The driving forces behind the flow of water in the recently depoldered area, the 'Kleine Noordwaard'

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Abstract

The fieldwork area ‘De Kleine Noordwaard’ is an area that is reopened for rivers and tides (depoldered) as part of the Room for the River project in the Netherlands. The project is initiated to decrease flood risk along the river Rhine, by capturing and storing water in the newly created channels and floodplain. The area is being monitored and works as a study and pilot area to find out what happens to a polder when it is given back to nature. It is expected to catch sediment and grow, keeping up with sea level rise. The driving force behind the sediment distribution and deposition in the area is the water flow. The water flow is monitored using H-ADCP’s at both the in- and outlet of the area. Using field data, the data of these H-ADCP’s is used to construct a flow volume balance for the area. Analysis of this flow volume balance shows that the area is mainly functioning as a side channel with a small storage capacity. The water flow through the area is determined by water levels at the up- and downstream boundary of the area, creating a gradient over the area. The gradient in water level over the area is being determined by the discharge of both the Rhine and the Haringvliet sluices, and transformed by the tidal wave. How much influence the tidal wave has on this gradient depends strongly on the original magnitude of the gradient. High gradients are only slightly changed by the tidal wave while low gradients are suspect to a much larger change. This causes situations at which the water flow through the area is going in the upstream direction instead of the regular downstream direction.

Keywords: depoldering, room for the river, Kleine Noordwaard, water, flow, river, tide, gradient, flood risk, storage, discharge, Rhine, Haringvliet, Biesbosch,

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1. Introduction

River deltas and tidal wetlands are formed by the interaction between rivers and the sea, creating new land. This newly created land is often very flat, making it a perfect location for humans to settle and use the land as agricultural land, which is even more promoted by the rich organic soil (Syvitski, 2008). This causes deltas to be densely populated and often strongly influenced and modified due to human activities. The downside of this flat land is that the area is subject to regular flooding. Rivers often overflow the delta, inundating large parts of it and providing fresh sediment. Since deltas are located at the coast, sea level rise is also a constant threat.

Due to human activities (e.g. embanking, damming and relocating rivers) a shortage in sediment supply has developed, causing subsidence of the area. Climate change and sea level rise cause an increasing amount of stress on river deltas, as they intensify the relative subsidence (Syvitski et al., 2009). The classical "hold the line method" (heightening and building dikes) is no longer seen as a feasible and sustainable method in water management (Ledoux et al., 2005). This exerts a pressure on the management of these areas, creating a demand for new solutions to the problem of subsidence. One possible solution is reactivating the sediment supply, creating a new sediment balance which can prevent subsidence. The biggest question however is whether sediment supply will be able to keep up with sea level rise.

The main source of sediment has always been the river itself, bringing sediment from the mountains into the delta, and thus elevating and nourishing the area. In most areas, the sediment from the river stays within the (man-made) river boundaries, unable to spread over the floodplains due to human interference with the river. The sediment from the river needs to reach the floodplains in order to be able to restore the sediment balance. The balance can be restored by giving land back to the river, giving it more room and freedom. Returning land to the river is a green method of restoring the sediment balance to counteract the ongoing subsidence.

This project is part of the Room for the River project in the Netherlands, the goal of this project is to test the influence of returning land to nature. Research is done in a small intertidal area, the Biesbosch, in the Netherlands. In this area several polders have been given back to nature, allowing a full in and outflow of water and thus sediment. To find out how much water and sediment is actually flowing in to this area, data has been collected on flow velocities, sediment concentrations, deposition and erosion. The results of this research must give a better understanding of the development of a depoldered area.

Within this large project a smaller research project is started in the Biesbosch called "Delta engineering: drowning or emerging". This research project is being led by two PhD-students which focus on the following objectives: 1) To quantify the factors and mechanisms that control the sediment budget of a delta system; and 2) To assess the impacts of changing sediment budgets on the development of drowning deltas under changing climate, rising sea level and increasing river peak discharge.

This research is part of the smaller research project and it will focus on answering the following main question: *How are the water volumes flowing in and out of the 'Kleine Noordwaard' controlled and how is the system driven?*

To answer this main question several sub questions have been created:

- *What factors influence the flow volumes and how can we determine them?*
- *How much water can the area hold and at which circumstances is the area completely filled?*
- *Can we distinguish what the influence of each factor on the total flow is?*
- *Can we determine how the relation between flow and the influencing factor works?*
- *How does the system work compared to other similar regions, where do differences come from?*

The combined answers to these smaller questions will provide a clear understanding of the water balance in this newly created area thus answering the main question.

2. Growing and drowning deltas

Deltas and wetlands all over the world are having problems keeping up with sea level rise, creating lots of problems and even causing them to drown. The drowning of deltas is a problem that is observed frequently during the Anthropocene but is not observed in any of the geological datasets from before the Anthropocene (Syvitski et al., 2009, Kirwan & Megonigal, 2013). It is therefore seen as a problem caused by human activities which might also be resolved by human interaction.

2.1 Sediment starvation

In a natural system rivers bring fresh sediment to the deltaic area by overflowing and flooding the area periodically. This flooding brings fresh sediment, elevating the area whilst providing a rich and fertile soil (Syvitski, 2008). The nutrients and sediments provided by the river are essential for building up wetlands and preventing deltas from sinking. Currently these nutrients and sediments are not reaching the delta anymore. Over 20% of the global sediment load is being trapped by dams and reservoirs, preventing it from reaching the coast (Syvitski et al., 2005). The building of dikes and channelizing of rivers prevents the river from flooding the surrounding lands and delivering sediment (Fig. 2.1). Sediment being delivered to a sinking delta will remain in the area as the accommodation space is large, therefore causing aggradation of the delta. The availability of sediment is being restrained by all these human impacts, resulting in severe flooding of deltas. In the past decade, 85% of the deltas experienced severe flooding (Syvitski et al., 2009). Next to sediment, rivers also bring a lot of nutrients, creating a fertile ground. This is the ideal surface for vegetation to grow on and increase the aggradation rate by creating organic matter, building up the delta surface (Kirwan & Megonigal, 2013). Direct human modification is therefore one of the main causes for the observed lack in growth in deltas, as it prevents aggradation in multiple ways.

