediment transport [m^2/trip/vessel]	Amount of vessels [vessel/year]	Annual sediment transport by bulk transport [m^2/year]
Small	$7.07*10^{-7}$	0.042	13050	$5.48*10^{2}$
Average	$3.09*10^{-5}$	1.82	34800	$6.33*10^{4}$
Large	$1.52*10^{-4}$	8.97	6550	$5.88*10^{4}$
Total annual sediment transport by bulk transport (Downstream)				$\mathbf{1.23*10^{5}}$

5. Sensitivity analyses

In this section, a sensitivity analysis was conducted to gain insights into the most influential parameters that can affect sediment transport. The focus was on examining the effects of the propeller jets and the backflow in this analysis.

There are various ways to do a sensitivity analyses. Two approaches were considered. The first considered approach is to systematically vary each parameter individually with the same amount (adding and subtracting 10%) while keeping the others constant. This approach allows to observe the isolated impact of each parameter on sediment transport. By analysing variations in the impact of every individual parameter, it is possible to understand the relative importance of each parameter and its contribution to sediment transport. Furthermore, this approach allows to identify the most influential parameter when every parameter gets influenced equally (adding and subtracting 10%). The second considered approach has the same base but is slightly different. This involved systematically varying each parameter individually based on the possible impacts while keeping the other parameters constant. So the individual variations would differ for every parameter based on logical substantiations and are not the same as the previous approach. By doing so, the isolated impact of each parameter on sediment transport can be shown. This approach allows to identify the relative importance of individual parameters and understand their specific contributions to the overall process.

Both approaches have their advantages and would provide a good comparison of the influence of each parameter. However, the goal of this sensitivity analysis was to identify the most influential parameters. To achieve this, it is then crucial to have consistent adjustments applied to all parameters. Therefore, the first approach, which involved adding or subtracting 10% from the original parameter values to observe the effects on sediment transport, was chosen. Besides, to determine a logical variance for each parameter concerning the second approach introduces objectivity and is therefore not desirable.

To study the effects on an individual vessel, it was necessary to select a reference vessel. The chosen reference vessel for the sensitivity analyses is the M8 Groot Rijnschip, representing the average single vessel. Again, this vessel is the most frequently observed type in the Waal river, accounting for 43,800 vessel movements annually, which constitutes to 40% of all primary shipping classes presented in Table 11.

In the sensitivity analyses only influential variable parameters were tested. For the propeller jets, two variable parameters were tested. These parameters were the power efficiency rate (η) and the keel clearance (ukc). Both parameters were examined to understand their impact of the propeller jets with regards to the riverbed. For the backflow (regarding the empirical approach) also two variable parameters were tested. These parameters were the vessel width (B_s) and vessel velocity (V_s). Subsequently, the results have been listed in a table and conclusions have been elaborated.

In addition to performing a sensitivity analysis to assess the influence of variable parameters, the effects of climate change have also been examined. Climate change plays a significant role in river conditions with regards to the discharge and water depth, consequently affecting the keel clearance of vessels (Mens, 2022). To simulate extreme dry conditions, the keel clearance of the reference vessel was reduced. Besides, recommendations have been formulated for Rijkswaterstaat to address sediment transport in preparation for potential future scenarios.

5.1 Propeller jets

The results of the sensitivity analyses for both the power efficiency rate (η) and the keel clearance (ukc) regarding the propeller jets are illustrated below. The original values from Figure 8 are excluded to improve the readability of Figure 15 and Figure 16.

Power efficiency rate

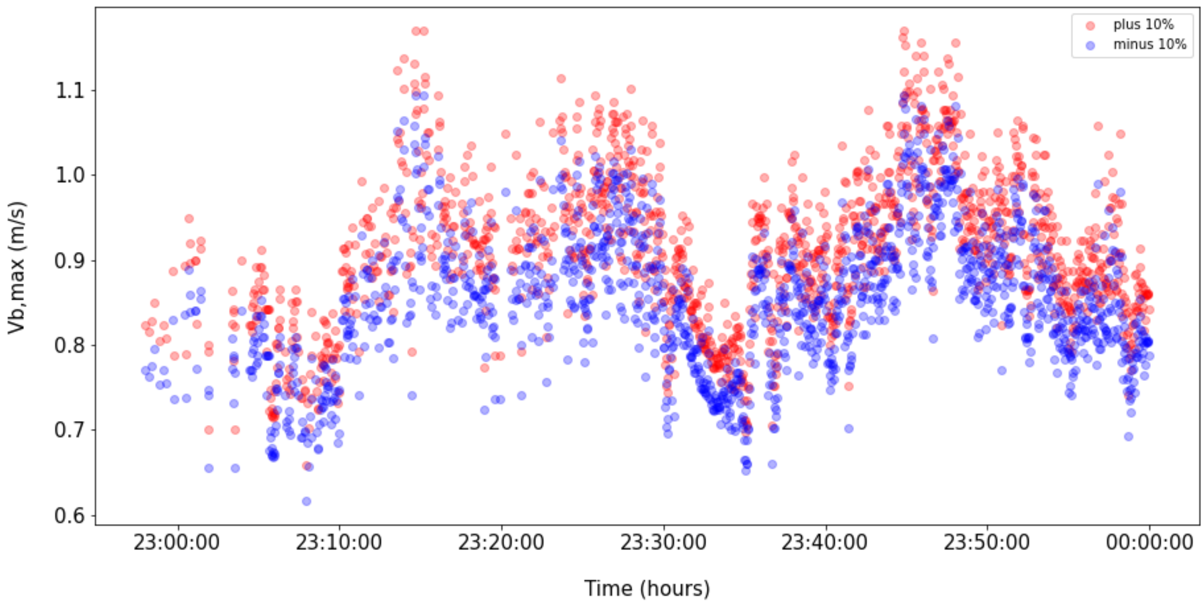

Figure 15 Sensitivity power efficiency rate (Propeller jets)

Table 25 below shows the quantitative effects of the sensitivity of the power efficiency rate compared to the original (Normal) situation for $V_{b,max,0}$.

Table 25 Variations in return current velocities due to power efficiency rate (Propeller jets)

	Normal	**Minus 10%**	**Plus 10%**
Average $\boldsymbol{V_{b,max,0}}$	0.88	0.85 (-3.4%)	0.91 (+3.4%)
Minimum $\boldsymbol{V_{b,max,0}}$	0.64	0.62 (-3.1%)	0.66 (+3.1%)
Maximum $\boldsymbol{V_{b,max,0}}$	1.13	1.09 (-3.5%)	1.17 (+3.5%)

Keel clearance

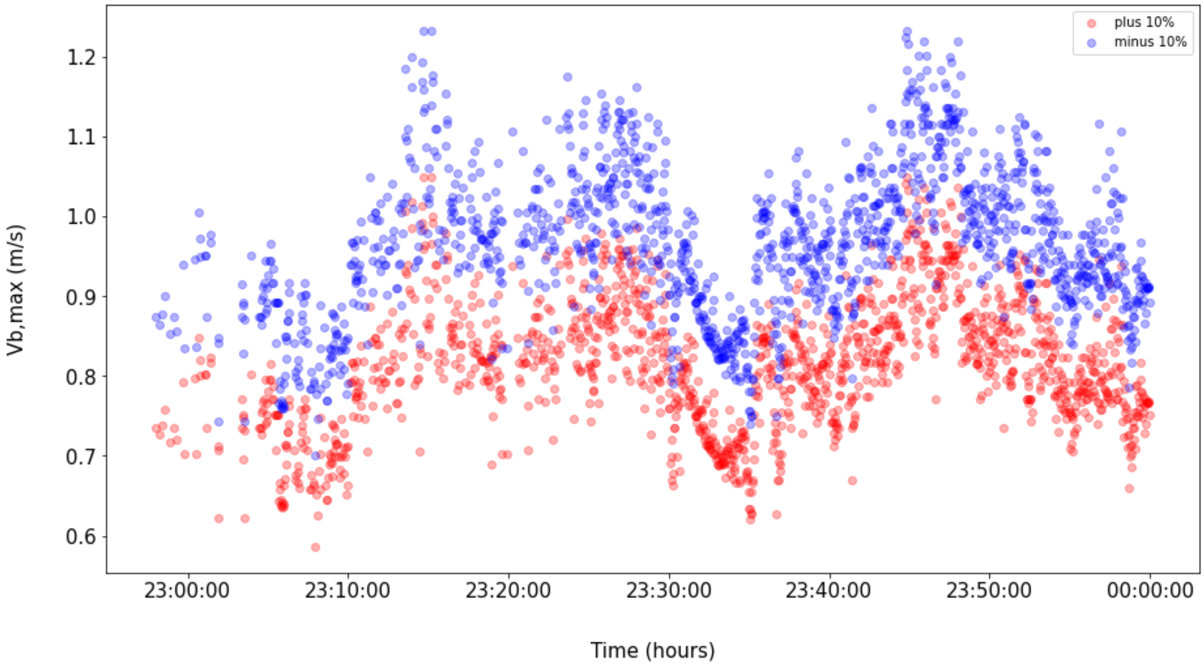

Figure 16 Sensitivity keel clearance (Propeller jets)

Table 26 below shows the quantitative variations of the sensitivity of the keel clearance compared to the original (Normal) situation for $V_{b,max,0}$.

Table 26 Variations in return current velocity due to keel clearance (Propeller jets)

	Normal	**Minus 10%**	**Plus 10%**
Average $\boldsymbol{V_{b,max,0}}$	0.88	0.97 (+10.2%)	0.82 (-6.8%)
Minimum $\boldsymbol{V_{b,max,0}}$	0.64	0.70 (+9.4%)	0.59 (-7.8%)
Maximum $\boldsymbol{V_{b,max,0}}$	1.13	1.23 (+8.8%)	1.05 (-7.1%)

5.2 Backflow

The results of the sensitivity analyses for the vessel width (B_s) regarding the backflow (empirical approach) are illustrated below. The original values from Figure 8 are excluded to improve the readability of Figure 17 and Figure 18.

Vessel width

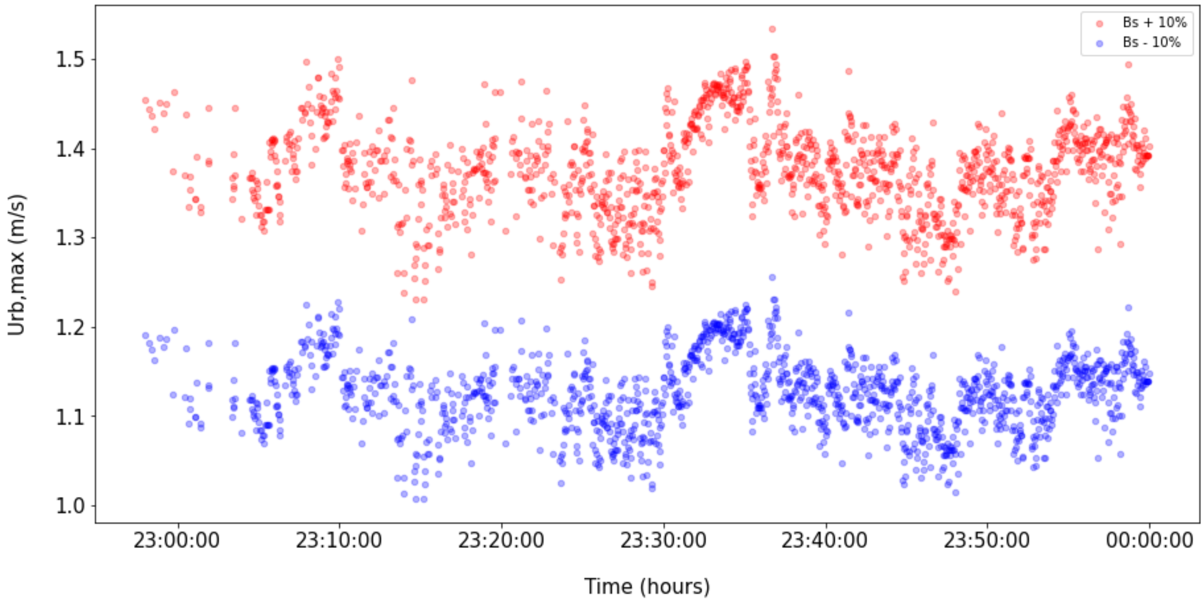

Figure 17 Sensitivity analyses vessel width (Backflow)

Table 27 below shows the quantitative variations of the sensitivity of the vessel width compared to the original (Normal) situation for $U_{rb,max}$.

Table 27 Variations in return current velocity due to vessel width (Backflow)

	Normal	Minus 10%	Plus 10%
Average $U_{rb,max}$	1.25	1.12 (-10.4%)	1.38 (+10.4%)
Minimum $U_{rb,max}$	1.12	1.00 (-10.7%)	1.23 (+9.8%)
Maximum $U_{rb,max}$	1.39	1.26 (-9.6%)	1.53 (+10.1%)

Vessel velocity

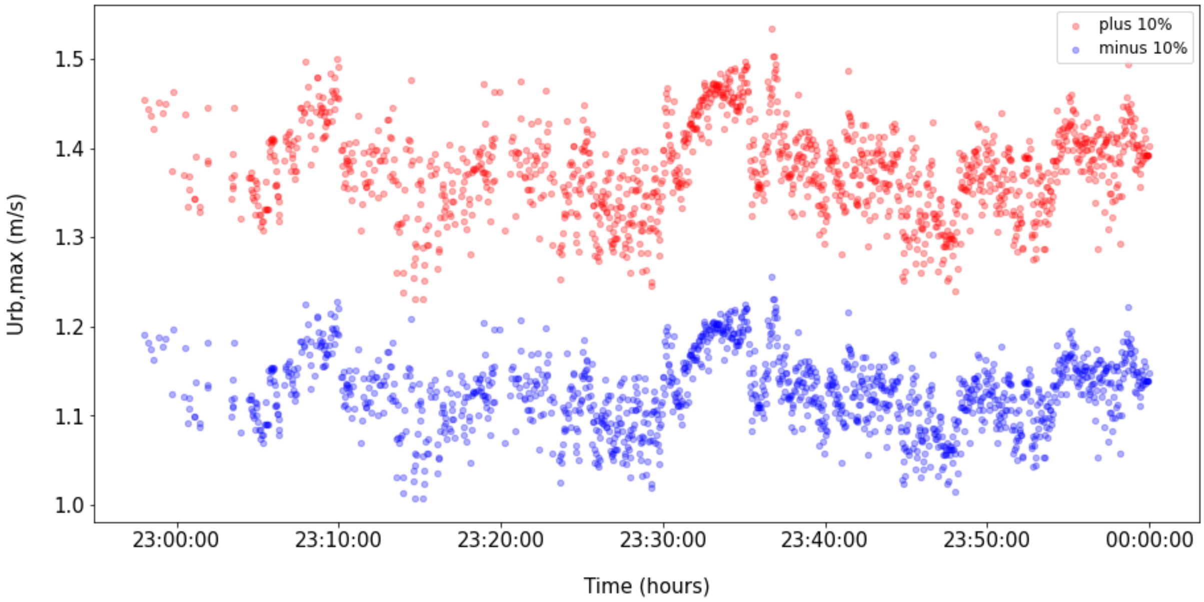

Figure 18 Sensitivity analyses vessel velocity (Backflow)

Table 28 below shows the quantitative variations of the sensitivity of the vessel velocity compared to the original (Normal) situation for $U_{rb,max}$.