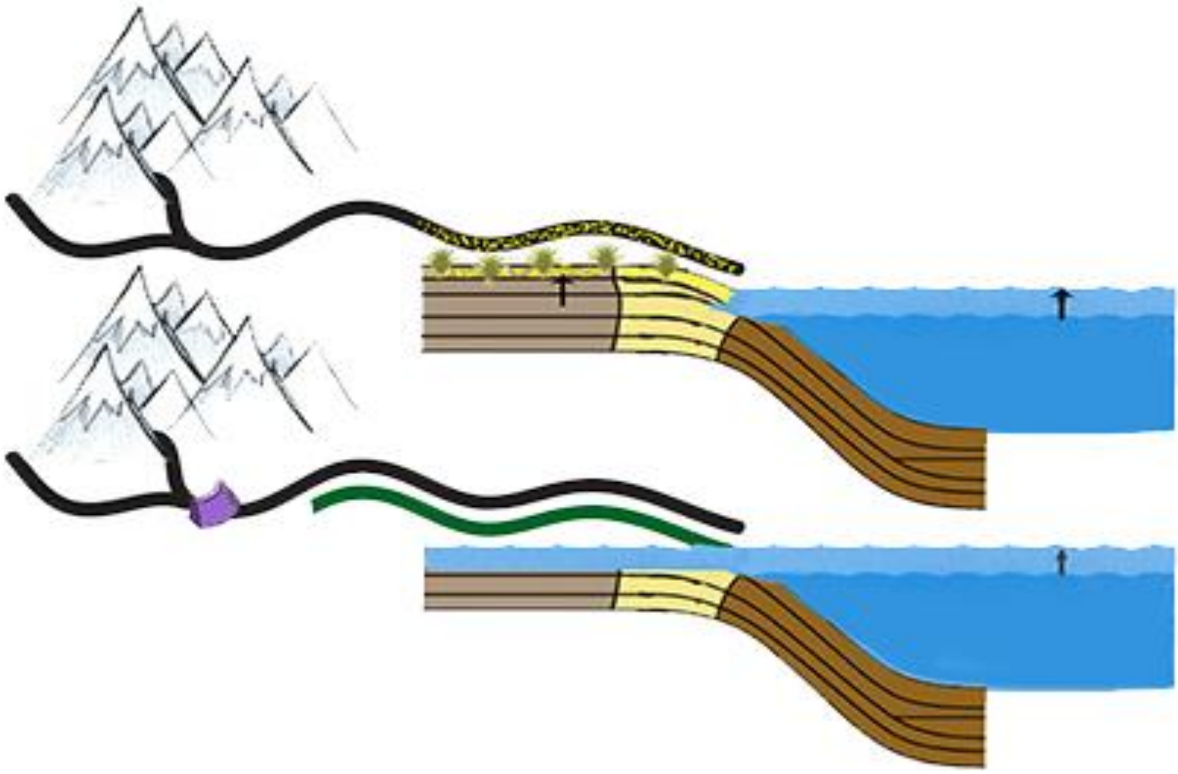


Figure 2.1 up: Conceptual idea of what happens under natural conditions; rivers erode the upstream (mountainous) areas and transport sediment downstream, dropping the sediment in the deltas making them grow and keep up with sea level rise.
Figure 2.1 down: same concept but including human interference, damming upstream and diking downstream prevent sediment from reaching the delta and eventually cause the delta to drown.

2.2 Subsidence

The sea level rise rates observed at the moment exceed any of the predictions based on climate driven scenarios (Nichols, 1995; IPCC, 2015). This is not only being caused by direct human impact but also due to indirect human impact. Groundwater extraction, oil and gas drillings and artificial drainage of wetlands cause the land to subside. According to Törnqvist et al. (2008), the compaction of young sediments in rural areas can be up to a magnitude faster when ground water is extracted. Subsidence rates and wetland loss are closely linked. By changing subsurface fluid withdrawal rates the subsidence rates and wetland losses can be decreased (Kolker et al., 2011). Most deltas have severe problems with subsidence as this causes the land to literally sink.

2.3 Relative sea level rise

Relative sea level rise is currently one of the biggest problems and concerns for deltas in the future. At the moment there are deltas submerging and sinking over the entire world due to sea level rise (Syvitski et al., 2009). This is quite remarkable since almost no deltas or wetlands have been drowned in the past 4000 years while the sea level has risen up to two meters in that same period (Kirwan & Megonigal, 2013). The reason for this is that there is a strong feedback between flooding, plant growth and elevation change which counteracts the drowning of wetlands (Kirwan et al., 2010, Fagherazzi et al., 2012). Human activities have changed the way this feedback works by changing the system and with that destroying the balance within the system. The reduced sediment loads and subsidence are the major causes for an elevation deficit, which in combination with global sea level rise leads to submergence of marshes and land (Morton et al., 2002; Reed, 2002; Day et al., 2007).