Table 28 Variations in return current velocity due to vessel velocity (Backflow)

	Normal	**Minus 10%**	**Plus 10%**
Average $\boldsymbol{U_{rb,max}}$	1.25	1.13 (-9.6%)	1.37 (+9.6%)
Minimum $\boldsymbol{U_{rb,max}}$	1.12	1.02 (-8.9%)	1.22 (+8.9%)
Maximum $\boldsymbol{U_{rb,max}}$	1.39	1.25 (-10.1%)	1.53 (+10.1%)

5.3 Results sensitivity analyses

Figure 19 illustrates a histogram which gives an overview of the sensitivity of the variable parameters ‘Power efficiency rate’, ‘Keel clearance’, ‘Vessel width’ and ‘Vessel velocity’. The ‘Power efficiency rate’ and the ‘Keel clearance’ were tested regarding the propeller jets. The ‘Vessel width’ and ‘Vessel velocity’ were tested regarding the backflow calculated by the empirical approach. It is important to mention that for the ‘Normal’ values, the average values are used.

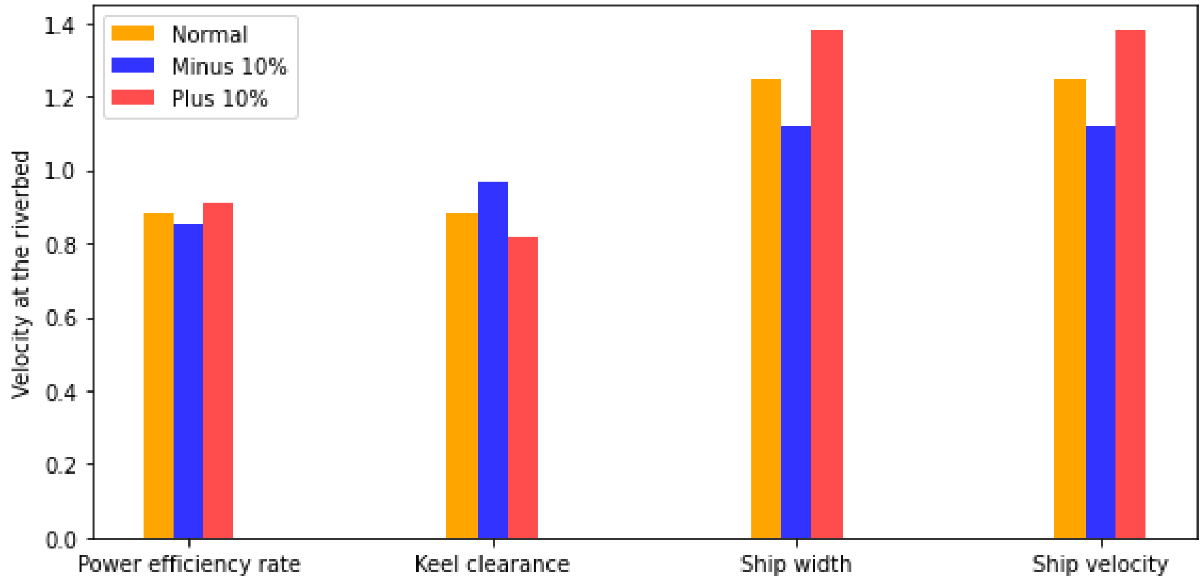

Figure 19 Histogram sensitivity analyses for variable parameters

The power efficiency rate showed small linear variations for both a decrease (minus 10%) and increase (plus 10%) of the parameter. The average value of the velocity from the propeller jets decreased with 3.4% once the rate got reduced with 10%. The average value of the velocity from the propeller jets increased with 3.4% once the rate got increased with 10%. The keel clearance showed reasonably large variations for both a decrease (minus 10%) and increase (plus 10%) of the parameter. It also showed a reverse effect compared to the power efficiency rate. The average value of the velocity from the propeller jets increased with 10.2% once the keel clearance got reduced with 10%. The average value of the velocity from the propeller jets decreased with 6.8% once the keel clearance got increased with 10%.

For the backflow the effects of the vessel width and velocity the effects were linear. However, the variations were larger compared to the variations for the propeller jet. The reason for this is because the return current values of the backflow are larger compared to values for the propeller jet. The average value of the velocity from backflow decreased with 10.4% once the vessel width got reduced with 10%. The average value of the velocity from the backflow increased with 10.4% once the width got increased with 10%. The same happened to the sensitivity for the vessel velocity. The average value of the velocity from backflow decreased with 9.6% once the velocity got reduced with 10%. The average value of the velocity from the backflow increased with 9.6% once the velocity got increased with 10%. The values are summarized in Table 29.

Table 29 Results sensitivity analyses

	Normal	**Minus 10%**	**Plus 10%**
Propeller jets ($V_{b,max,0}$)			
Power efficiency rate	0.88	0.85 (-3.4%)	0.91 (+3.4%)
Keel clearance	0.88	0.97 (+10.2%)	0.82 (-6.8%)
Backflow ($U_{rb,max}$)			
Vessel width	1.25	1.12 (-10.4%)	1.38 (+10.4%)
Vessel velocity	1.25	1.13 (-9.6%)	1.37 (+9.6%)

5.4 Sediment transport in extreme conditions

It should be mentioned that the keel clearance also has an impact on the backflow. The keel clearance affects both the propeller jets and backflow. In the previous section, the keel clearance was only tested within the sensitivity analyses for the propeller jets and not the backflow. This section shows the importance of the keel clearance for inland shipping with regards to sediment transport. Especially climate change plays a huge role in the water depth and thus the keel clearance of a vessel. Due to climate change, the water demand increases as summers get drier and hotter (Mens, 2022). The severe rainfall deficits in the dry summers influence crops, leads to increasing fire risks and results in lower river discharges. These low river discharges of the last couple of years in the Netherlands qualify as extreme events in the current climate but they may become more frequent in the future (Mens, 2022). As a result of these extreme events, the water depth within the Waal river decreases. A decrease in the water depth also means a decrease in keel clearance. This has consequences for the shipping industry.

Figure 20 illustrates the difference between the original situation (orange) and an extreme dry event (blue) in which the keel clearance (because of a lower water depth) got reduced by 1.0 meters. The original situation originated from section 3.4.1 in which the average vessel 'M8 Groot Rijnschip' was used with regards to the propeller jets.

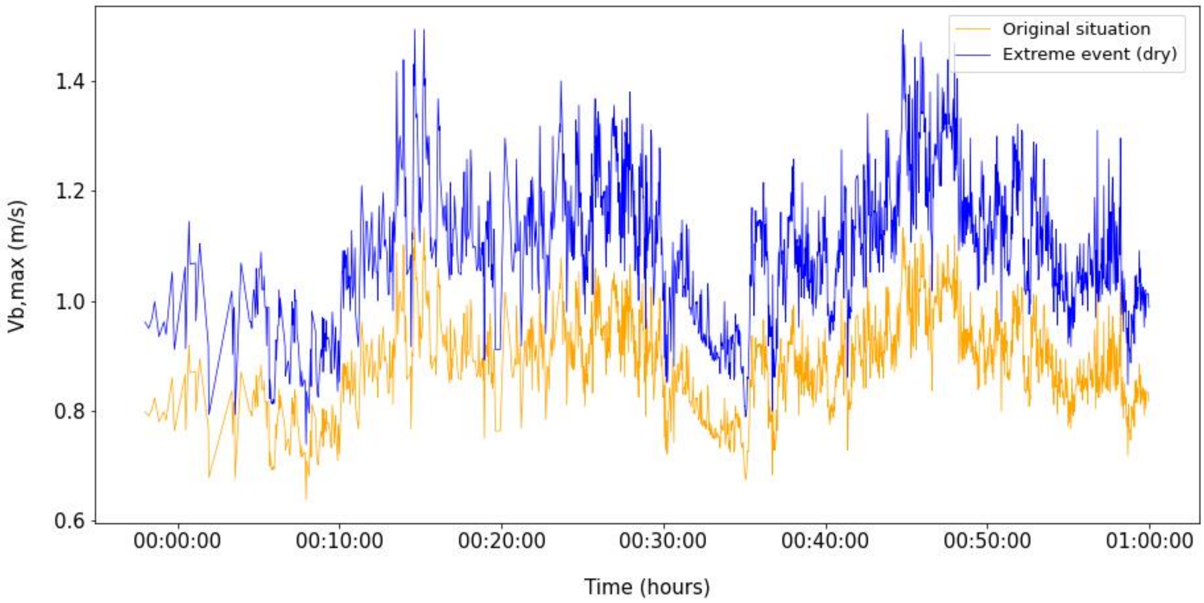

Figure 20 Effect keel clearance in dry conditions on return current velocity by propeller jets

Table 30 below shows the average return current velocity value with regards to the propeller jets for the normal situation and an extreme dry event in which the keel clearance got reduced with 1.0 meter.

Table 30 Average values return current velocity due to propeller jets in an extreme dry event

Propeller jets ($V_{b,max,0}$)	**Normal**	**Extreme dry**
Keel clearance	0.88	1.09 (+23.7%)

Figure 21 illustrates the difference between the original situation (orange) and an extreme dry event (blue) in which the keel clearance (because of a lower water depth) gets reduced by 1.0 meters. The original situation originated from section 3.4.2 in which the average vessel 'M8 Groot Rijnschip' was used with regards to the backflow.

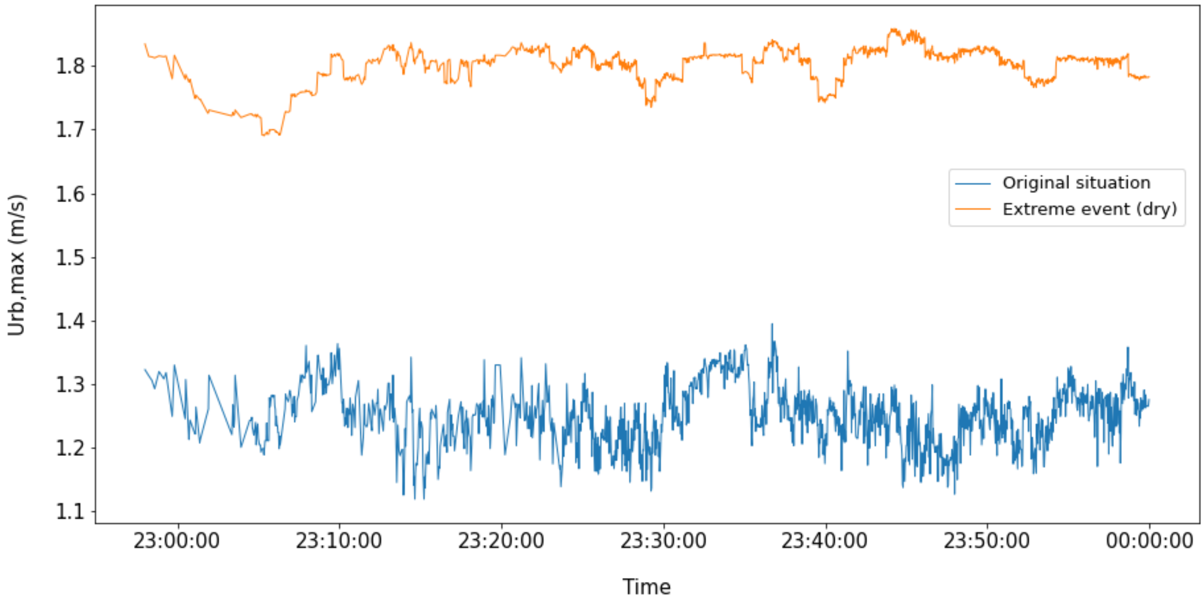

Figure 21 Effect keel clearance in extreme dry conditions on return current velocity by backflow

Table 31 below shows the average return current velocity value with regards to the backflow for the normal situation and an extreme dry event in which the keel clearance got reduced with 1.0 meter.

Table 31 Average values return current velocity due to backflow in an extreme dry event

Backflow ($U_{rb,max}$)	**Normal**	**Extreme dry**
Keel clearance	1.25	1.74 (+39.2%)

The increased return current velocities impact the grain-shear velocity (u'_*) with regards to the sediment transport. The new grain-shear velocity is calculated below in equation [25]:

$$u'_* = 1.09 + 1.74 = 2.83\ m/s \qquad [25]$$

The bed-load transport for the particles is calculated as follows in equation [26]:

$$q_b = 0.005 * (2.83)6.45 \left(\frac{2.83\ - 1.07}{[(2.65-1)*9.81*2.73*10^{-3}]^{0.5}}\right)^{2.4} \left(\frac{2.73*10^{-3}}{6.45}\right)^{1.2} \qquad [26]$$

$$q_b = 8.68 * 10^{-5}\ m^2/s$$

For an average vessel the sediment transport, according to Van Rijn (1993), is equal to 8.68*10^{-5} m^2/s in an extreme event in which the keel clearance got reduced with 1.0 meter. This is an increasement of 181% compared to normal conditions (3.09*10^{-5} m^2/s).

5.5 Recommendations for managing sediment transport

Based on the outcomes shown in Table 29, it is evident that the chosen variable parameters significantly impact sediment transport according to the sensitivity analyses.

To manage these sediment transports, certain actions can be taken, and practical measures can be implemented to provide Rijkswaterstaat and the users of the Waal with strategies to address a too much sedimentation in the future. These measures for the variable parameters are listed below. The variable parameters are ordered by their impact on sediment transport.

1. Reducing the vessel width:
    - Encouraging the utilization of smaller vessels would be beneficial. This could involve promoting the use of vessels with narrower dimensions, which would decrease their impact on the waterway.

2. Decreasing the vessel velocity:
    - Implementing speed limits along specific sections of the waterway, particularly in areas where sedimentation or erosion poses a concern, can be a measure. By enforcing lower speeds, the disturbance caused by the vessel's movement can be minimized, reducing the likelihood of sedimentation.

3. Modifying composition of riverbed
    - Modifying the composition of the riverbed by introducing heavier sediment particles can also help minimize sediment transport. This alteration would impede the movement of finer sediment, reducing the occurrence of sedimentation.

4. Lowering the power efficiency rate:
    - Like the approach for reducing vessel velocity, enforcing speed limits at critical points along the waterway can help mitigate the impact of high-power efficiency rates. By slowing down vessels, the energy exerted and subsequent disturbance to sediment can be decreased.
    - Supporting the use of smaller vessels not only aids in reducing vessel width but also contributes to lowering the power efficiency rate. Smaller vessels generally require less power to operate, resulting in reduced disturbances and sedimentation risks.

Overall, implementing these measures such as promoting smaller vessels, enforcing speed limits and modifying the riverbed can help to manage sediment transport in the future and assist Rijkswaterstaat and Waal river users in managing an overload of sediment transport effectively. However, sediment transport is also useful in rivers. Rivers need sediment to counteract subsidence, future sea level rise and channel incision that destabilizes infrastructure (Cox et al., 2021).

An important aspect of this section is assessing the feasibility of the proposed measures. The approach to reduce the vessel width could be conducted by encouraging shippers the use smaller ships when possible. The option to decrease the vessel velocity at specific points along the Waal river where sedimentation could become problematic is in line with the solution of lowering the power rate of the ships. However, it's important to note that implementing these three measures could have financial implications for transportation of goods and, consequently, shippers. Among the proposed methods, modifying the composition of the riverbed at certain points where sedimentation is a significant issue emerges as the most practical option for Rijkswaterstaat. Nonetheless, one potential downside is the possibility of high costs associated with such modifications. Careful consideration of the economic implications is necessary while evaluating the most suitable course of action.