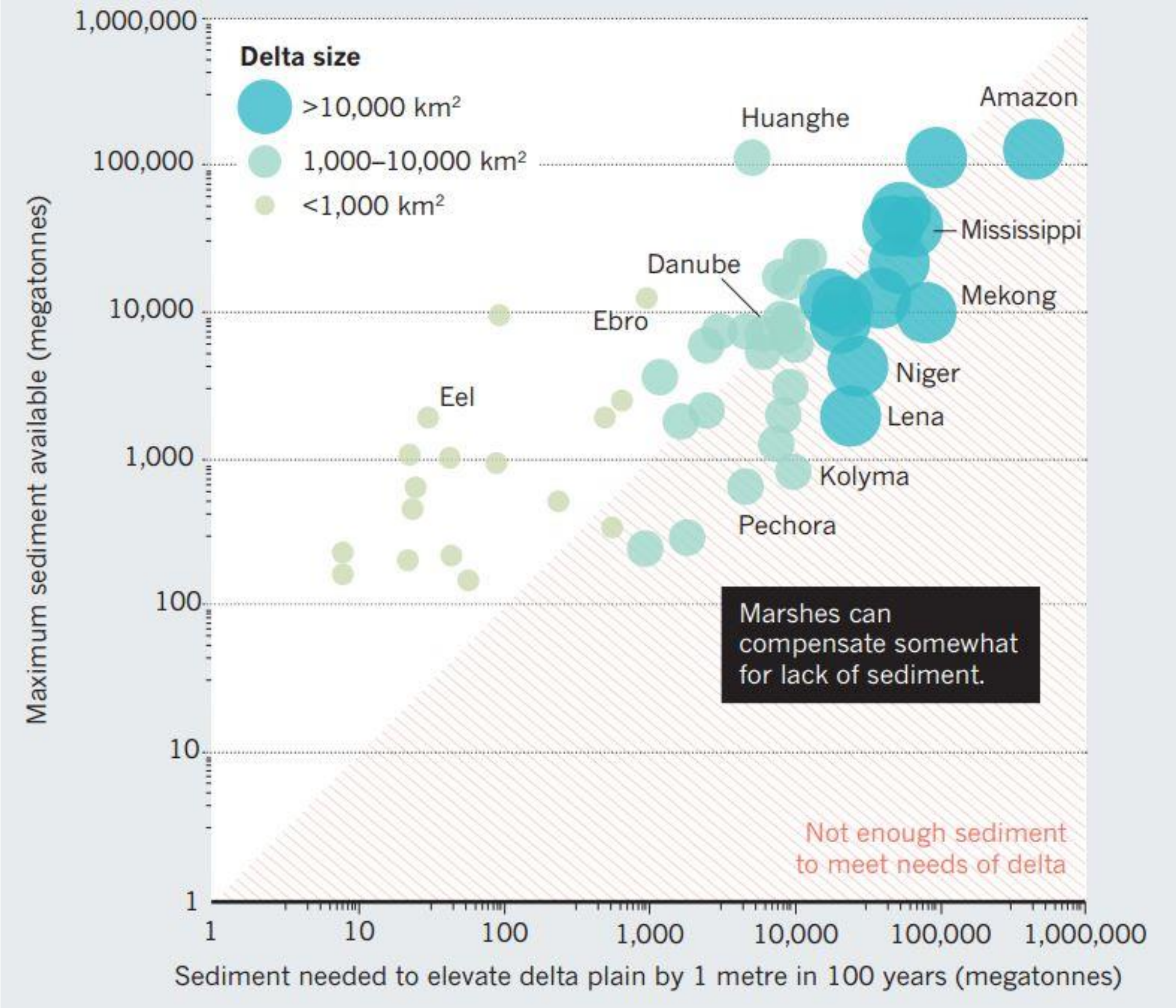


Figure 2.2: Most medium- and large-sized delta cannot grow fast enough to keep up with sea-level rise in the next century. Damming and diking reduces sediment load further and pushes more deltas into the red. (Giosan et al., 2014)

The basics are quite simple, the change in delta surface relative to the local mean sea level (Δ_{RSL}) is based on five factors: $\Delta_{RSL} = A - \Delta E - C_N - C_A \pm M$. A is the delta aggradation, the volume of sediment that is delivered to, and remains at, the delta by rivers and oceans. ΔE is the eustatic sea level which is determined by the volume of water present in the global ocean. Natural compaction, C_N, and accelerated compaction, C_A, cause the sediments in the delta to compact. The formula is completed by the letter M which is the vertical movement of the land surface, determined by the earth’s isostatic and tectonic movement (Syvitski et al., 2009). Most deltas cannot grow fast enough to keep up with the sea level rise in the next century as the sediment supply and thus aggradation A is not large enough (Fig.2.2) (Giosan et al., 2014). This pushes deltas into the red zone of figure 2.2 which causes the deltas to drown due to a lack of sediment supply, caused by human interference.

2.4 Restoring the sediment balance

Global sea level rise increases the threat for wetlands to be inundated. Climate change and sea level rise predictions (IPCC, 2014) are currently suggesting an increase of the problems we already observe in a lot of wetlands around the world. Global sea level rise is a problem that cannot be changed on short terms, the other causes of drowning deltas can be changed on the short term. By giving land back to nature it is possible to restore the sediment input in the area and simultaneously reduce the amount of groundwater that is being withdrawn from the area. This gives the wetland an increased chance of keeping up with global sea level rise as the two major causes of subsidence are being stopped. Another advantage of creating new wetlands by depoldering areas is that the areas can benefit fisheries and provide a sink for carbon and nutrients (Jickells et al., 2000). This theory has been tested in a couple of researches under different circumstances but it is still a very new and revolutionary approach in flood defence.

Research in the Humber estuary, where managed realignment is being implemented on a large scale shows promising results. The estuary's erosive impact on flood defences is being reduced as mudflats and saltmarshes dissipate wave energy (Edwards et al., 2006). In the case of the Humber estuary the impact of sea level rise is locally reduced due to an increase in tidal volume (French, 2006). It is therefore seen as the key to sustainable long term flood and coastal management as the traditional hold the line policy is no longer regarded as a long term solution (Ledoux et al., 2005). In the Ebro delta different areas were compared to each other, three areas receiving no river sediment compared to one area which does receive river sediment. The results of the research show that the part of the delta that does receive river sediment and fresh water shows significantly higher rates of soil accretion (Ibáñez et al., 2010). Modelling studies in the Biesbosch area also show promising results for this method of flood defence (Verschelling, 2015). Research of Kirwan & Megonigal (2013), shows that marshlands are able to keep up with sea level rise when sediment and mineral input into the area is available (Fig. 2.3). The largest part of the total accretion for infrequently flooded marshes is organic matter, these marshes are typical of high-elevation marshes and/or periods of slow sea-level rise (left side of graph). However, the same marsh becomes increasingly mineral rich as it is longer inundated or when sea level rise increases (right side of graph). Therefore the threshold rate of sea-level rise often is a function of sediment availability. Marshes that have always been stable (green circle) under pre human era sediment loads can become unstable and submerges (blue circle) if sediment loads are reduced. This suggests that the reduction of sediment loads, caused by human interactions such as land use change and dam construction, can cause marshes to become less stable in the future, even if sea-level rise rates remain unchanged (Kirwan & Megonigal, 2013). In short, they prove that tidal areas may become unbalanced, causing them to drown, when sediment is no longer delivered to the tidal areas. This deficient of sediment delivery to tidal areas and deltas is caused by human interference, indirectly causing the drowning of large regions world-wide.

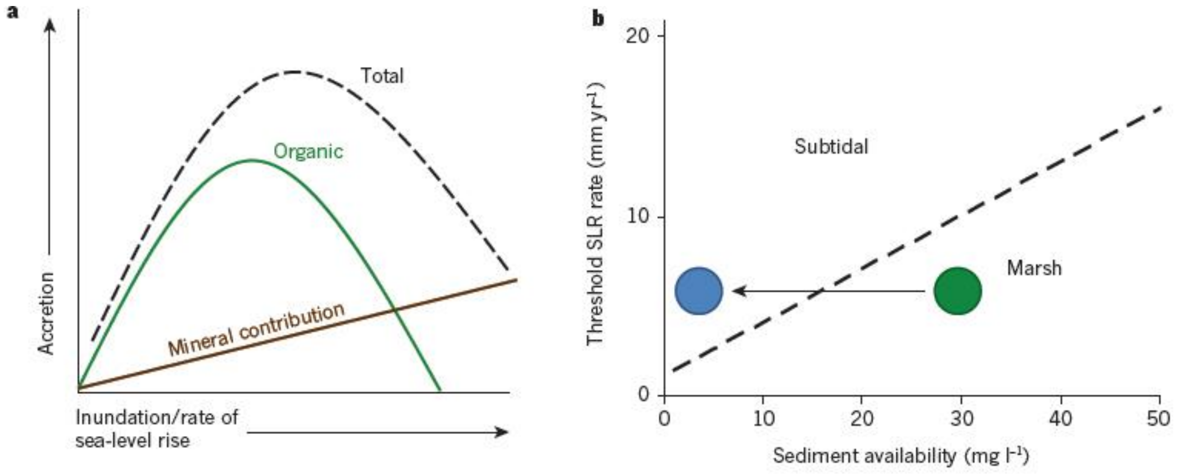


Figure 2.3: Conceptual links between sea-level rise and marsh accretion. A) The hypothetical contribution of organic and mineral matter to accretion as a function of inundation in a sediment-deficient marsh. B) Threshold rates of sea-level rise (SLR) beyond which marshes cannot survive as a function of suspended sediment concentration in an estuary. Dashed line represents threshold rates from the 1-m tidal range case under moderately rapid sea-level rise (5 mm yr^{-1}*). A marsh that is stable under historical sediment loads (green circle) submerges if sediment loads are reduced (blue circle). (Kirwan & Megonigal, 2013)*