6. Discussion

The discussion section focused on the analysis and evaluation of the research model and its results. This involves a careful examination of the limitations inherent in the model, which arise from simplifications and assumptions made during its development. Additionally, the discussion compared existing literature with the findings of this study.

6.1 Limitations

The limitations within this discussion section are divided over a couple of main parts of this Master thesis and listed below. The parts are the data, the general model, the propeller jets, the backflow, the sediment transport and the sensitivity analyses.

Data

- The CoVadem data utilized in the study was not consistently accurate. Prior to its integration into the model, the data had to undergo a filtering process. This was necessary because certain measurements of the water depth and keel clearance exhibited values of zero or close to 100 meters, which are unrealistic and likely due to measurement errors associated with the multibeam technology. Consequently, the data was filtered to remove these anomalies. Because of the filtering process, gaps or missing data points were observed in certain instances, as evident from the plotted results. The impact of this filtering is clear in Figure 8, Figure 9 and Figure 10. Namely, a noticeable gap in the data points can be observed between 00:00:00 and 00:10:00, indicating missing data during that time interval.
- The selected vessels for the three shipping classes in CoVadem's dataset did not travel along the exact same route within the Waal river. It was not possible to find vessels that had the exact start/end location and position in the Waal. Thereby, heavily loaded vessels from the class 'Large' may deviate from this route to navigate through deeper parts of the river. Although, efforts were made to obtain data that corresponds to the same location as the CoVadem data, it is challenging to precisely synchronize the data collection process. For the selected data, Deest was consistently designated as the starting location, while Druten served as the end destination. All this may have led to differences in water depth and keel clearance among the different kind of vessel classes 'Small', 'Average' and 'Large'.
- The used CoVadem data also showed variations in the collection date/time of the vessels' data. These differences could lead to variations in water depth because climate influences like for example wind and or draught or wet periods subsequently affects the keel clearance when comparing the 3 shipping classes. Also this may have led to differences in water depth and keel clearance among the different kind of vessel classes 'Small', 'Average' and 'Large'.

Model

- The formulas used within Python assumed steady and uniform 2-dimensional flow conditions.
- The model focused solely on the impact of downstream traffic on the Waal river, due to a lack of data in the upstream direction.
- The model employed in this study utilized a simplification method to estimate the bulk transport in the Waal river. In total, there are approximately 100,000 vessel movements of 16 vessel types (as classified by the 'RWS klasses') traveling in both upstream and downstream directions through the Waal. The distribution of traffic in both directions is evenly divided (Sloff, 2022). Due to the time constraints of this Master thesis, it was not feasible to calculate the effects of each vessel type individually, as it would require extensive time to gather values for all the parameters involved. Therefore three main classes were taken ('Small', 'Average' and 'Large') and for every class a reference vessel was taken to limit the time for gathering the values of the parameters.

Propeller jets

- Larger vessels contain thrusters to provide sideward motion for a vessel. In this study only the propeller jets are included because there is only forward motion needed between the locations of Deest and Druten. Besides, the influence of the thrusters is relatively small since the jets mostly occur at the stern side due to the main propellers.
- The variable horizontal distance for every chosen vessel is set at 10 meters based on the work of Guarnieri et al. (2021). It is possible that this distance varies for different vessel types and their propellers.

Backflow

- In this Master's thesis, two approaches for analysing the backflow were explored: the empirical approach and the analytical approach. After careful consideration, the empirical approach was ultimately chosen over the analytical approach due to the following limitations:

  1. Waterway width: The analytical approach is suitable for waterways with specific width-to-vessel-length ratios or width-to-vessel-width ratios. However, the Waal river has a wide width of approximately 150 meters, making the empirical approach more appropriate for this study.

  2. River profile: The formulas used in the empirical approach are applicable to rivers with a rectangular cross-section, while the Waal river has a trapezoidal profile. Although the error introduced by this difference is relatively small, around a few percent, it should be acknowledged as a limitation.

  Considering these limitations, the empirical approach was considered more suitable for this study due to its stability, accuracy, and compatibility with the characteristics of the Waal river.

Sediment transport

- In essence, the investigated sediment transport formulas of Section 2.3 are based on the shear stress exerted by the flow in open water channels. However, it is important to note that the conditions beneath or behind a vessel may not necessarily meet these assumptions, so some caution should be exercised for the final answer. The flow beneath a vessel can be characterized as a form of Couette flow, initially experiencing a strong acceleration and developing a turbulent boundary layer that fully develops further beneath the vessel. Additionally, there is a sudden vertical acceleration behind the vessel, accompanied by the propeller jet. It is difficult to exactly describe these effects by the current transport formulas such as van Rijn (1993), as they are not derived for such specific situations. In other words, the problem falls outside the range for which these formulas were developed, (Sloff, 2023). The issue with these formulas (and other commonly used variants) is that they do not account for the effects of turbulent energy in shear stress, nor do they consider the influence of the propeller jet. However, this method is chosen to give a rough estimation of the sediment transport in the Waal river by considering the return flow velocities of the propeller jets and backflow.

- Within the sediment transport equations it is assumed that the velocities for the propeller jets and backflow are summed up for the determination of the depth averaged grain-shear velocity.
- For the sediment transport formulas it is assumed that the sediment particles are spherical of uniform density and the forces due to the fluid accelerations are of a second order (Van Rijn, 1993).

Sensitivity Analyses

- The sensitivity analyses conducted in this study focused exclusively on variable parameters, namely the power efficiency rate, keel clearance, vessel width, and vessel velocity. These specific parameters were selected for analysis to assess their impact on sediment transport. The findings from these analyses served as the basis for providing feasible measures and guidance in managing sedimentation issues.
- The keel clearance played a significant role in determining the backflow, particularly in relation to the propeller jets (Sloff, 2022). However, its influence is relatively greater within the propeller jets compared to the backflow. As a result, the keel clearance parameter is specifically included and analysed within the context of the propeller jets, as its impact is most pronounced in this area. The return current velocity values for both the propeller jets and backflow are combined or added together. This suggests that the keel clearance parameter likely has the most substantial impact among all the parameters considered. In other words, the keel clearance parameter is potentially the most influential factor affecting the overall outcome of the analysis.
- The sensitivity analyses focused exclusively on examining the effects of the M8 Groot Rijnschip, which belongs to the 'average' vessel class. Only this specific vessel class was considered in the analyses to assess its impact on the variables being studied.

6.2 Comparison with the literature

In this section the study conducted in this master thesis will be comparted to existing literature. As can be written in this Master thesis, not a lot of research has been done towards the impact of inland shipping on sediment transport in rivers. The base of the study was to investigate the impacts of a vessel on the flow which would eventually lead to flow disruptions. Notably, two significant flow disruptions associated with inland shipping are propeller jets and backflow, as affirmed by (Sloff 2022; Guarnieri et al. 2021). Additionally, Sloff (2022) mentioned that secondary effects, such as small waves around a vessel and turbulences, also contribute to flow disruptions. The formulas used to quantify the return current velocities at the riverbed caused by the propeller jets and backflow are derived from both (Sloff 2022; Verheij et al. 2008). Sloff (2022) also claimed that the between the propeller jets and the backflow, the backflow leads to higher flow disruptions. This can be substantiated by this master thesis. Table 32 below shows the values for the return current velocities as calculated in Section 3.4 and 4.3.

Table 32 Return current velocities propeller jets and backflow

Return current velocities	Propeller jets [m/s]	Backflow [m/s]
M4 Dortmundt-Eems	0.48	0.64
M8 Groot Rijnschip	0.88	1.25
6 Baks Duwstel lang	1.12	2.79

Upon calculating the influence of a vessel on the flow, sediment transport formulas were employed to determine the sediment transport in the Waal river. It is noteworthy that no similar methods were found in the existing literature to determine sediment transport using return current velocities in sediment transport formulas. The sediment transport formula by Van Rijn (1993) is based on the shear stress induced by flow in open water channels. However, it is important to acknowledge that the conditions beneath or behind a vessel may not conform to these assumptions, necessitating caution in interpreting the results.