2.5 Gaps in our knowledge

Depoldering areas in wetlands is seen as returning the area to its natural state, allowing it to develop as it would in a world without human modifications. This is exactly what is happening when polders are being given back to the river and sea, the starting point however is different. Under natural conditions the delta is slowly keeping up with sea level rise and the delta is slowly aggradating vertically or horizontally. When giving back areas to nature, the starting point is completely different. These areas are often much lower and larger than they would be in nature. When an area has not been flooded for over 50 years, the area is missing 50 years of sediment in its balance, causing it to lay much lower than it would have when this sediment was deposited in the area. A lot of morphological adjustment is needed for these areas to become natural wetlands again (French, 2006). Whether these depoldered areas will ever fully function as a natural, balanced wetland remains to be seen. Therefore research is needed, to find out if the theory works as well in reality as it does on paper. The ‘Kleine Noordwaard’ is an area that is recently depoldered, making it perfect for this research. The area is located in the nature reserve called the Biesbosch in the Netherlands.

3. The Biesbosch Area

The Biesbosch is a nature reserve in the Netherlands, it is located in between the major cities of Dordrecht, Werkendam and Geertruidenberg (Fig. 3.1).

Figure 3.1: Location of the Biesbosch, showing the major cities and waters.

3.1 Origin of the Biesbosch

The present day Biesbosch is formed by several events and human interactions that are placed on a timeline in figure 3.3. The Biesbosch developed as an inland delta after the second Elisabeth flood in 1421. Due to extreme flooding a marginal sea was created that covered nearly 300 km^2 (van der Ham, 2003). The interaction between the discharge and sediment load of both the Rhine and the Amer and the tidal water level variation resulted in the ideal situation for sediment deposition, so sandy plates and intertidal areas were formed (Kleinhans et al., 2010). Land reclamation and other human interventions such as dikes were built since 1850 and modified the area, preventing a lot of the shoals to be flooded. Around 1850 they also started digging the Nieuwe Merwede canal, which cut the area in half (Kleinhans et al., 2010). This created several permanently dry areas which are used as farming lands, part of the shoals have not been embanked and are still regularly flooded. The development of the Biesbosch area between 1560 (left) and 1568 (right) is visible in figure 3.2.

Figure 3.2: Historical maps of the Biesbosch 1560 (left) and 1568 (right). Major cities indicated by D: Dordrecht, W: Werkendam, and G: Geertruidenberg. For scale: the distance between Dordrecht and Werkendam is 15.6km. (Kleinhans et al., 2010)

Before 1970 the area had an open connection with the North Sea via the Haringvliet. This allowed the tidal wave to travel freely into the area, creating an area that was strongly influenced by tide. The tidal range reached up to 2 meters in the Biesbosch area due to the funnelling of the tidal wave. In 1970, the Haringvliet barrier was created as a part of the Delta works. This blocked the tidal wave and reduced the tidal range to almost zero. In 2005 the Haringvliet barrier was adjusted and partly reopened in order to bring back the tidal influence. This has been done in order to bring back several endangered species and create a more diverse nature reserve. The tidal range has been brought back to a range of 30-60 centimetres, depending on the location. During storms the Haringvliet still closes completely to prevent flooding, blocking off the tidal wave, but this only happens incidentally.

The Haringvliet barrier is located at the mouth of the sea arm, forming a barrier between the North Sea and the rivers. The barrier is responsible for eliminating a large part of the tidal influence but it also prevents river water from flowing into the sea. The barrier consists of 34 sluices which regulate the water level. The sluices discharge the water from the Rhine and the Meuse into the North Sea, whether these sluices are opened or closed depends on the amount of water flowing into the country. If river discharges are low (1100 m3/s at Lobith), the sluices are closed. When river discharges are high the sluices are pumping water into the North Sea and towards the Nieuwe Waterweg to prevent flooding (RWS).

The closing of the barrier at low Rhine discharge will prevent water from discharging into the sea, piling it up in the Haringvliet. This causes the water levels in the Biesbosch to rise, influencing the water balance. On the other hand, pumping of water will lower the water level which also affects the water balance in the research area. Only under “normal” conditions water is being allowed to discharge freely into the sea.

In the future (2018) when water levels in the estuary are lower than the water levels at sea, salt water will penetrate into the Biesbosch. Partly opening the sluices must bring back salt water in the Haringvliet, allowing fish and other marine animals to be reintroduced into the area. Allowing water to flow from the sea into the Haringvliet pushes up the water levels during low discharge periods, on its turn affecting the water balance in the research area. This however, is only a problem for the future as these plans will be implemented in 2018. The activity of the Haringvliet barrier needs to be taken into account when analysing the water balance in the research area and future plans will make this even harder.

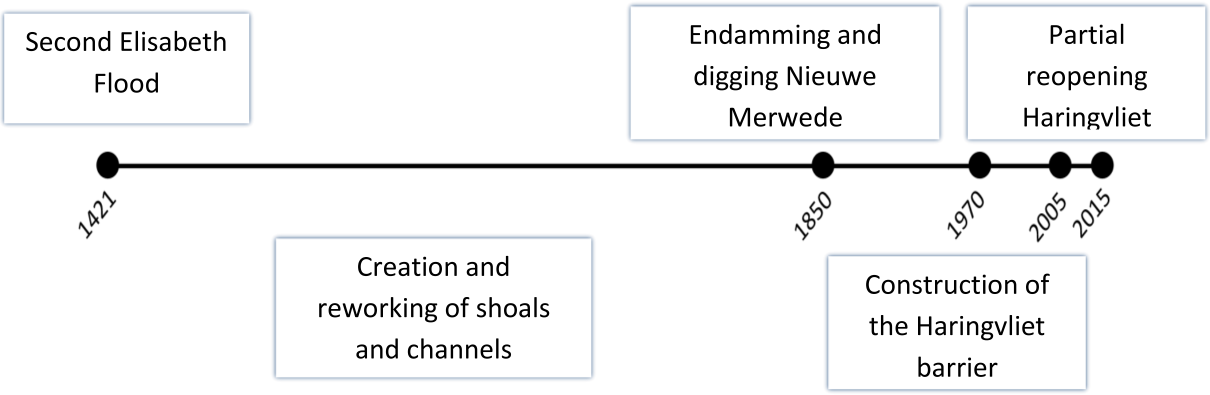


Figure 3.3: Timeline showing the key events in the development of the Biesbosch area.