The flow beneath a vessel can be described as Couette flow, initially experiencing significant acceleration and developing a turbulent boundary layer further beneath the vessel. Moreover, a sudden vertical acceleration occurs behind the vessel, accompanied by the propeller jet. These effects are beyond the scope of current transport formulas like Van Rijn (1993), as they were not specifically derived for such situations. In essence, the problem lies beyond the range for which these formulas were originally developed. An issue with these formulas, including commonly used variants, is their failure to account for the effects of turbulent energy in shear stress and the influence of the propeller jet (Sloff, 2023). While it is possible to consider turbulences, doing so would require a complex model that exceeds the scope of this Master's thesis. Despite these limitations, the chosen method provided a rough estimation of sediment transport caused by inland shipping in the Waal river by considering the flow velocities of the propeller jets and the backflow.

The yearly movement of sediment in large quantities downstream amounted to $3.71*10^8$ m^2/year. Unfortunately, no prior data within existing literature existed to serve as a point of comparison for this calculated sediment transport volume. Sloff (2022) and Kitsikoudis (2023) emphasized the novelty of the study area, highlighting the scarcity of literature on the subject. As a result, the computed sediment quantity could not be compared with established research. In an interview, Sloff (2023) emphasized the significance of encouraging scholars and researchers to delve into this matter to facilitate meaningful comparisons and insights.

7. Conclusion

This Master's thesis has aimed to investigate the influence of inland shipping on sediment transport within the Waal river, focusing on the effects of vessel-induced flow disruptions and their potential consequences for nautical depths, riverbed stability and infrastructure. The study has addressed a significant knowledge gap regarding the specific effects and implications of inland shipping activities on sediment transport within the Waal river by using the CoVadem data. The conclusion starts with a thorough answers to the research questions that were introduced in Section 1.2. The findings and analyses presented throughout this thesis converge to provide a comprehensive understanding and address the research inquiry in a meaningful and substantial manner. In addition, valuable recommendations for future research are implemented. These recommendations stem from the gaps and limitations identified during the study.

7.1 Answers on research questions

1. *What parameters, induced by inland shipping, influence sediment transport in the Waal river?*

The answer to this research question has been elaborated in Section 2. Within this section a distinction has been made for two different interactions. The first interaction is the influence of inland shipping on the flow in a river. Secondly, the interaction of the affected flow regarding sediment transport is explained. The literature showed several effects which lead vessel-induced water movement (Sloff 2022). Within this Master thesis only the main effects were discussed. These primary effects are propeller jets and the backflow. Both the propeller and backflow lead to flow disruptions (Guarnieri et al. 2021). As a result of that erosion and deposition of sediment is possible.

The first primary effect were the propeller jets (Sloff 2022). The main propeller(s) is/are located at the stern side of the vessel. In this Master's thesis, the focus is primarily on analysing the effects of the main propellers on the flow dynamics. The main parameters that lead to propeller jets were power efficiency rate, engine power, propeller diameter and water density. The second primary effect was the backflow (Sloff (2022). When a vessel moves forward, it causes the displacement of water at the front, initiating a flow that extends along the sides and beneath the hull before eventually filling the void created behind the vessel. In rivers or canals with restricted depths, a backflow phenomenon occurs beneath and beside the vessel, moving in the opposite direction of the vessel's motion. The main parameters that lead to a backflow in the Waal river were vessel velocity, vessel width, water depth and keel clearance. Eventually the propeller jets and backflow lead to sediment transport. According to the method by Van Rijn (1993) the main parameters were depth averaged bed-shear velocity, depth average critical bed-shear velocity and the water depth.

2. *What is the effect of a single vessel on sediment transport using the CoVadem data in the Waal river?*

The answer to this research question has been elaborated in Section 3. This section encompasses the introduction of the CoVadem data, followed by the selection of a reference vessel to evaluate the impact of a single vessel on sediment transport in the Waal river using the Python model. The parameter values corresponding to the propeller jets and backflow formulas from Section 2 have been justified and supported in Appendix B. Parameter values average vessel. Lastly, the obtained results were presented. The main purpose of the CoVadem data within this thesis was the keel clearance and water depth data of the passing vessels within the Waal river. Thereby, the data also provided ship specifics, coordinates, vessel speeds and movement directions. To examine the impact of an individual vessel on sediment transport in the Waal river, it was essential to select a reference vessel. The selected reference vessel for the model is an M8 Groot Rijnschip, chosen to represent the average single vessel. The reason for taking average velocities is that for both the propeller jets and backflow outliers were visible in the data. Just like the data for the propeller jets, there is a lack of data at the start of the travel due the filtering process of outliers in water depth. After implementing the average velocities of the propeller jets and backflow the sediment transport for an average vessel was calculated according to Van Rijn (1993). The sediment transport for an average vessel through the Waal river equalled a value of $3.09*10^{-5}$ m^2/s.

3. *What is the effect of the entire bulk transport on sediment transport using the CoVadem data in the Waal river?*

The answer to this research question has been elaborated in Section 4. This section focuses on the analysis of the annual bulk transport and started by presenting the distribution of the annual bulk transport, followed by the inclusion of parameter values related to propeller jets and backflow. Ultimately, the results obtained by the Python model showed the contribution of the entire bulk transport in the Waal river to sediment transport, using the CoVadem data.

The annual bulk transport data was obtained from M. Van de Ven (2021) as the initial step. A categorization for the entire annual bulk transport in the Waal river was made into three shipping classes: 'Small,' 'Average,' and 'Large.' This categorization was implemented to simplify the dataset and reduce the amount of data to be processed. The total annual sediment transport by bulk transport in the river downstream is estimated at $1.23*10^{5}$ m^2/year.

4. *What measures could Rijkswaterstaat and shippers apply to effectively manage sediment transport in the Waal river?*

The answer to this research question has been elaborated in Section 5. To address this research question, a sensitivity analysis was performed, focusing on the impact of various parameters related to propeller jets and backflow (using the empirical approach). Subsequently, the section investigated the influence of extreme events and practical measures were identified and implemented for Rijkswaterstaat and the users of the Waal, aiming to effectively handle sediment transport concerns in the future. The sensitivity analyses examined the power efficiency rate, keel clearance, vessel width, and vessel velocity. It was observed that reducing the power efficiency rate, vessel width, and vessel velocity all have a significant impact on reducing sediment transport in the Waal river. These effects all had a linear effect. Furthermore, it was evident that increasing the keel clearance also contributes to the reduction of sediment transport within the river.

Within the sensitivity analyses also the effect of climate change has been investigated. Climate change plays a huge role in the water depth and thus the keel clearance of a vessel. Due to climate change, the water demand increases as summers get drier and hotter (Mens, 2022). For the average reference vessel, the return current velocities have been simulated in an extreme dry event in which the water depth and thus the keel clearance got reduced by 1.0 meters. As a result, the propeller jets increased with 23.7% and the backflow increased with 39.2% in extreme dry conditions compared to normal conditions. The sediment transport, according to Van Rijn (1993), is in an extreme dry event equal to $8.68*10^{-5}$ m^2/s when the keel clearance got reduced with 1.0 meter. This is an increasement of 181% compared to normal conditions ($3.09*10^{-5}$ m^2/s).

Finally, the sensitivity analyses conducted on the chosen variable parameters indicate their significant influence on sediment transport. These measures included, reducing the vessel width, decreasing the vessel velocity, increasing the keel clearance and lowering the power efficiency rate. The feasibility of the measures is also checked. Encouraging shippers to use smaller ships could be achieved by reducing vessel width. Similarly, decreasing vessel velocity at specific points along the Waal river, where sedimentation may be problematic, aligns with the solution of lowering power rates of ships. However, implementing these measures could affect transportation costs for goods and shippers. Modifying the riverbed composition at critical points emerged as the most practical option for Rijkswaterstaat. Yet, this approach may entail higher costs. A thorough assessment of economic implications is crucial in determining the most suitable course of action.

7.2 Reflection on objective

The main objective of this Master's thesis was to comprehensively analyse the influence of inland shipping on sediment transport in the Waal river. This thesis focused on investigating the impact of individual vessels as well as the overall bulk transport on sediment transport within the river. Thereby, practical measures were proposed to assist Rijkswaterstaat and its stakeholders in effectively managing sedimentation issues in the future. However, there have been some deviations from the original objective. The initial plan was to utilize data from both Druten and Erlecom to gain a comprehensive understanding of the total sediment transport within the entire Waal river. However, in this research, only the data from Deest to Druten has been utilized, focusing solely on downstream data. The CoVadem data showed mainly movements of all its pilot boats towards the North Sea (downstream). There are not enough suitable movements away from the North Sea (upstream). Therefore, only the movements downstream were examined for the determination of the effects of inland shipping in the Waal. Additionally, the study focused on straight movement of the vessels (between Deest and Druten) since the influence of thrusters has not been investigated. As a result, the analysis provided insights solely into sediment transport on the right side of the Waal river between Deest and Druten (downstream), if it aligns with the travel direction of the boats.

7.3 Recommendations for future research

To enhance the research and provide a more comprehensive understanding of the effects of inland shipping on sediment transport in the Waal river, the following actions are recommended:

- Retrieve additional data for sailing directions upstream: Gathering data from downstream direction would provide a more complete picture of sediment transport along the entire stretch of the Waal river. By analysing data from both the downstream and upstream direction, a more accurate assessment of the cumulative impact of inland shipping on sediment transport can be obtained.
- Obtain CoVadem data around Erlecom or Nijmegen: Acquiring data specifically from the vicinity of Erlecom is crucial to capture the local dynamics of sediment transport. This region may have unique characteristics or challenges that influence sedimentation patterns due to its meandering structure. Incorporating this data will contribute to a more localized and precise analysis.
- Capture sideward vessel motion: Including data on the sideward motion of vessels adds another layer of complexity to the analysis. By considering the lateral movement of vessels, the full range of vessel dynamics and their influence on sediment transport can be accounted for. Incorporating data from Erlecom or Nijmegen, which captures this aspect, will provide valuable insights into the lateral dispersion of sediments.
- Obtain data from the same day, time, and different vessels: It is essential to collect data for the three vessel classes (small, average, and large) on the same day and at the same time. Additionally, using different vessels within each class will account for variations in vessel characteristics and operating conditions. By ensuring consistency in data collection, the analysis will provide more accurate comparisons and reliable conclusions.
- Aim for consistent pilot boat travel: Establishing consistent routes for pilot boats that travel the same positions in the Waal river with equal water depths would yield valuable information. This approach allows for a direct comparison of sediment transport patterns under similar conditions, highlighting the specific impact of different vessel classes on sedimentation.
- Consider all 16 different vessel types: If time and resources permit, expanding the analysis to include all 16 different vessel types would lead to a more comprehensive evaluation. By collecting and incorporating individual parameters for each vessel type, a more detailed and accurate calculation of the total bulk transport can be performed.
- Determine the sediment transport by considering turbulences: As stated the current used sediment transport formula by Van Rijn (1993) (and other commonly used variants) does/do not consider turbulence effects. A possible plan for future research could be to use a Delft3D model to consider the turbulences (Sloff, 2023).

By incorporating these recommendations into future research efforts, a more nuanced understanding of the impacts of inland shipping on sediment transport in the Waal river can be achieved. This expanded analysis will contribute to informed decision-making and the development of effective strategies to manage sedimentation and erosion challenges in the region.

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Appendixes

Appendix A. List of symbols

Symbol	**Definition**	**Unit**
A_c	*Undisturbed wet cross-section*	*m²*
A_s	*Midship underwater cross-section*	*m²*
B_s	*Vessel's beam at midship section*	*m*
C	*Chézy coefficient*	$m^{1/2}/s$
C_{90}	*Chézy coefficient related to D90*	$m^{1/2}/s$
C'	*Chézy-coefficient related to grain roughness*	$m^{1/2}/s$
D	*Draught of vessel at midship section*	*m*
D_0	*Effective diameter propeller*	*m*
D_{50}	*Median (50%) sediment particle diameter*	*m*
D_*	*Dimensionless particle parameter*	-
D_{90}	*90% sediment particle diameter*	*m*
g	*Gravitational acceleration*	m/s^2
h	*Water depth*	*m*
h_p	*Vertical distance propeller axis and riverbed*	*m*
η	*Power efficiency rate*	*%*
μ_r	*Ripple factor*	-
P	*Power*	*W*
q_b	*Bed load transport*	m^2/s
ρ	*Density water*	kg/m^3
r	*Variable vertical distance*	*m*
R_b	*Hydraulic radius*	*m*
s	*Grain density*	-
T	*Length top of river cross-section (bank to bank)*	*m/s*
u	*Mean return flow velocity*	*m/s*
u_*	*Shear velocity*	*m/s*
$u_{*,cr}$	*Critical bed-shear velocity according to Shields*	*m/s*
$U_{rb,max}$	*Maximum return current velocity along vessel at midships section*	*m/s*

U_r	*Return current velocity*	*m/s*
V_0	*Outflow rate*	*m/s*
$V_{b,max,0}$	*Maximum velocity behind the vessel at riverbed*	*m/s*
V_{axis}	*Velocity horizontal behind the propeller axis*	*m/s*
V_m	*Velocity at the bottom of a moving vessel*	*m/s*
V_s	*Vessel velocity*	*m/s*
V_{still}	*Velocity at the bottom of a stationary vessel*	*m/s*
w_s	*Settling velocity*	*m/s*
x	*Variable horizontal distance*	*m*
z_{lim}	*Sinkage*	*m*
α	*Correction factor average return current*	-
α_{schijf}	*Correction factor Schijf*	-
θ_{cr}	*Critical particle mobility parameter according to Shields*	-
ϕ	*Sediment transport parameter*	-
ψ	*Flow parameter*	-
τ^*	*Shear stress/Shields parameter*	-
ν	*Kinematic viscosity*	*m^2/s*
U'_r	*Return current velocity compared to the water velocity*	*m/s*
V'_{lim}	*Limit speed*	*m/s*
V'_s	*Relative vessel speed compared to the water velocity*	*m/s*

Appendix B. Parameter values average vessel

This section focuses on the parameters related to the propeller jets' impact caused by a single vessel, which are presented in Table 1. Specifically, the values of these parameters are discussed in relation to the Python model representing the M8 Groot Rijnschip operating in the Waal river. The variable parameters derived from CoVadem's data will not be discussed in detail here, as they are addressed in Section 3.1.

B.1 Propeller jets

Power efficiency rate (η)

The power efficiency rate of a vessel is typically measured by its fuel consumption per unit of distance travelled. The actual power efficiency rate of a vessel can vary widely depending on several factors, including its size and shape, engine type, operating conditions, and cargo load. In general, larger and more modern vessels tend to be more fuel-efficient than smaller and older vessels. A vessel can never go faster than its maximum speed limit. A vessel's captain will never go faster than 80% of the maximum speed limit because going faster than that would not result in a significant increase in speed compared to the extra amount of fuel required (Sloff, 2022).

Power (P)

The power of a large Rhine vessel can vary depending on various factors such as its size and type of engine used. Typically, Rhine vessels require significant power to navigate the river's current and transport heavy loads. An average Rhine vessel is about 110 meters long and has a power output of approximately 3000 to 4000 horsepower (2.2 to 3 MW). The power is generated by diesel engines that are connected to propellors. Like the power efficiency rate, the power of an M8 Groot Rijnschip depends on several factors (EEDI, 2023). The used value for the power is equal to 3 MW.