3.2 Present day Biesbosch

The Biesbosch area nowadays is a national park and thus a protected wildlife and nature reserve area located near the city of Dordrecht. The area comprises 90 square kilometres of water and islands combined with sandy and muddy intertidal areas in between the rivers Boven-Merwede and the Amer. The area has fully diked polders and multiple wetlands which area linked by several channels that are flowing through the entire area. The Nieuwe Merwede cuts the area in half, functioning as the main river discharge route.

The Biesbosch is an intertidal area, which means that it is affected by tidal cycles. This causes a daily in and outflow of water generated by the tide. These tidal movements differ throughout the month as the neap and spring tide cycle affects the height of the tide. The tidal wave in the Biesbosch area is not a natural one as it is moderated by the Haringvliet barrier. The tide reaches up to 30 to 60 cm depending on the location (De Boois, 1982).

Next to these tidal water movements, water from the rivers is also flowing through the area. In the North, the area is directly connected to the Nieuwe Merwede, which is a branch of the river Rhine. On the Southside of the Biesbosch another river is flowing into the area, the Amer, which is a branch of the river Meuse. These rivers flow (partly) through the research area, causing the area to function as a side channel and retention basin.

Wind can have an influence on the amount of water flowing through the area. The downstream flow direction of the river water is crossing the area diagonally, flowing from the North East corner towards the South West corner. The mean wind direction (SW) is obstructing the water flow as it has an opposite direction. But of course this can change from storm to storm, causing the winds to have an unpredictable effect on the water flow.

3.3 Room for the River

In the Netherlands a new approach in river management has been introduced which goes by the name ‘Room for the River’ (www.ruimtevoorderivier.nl); it focuses on creating more room for the rivers to be able to reduce high water levels. It is seen as a green and sustainable way of water and flood risk management. Floodplains have been lowered and cleared of housing and other obstacles, dikes are being relocated, all in order to create more space for river water to prevent flooding.

The approach involves the Biesbosch area. It contains multiple former polders which are reopened for rivers and tides as part of flood control measures. The ‘Kleine Noordwaard’ is such a former polder (Fig. 3.4), which has been given back to nature; water is now running freely though the area. This causes water levels to drop in the river and creates a small retention basin and a secondary discharge route for the water. It is in the first place a discharge route for water, but it also serves as a nature reserve which is protected by the state forestry service. This makes it a perfect area for research as it allows us to study what happens to a former polder when it is given back to nature. The main goal behind this pilot project is to find out how the area will develop and moreover if this is a sustainable way to fight the drowning of deltaic regions all over the world.

Figure 3.4: Overview of ‘De Kleine Noordwaard’, showing the channels dug into the former polder area. (Source: bvkoek.nl)

3.4 De Kleine Noordwaard

De Kleine Noordwaard is located at the edge of the Biesbosch area as indicated in figure 3.5. The area has one inlet and one outlet (indicated in the figure 3.6), allowing it to be observed as a closed system. Within the area there is a shoal and channel system. During high water most of the area is submerged and during low water only the channels are submerged. Combined with the tidal cycles that affect the area this creates an interactive shoal and channel system that transports water and sediment from the inlet towards the outlet through these shoals and channels. Since it is a closed system, all water in the area has to pass the in- and outlet, allowing the construction of a complete and closed flow volume balance.

The Kleine Noordwaard is influenced by the river Rhine which flows along the Northern border of the area, near the inlet and the Meuse which flows south of the Biesbosch area. Due to the direction of the river flow and the location of the research area, most of the water flowing through the inlet is provided by the Rhine. The Meuse only affects the water flow in the research area by pushing up the water and creating backwater effects. Therefore focus will be on the discharge of the Rhine whilst keeping in mind that high discharges from the Meuse might explain some unexpected results.

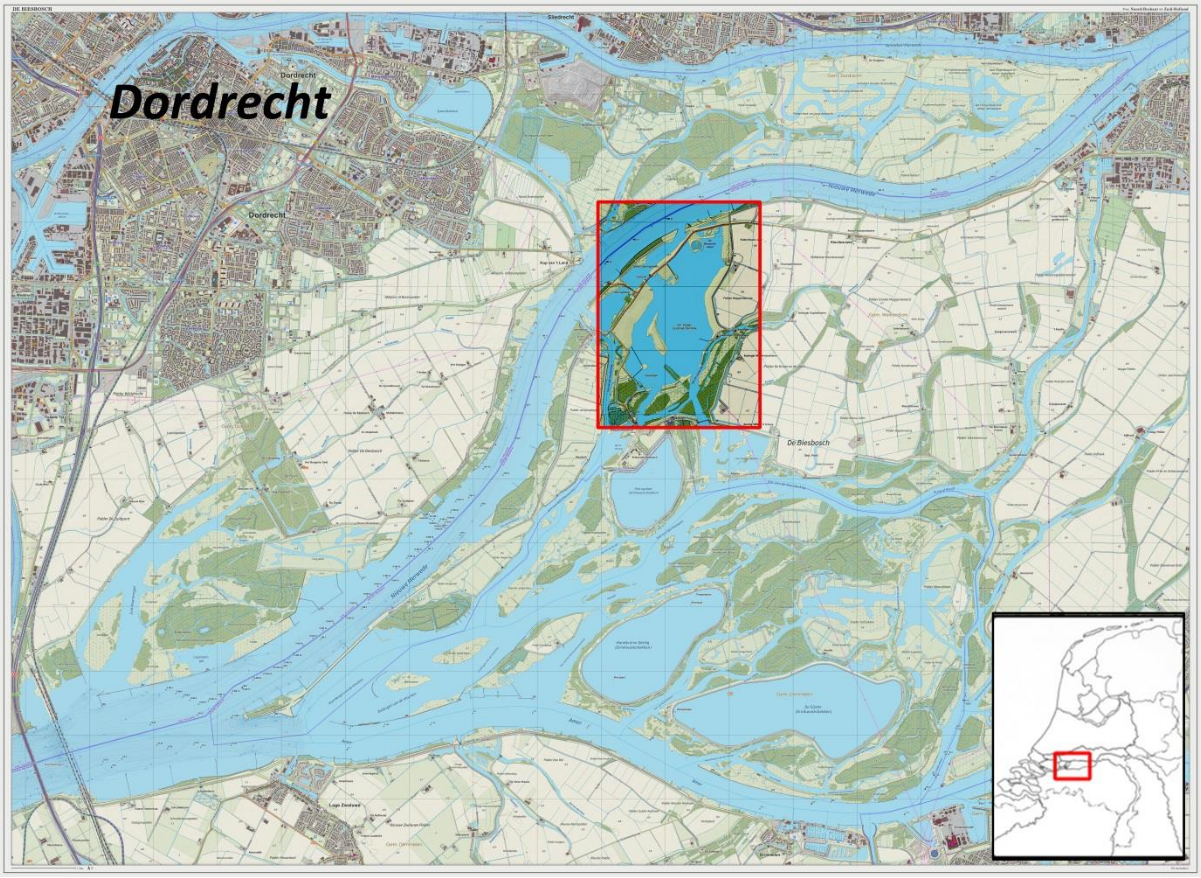


Figure 3.5: Location of the fieldwork area

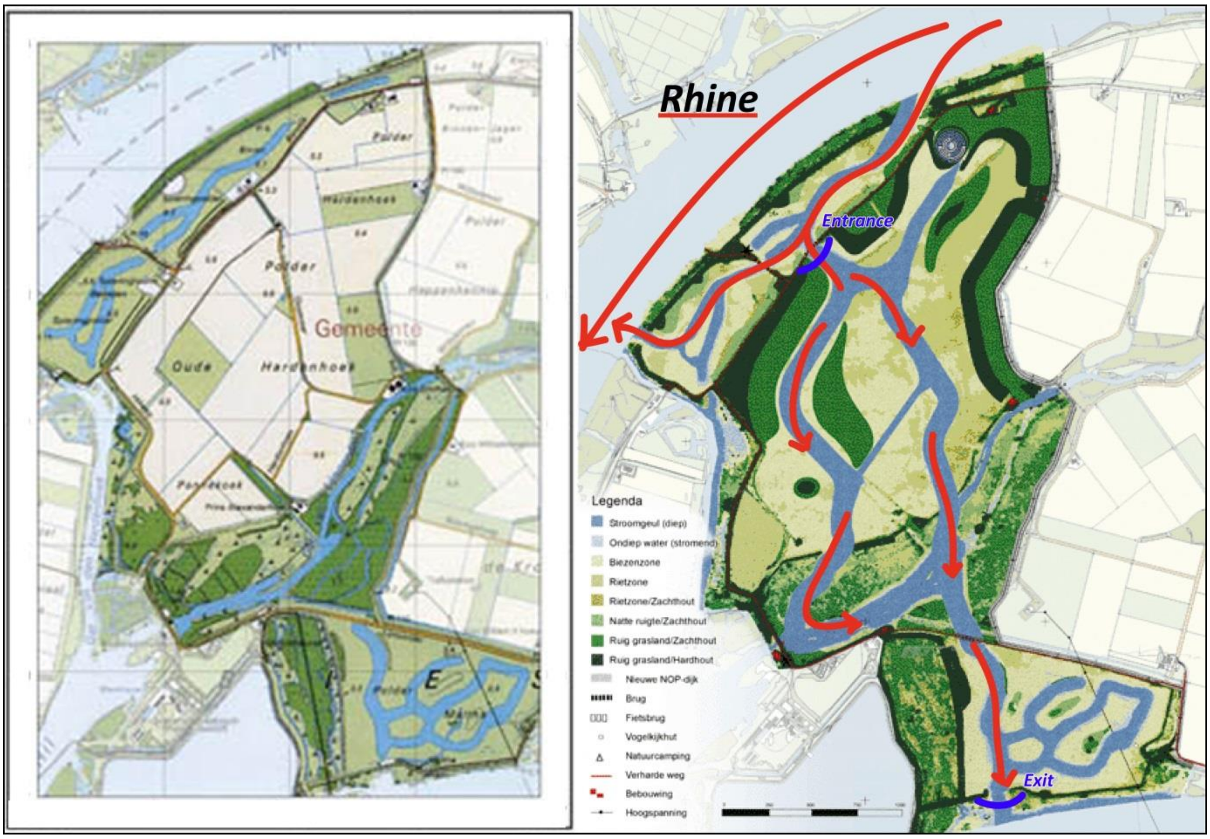


Figure 3.6: Overview of the fieldwork area before (left) and after (right) depoldering.

All these factors together make it a complex region as the water that flows through the area is being driven by multiple factors such as, tide, river discharge, storms, wind direction and the operation of the downstream Haringvliet barrier. These influencing factors and the direction their force works in have been visualized in figure 3.7. To find out how the balance between these factors is and how they affect the water flows intensive research has to be done.

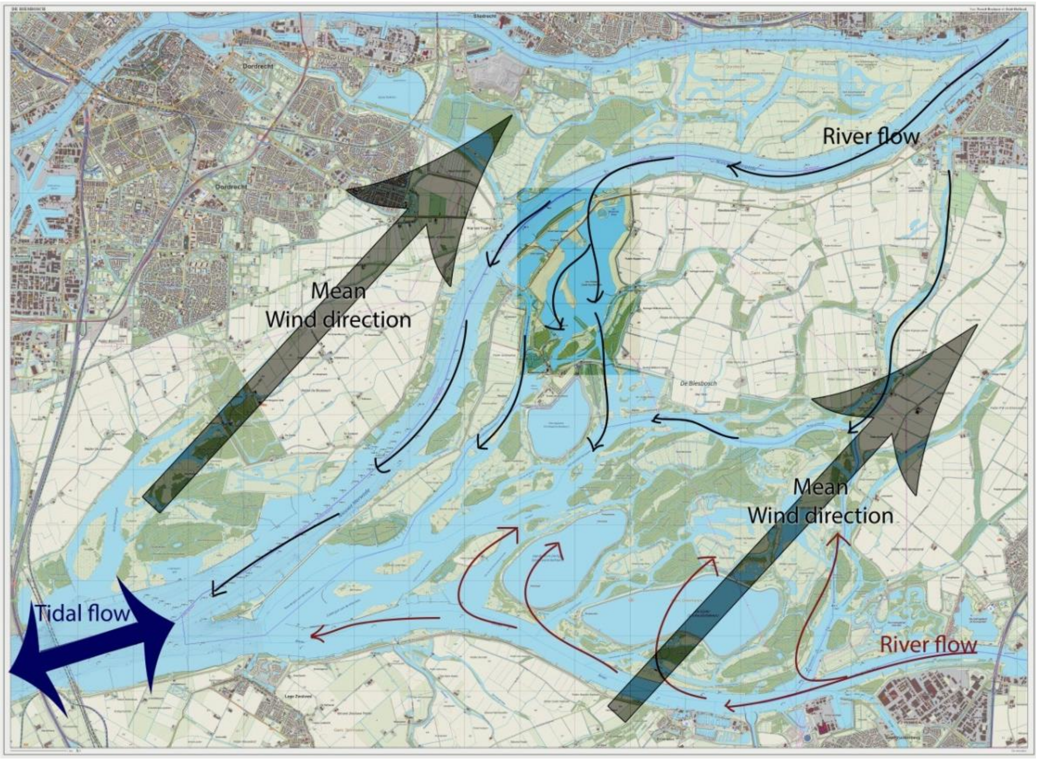


Figure 3.7: The natural influences on the flow balance in the fieldwork area.