Density water (ρ)

The density of water in the Waal River, like any other natural river, can vary depending on several factors such as temperature, salinity, and suspended solids. However, as a general approximation, the density of freshwater in rivers is typically close to 1000 kilograms per cubic meter (kg/m^3) at standard temperature and pressure conditions (25 degrees Celsius and 1 atmosphere of pressure), (Rijkswaterstaat, 2020).

Effective diameter propellor (D_0)

The effective diameter of a propeller is a term used to describe the diameter of the circle swept by the propeller blades as they rotate. It's the diameter of the circle that would be described by the outermost points of the propeller blades as they move through the water. The effective diameter of a propeller is an important factor in determining the performance of the propeller, as it affects the amount of water that is moved by the propeller in each rotation, and therefore the amount of thrust that is generated, (EEDI, 2023). The effective diameter for an M8 Groot Rijnschip in the Waal is 1.6 meters (Van de Ven, 2021).

Variable horizontal distance (x)

The variable horizontal distance is the distance between the axis of the propellor to a random point behind the propellor. Theoretical and experimental research has determined that the maximum speed of water flow at the bottom of a vessel, caused by the main propellor, occurs at 10 meters (Guarnieri et al., 2021).

Variable vertical distance (r or h_p)

The variable vertical distance is the distance from the axis of the propellor to the riverbed. This distance depends on the keel clearance and the dimension of the propellor. The variable vertical distance is the keel clearance plus half the propellor diameter (0.8 meter).

Table 33 below shows an overview of the values for the parameters regarding the propellor jets.

Table 33 Parameters values regarding the propellor jets

Symbol	Definition	Value	Unit
η	Power efficiency rate	80	%
P	Power	$3*10^6$	W
ρ	Density water	1000	kg/m^3
D_0	Effective diameter propellor	1.6	m
x	Variable horizontal distance	10	m
r	Variable vertical distance	Ukc+0.8	m
h_p	Vertical distance propellor axis and riverbed	Ukc+0.8	m

B.2 Backflow

The parameters for the effect of the backflow for the empirical approach and one-dimensional analytical approach are respectively given in Table 2 and Table 3. In the next two sections the constant parameters for the Python model are presented. The parameters that are not mentioned are variable and implemented in the model by CoVadem's data.

B.2.1 Empirical approach

The parameters for the empirical approach regarding the backflow are listed below. For the vessel-dependent parameters, an M8 Groot Rijnschip is used.

Vessel's beam at midship section (B_s)

The vessel's beam at midship section for an M8 Groot Rijnschip is 11.45 meters (shipid 14), CoVadem (2021).

Draught of vessel at midship section (D)

The values for the draught of the vessel at midship section is equal to the keel clearance which can be retrieved from the CoVadem data.

Table 34 below shows an overview of the values for the parameters regarding the propellor jets.

Table 34 Parameters values regarding the backflow (empirical approach)

Symbol	Definition	Value	Unit
B_s	Vessel's beam at midship section	11.45	m
D	Draught of vessel at midship section	Ukc	m

B.2.2 One-dimensional analytical approach

The parameters for the one-dimensional analytical approach regarding the backflow are listed below. For the vessel-dependent parameters, an M8 Groot Rijnschip is used.

Midship underwater cross-section (A_s)

The midship underwater cross section refers to a horizontal slice or section of a vessel's hull at the midpoint of its length. The midship under water cross-section for an M8 Groot Rijnschip is calculated according to equation [27]:

$$A_s = B_s * h \qquad [27]$$

The vessel’s beam at midship intersection equals 11.45 meter. The average water depth equals 6.45 meter which results in an midship underwater cross-section of 73.9 m^2.

Undisturbed wet cross-section (A_c)

The calculation of the undisturbed wet cross-section equals the wetted perimeter in the Waal river. The wetted perimeter can be calculated according to equation [28]:

$$A_c = b + 2\left(\left(\frac{T-b}{2}\right)^2 + h^2\right)^{1/2} \qquad [28]$$

With:

Table 35 Parameters values undisturbed wet cross section equation [28]

Symbol	Definition	Value	Unit
P	Wetted perimeter	190.8	m^2
b	Width river cross-section	150	m
T	Length top of river cross-section (bank to bank)	188.7	m
h	Water depth	6.45	m

The average width of the Waal river equals 150 meter (Rijkswaterstaat, 2023). Since the cross-section of the Waal is a trapezoid profile and the side slopes equal 1:3, the top length of the river cross-section equals 188.7 meter. For the water depth an average of various water depths in the Waal are taken and equals 6.45 meter. Therefore, the wetted perimeter and thus the undisturbed wet cross-section equals 190.8 m^2.

Gravitational acceleration (g)

The gravitational acceleration is 9.81 m/s^2.

Correction factor Schijf (α_{schijf})

The correction factor of Schijf is used to account for the non-uniform distribution of the return velocity and is typically set to 1.1 [-], (Sloff, 2022).

Correction factor average return current (α)

The correction factor for the average return current is equal to 1.53 (Robijns, 2014).

Table 36 below shows an overview of the values for the parameters regarding the propellor jets.

Table 36 Parameters values backflow with the analytical approach

Symbol	Definition	Value	Unit
A_s	Midship underwater cross-section (B_s*h)	73.9	m^2
A_c	Undisturbed wet cross-section	190.8	m^2
g	Gravitational acceleration	9.81	m/s^2
α_{schijf}	Correction factor Schijf	1.1	[-]
α	Correction factor average return current	1.53	[-]

Appendix C. Parameter values small and large vessel

This appendix shows the parameters associated with the propeller jets, the backflow (empirical approach), and sediment transport for two categories of vessels: 'Small' and 'Large'. In Section 3, all the parameters relevant to the Python model concerning the 'Average' class (M8 Groot Rijnschip) were gathered and discussed. The same process is repeated for the 'Small' and 'Large' vessel classes. The reference vessel for the 'Small' class is an M4 Dordtmund-Eems, which is equal to shipid 68 from the CoVadem data. The reference vessel for the 'Large' class is a 6 Baks Duwstel lang, which is equal to shipid 2 from the CoVadem data. For the propellor jets it is important to mention that 2 propellors are included in the model.

C.1 Propeller jets

The input parameters for the propeller jets for both the 'Small' and 'Large vessel classes are listed below.

Small class

Table 37 Parameters values regarding the propellor jets M4 Dordtmund-Eems

Symbol	Definition	Value	Unit
η	Power efficiency rate	80	%
P	Power	$2*10^6$	W
ρ	Density water	1000	kg/m^3
D_0	Effective diameter propellor	1.2	m
x	Variable horizontal distance	10	m
r	Variable vertical distance	Ukc+0.6	m
h_p	Vertical distance propellor axis and riverbed	Ukc+0.6	m

Large class

Table 38 Parameters values regarding the propellor jets 6 Baks Duwstel lang

Symbol	Definition	Value	Unit
η	Power efficiency rate	80	%
P	Power	$7.6*10^5$	W
ρ	Density water	1000	kg/m^3
D_0	Effective diameter propellor	1.6	m
x	Variable horizontal distance	10	m
r	Variable vertical distance	Ukc+0.8	m
h_p	Vertical distance propellor axis and riverbed	Ukc+0.8	m

C.2 Backflow

The input parameters for the backflow (empirical approach) for both the 'Small' and 'Large vessel classes are listed below.

Small class

Table 39 Parameters values regarding the backflow Dordtmund-Eems (empirical approach)

Symbol	Definition	Value	Unit
B_s	Vessel's beam at midship section	7.5	m
D	Draught of vessel at midship section	Ukc	m

Backflow (empirical)

Table 40 Parameters values regarding the backflow 6 Baks Duwstel lang (empirical approach)

Symbol	Definition	Value	Unit
B_s	Vessel's beam at midship section	22.8	m
D	Draught of vessel at midship section	Ukc	m