4. Methods

The goal of this research is to quantify how the different factors influence the flow and water balance in the research area. The flow and water balance is the driving factor behind sediment delivery and erosion in the area. Since it is a very complex region, a lot of different factors were monitored at the same time, therefore multiple data sources were used. These different sources of data must be treated differently and fitted into one system to be used for these analyses. How this data was used and how the eventual analysis was performed will be described in this chapter.

The system is closed with only one inlet and one outlet. The first step is to calculate the flow volumes going in and out of the area from the raw data of the monitoring system. By monitoring the flow volumes going in and out of the system a storage volume was calculated. The response of the system on different external factors was measured by analysing the flow going in, out and through the area under different circumstances. Multiple periods with different dominant influencing factors were selected and the water balance during these periods was analysed. By analysing the changes in the water balance in these different periods it was possible to quantify the effect of the different influencing external factors.

4.1 Calculating discharges

4.1.1 Flow velocities

SBB measured flow velocities at the in- and outlet of the research area using horizontal acoustic doppler current profilers (H-ADCP) at the four locations indicated in figure 4.1. Only the H-ADCP's at locations Brug Bandijk (B) and Opening Malta (D) were used In this research as they are located at respectively the in- and outlet of the area. These H-ADCPs were installed together with divers which monitor the water levels by measuring the change in total pressure. The flow velocities and the water levels at these locations have been monitored constantly since September 2010; the data does show several gaps as the monitoring was not done adequately. The flow velocities and water levels have been measured at intervals of 10, 15 or 30 minutes. H-ADCP data consists of flow velocity profiles taken into two directions, parallel (x) and perpendicular (y) to the flow (fig. 4.2), going horizontally through the channel. The flow velocities area measured in cells; each profile consists of 9 cells. For each cell an average flow velocity is measured by the H-ADCP, the sizes of these cells vary over time from 2 meters wide to 5 meters wide. The setting of both H-ADCP's is different, allowing it to optimally measure the flow through the channel at that specific location.

Figure 4.1: Locations of the measuring points in the area.

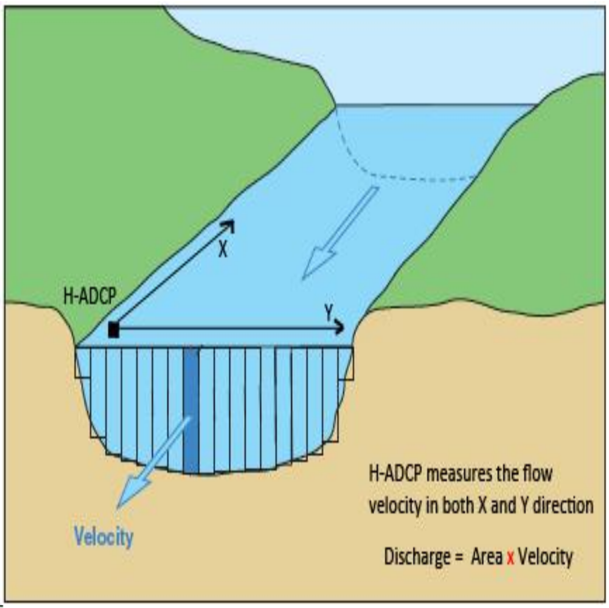


Figure 4.2: Location of the H-ADCP and the profile it measures.

4.1.2 From velocity to volume

The flow velocities measured by the H-ADCP were used to calculate the discharge that passes the point. The VPM (velocity profile method) was used to derive a mean flow velocity for each cell. The VPM assumes that there is a logarithmic velocity profile from the bed to the water surface (a vertical velocity profile), which is present in most rivers and channels. The presence of such a logarithmic profile has been tested and confirmed for the area in previous research (Visser, 2015). The velocity near the bottom (Z0) is assumed to be zero, this in combination with the velocity and height of the H-ADCP measurement (Fig. 4.3) allows the construction of a flow velocity profile by logarithmic extrapolation. From this flow velocity profile an average flow velocity is calculated by solving the integral of this profile for the water depth. This has been done for each of the nine cells of the H-ADCP, giving each cell an average flow velocity. The width of each cell has changed over time but is in all cases known. The height of the cell depends on the bathymetry and the water level. The bathymetry is measured with a multi beam echo sounder and water levels are measured using fixed divers installed next to the H-ADCP. The height of each cell is determined by adding distances X1, a fixed distance that is the distance between the bed (bathymetry) and the diver height, and X2, a variable distance that is the water level above the diver (Fig. 4.5). It is still possible to determine a discharge for each cell by multiplying the surface of the cell and the average flow velocity, thus $Q_{cell} = V_{Cell} * A_{Cell}$.

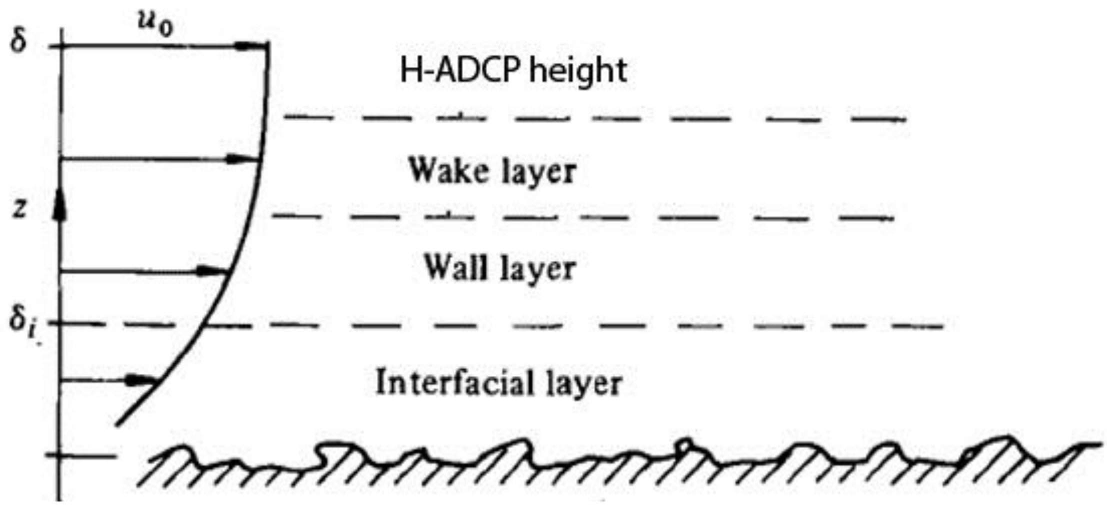


Figure 4.3: Logarithmic velocity profile and the relative height of the H-ADCP measurements.

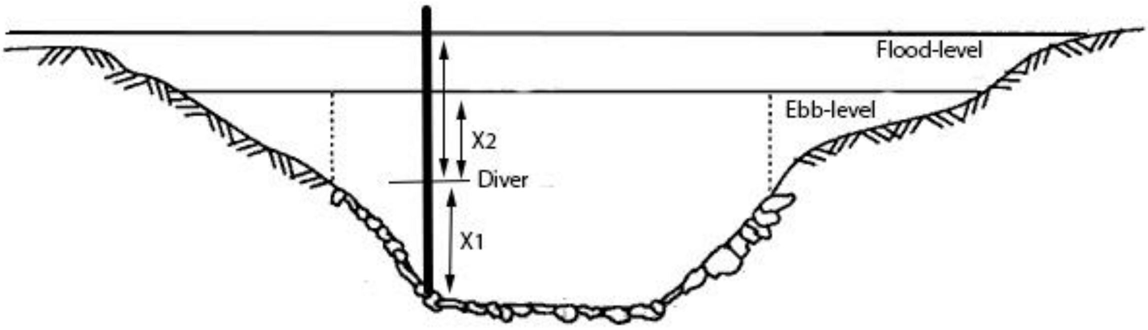


Figure 4.5: Construction height of the diver relative to the channel bed and water level.

4.1.3 From discharge per cell to total discharge

In the ideal situation the H-ADCP measures the full channel as in figure 10, in reality however it only measures part of the channel width. So to calculate the discharge of the channel more is needed than adding up the nine cellular discharges. To calculate the full discharge going through the channel additional measurements were done in the field. Detailed flow velocity profiles at both the in- and outlet were created using a vertical ADCP from a boat. By navigating the boat as slowly as possible from one bank to the other a series of flow velocity profiles were taken across the entire channel, from top to bottom, yielding the total Q through the channel. Again using the formula Q = V * A, a detailed and real discharge for the entire channel was calculated. These measurements are time consuming and cannot be done 24 hours a day. The measurements of the fixed H-ADCP's however are measuring 24 hours a day and require only maintenance. Data from the fixed H-ADCP's is available since 2010 with intervals, providing a large dataset. A relation between the discharge measured by the fixed H-ADCP's and the discharge measured by the boat was established. This relation was used to calculate a realistic flow volume with only the data from the ADCP's.

A scatter plot was created with on one side the discharge of the H-ADCP and on the other side the discharge from the V-ADCP data at the same moment. This was used to calculate a correlation factor linking a measured flow velocity to a flow volume. The correlation factor was calculated from a best fit line through the scatter plot. In order to have a realistic correlation line, real discharge measurements were done under different circumstances, providing a range of high and low discharges. Multiple correlations were applied to the dataset, varying from linear to exponential, logarithmic and power equations. The linear correlation showed the best results, which is also to be expected when correlating two measuring devices. The best fit however caused several problems in the high and low range of the data as it over or under estimates the flow volumes, causing a wrong water balance. Therefore the correlation line was forced through zero, as negative flow velocities were present in both datasets. This proved to be the best method of calculating a real discharge as it works in both the upper and lower limits of the dataset and in the averaged section as well.

4.1.4 Expanding the dataset

Because the fixed H-ADCP's are located at the entrance and exit channels of the area, it was possible to create a flow volume balance as it is a closed system. However, there are some problems with the older data, the flow volumes seem to be incorrect and often too large. This problem shows at both the in-and outlet, however at the outlet the problems are more extreme than at the inlet. Diving into these problems showed two causes of these problems: the changing size of the measuring cells and the changing bathymetry of the channel over time.

The changing size of the measuring cells causes an overestimation of the discharge using this method as it overestimates the size of the channel. The size of the channel is overestimated as in the current situations the nine cells add up to a distance of 20 meters while in the previous situations it added up to 47 meters. Multiple methods to correct this were tested but most proved unsuccessful. A correlation between the old and new situation would not work properly because the bathymetry also changed, making the correlation more complicated than just a linear relation. Other solutions based on calculating the percentage flowing through the measured part of the channel compared to the total channel also did not work. The final solution that proved to work the best is a very simple one: instead of using H-ADCP flow velocities from all the measuring cells only a selected part was used. The number of cells used in the method is based on the calculations in table 4.1. There are 6 periods of data which are measured using different settings on the H-ADCP device. The left column shows the period, the start column shows the blanking cell size, cell size is the size of each measuring cell, total gives the total range measured and the last column shows how many cells were used in the calculation. The number of cells needed in the calculation is based on the number of cells needed to reach the currently measured distance. Since the correlation of flow volumes is based on the current situation, all older situations were linked to the current situation.

Table 4.1: Starting distance, cell size, total profile length and the number of cells used in calculations.

BrBan (Inlet)	*Start (cm)*	*cell size (cm)*	*total (cm)*	*Number of cells*
2011 - 1	200	499	4691	3.67
2011 - 2	200	499	4691	3.67
2011 - 3	200	499	4691	3.67
-				
2012 - 1	50	220	2030	9.00
2014 - 1	200	200	2000	9.15
2014/2015	50	220	2030	9.00

OpMal (Outlet)	*Start (cm)*	*cell size (cm)*	*total (cm)*	*Number of cells*
2011 - 1	200	499	4691	5.41
2011 - 2	200	499	4691	5.41
2011 - 3	100	300	2800	9.33
-				
2012 - 1	200	300	2900	9.00
2014 - 1	200	399	3791	6.77
2014/2015	200	300	2900	9.00

The bathymetry provided a different problem as it has changed only partially over time. The outlet channel (OpMal) has only changed in the order of centimetres and can therefore be seen as a channel that remained the same. The inlet (BrBan) however has changed considerably (Fig. 4.6); especially between 2010 and 2011 major changes occurred. These changes were caused by a high water peak in the beginning of 2011, which is included in the data set. After this peak the situation became stable and has only changed in the order of centimetres. Therefore the depths of all periods are based on the bathymetry of 2013 except for the period of the high water peak; in this period the depths are based on the bathymetry of 2010. Since the changing cell size problem solution does not depend on any other influencing factors, adapting the depths in the model was sufficient to calculate correct discharges.

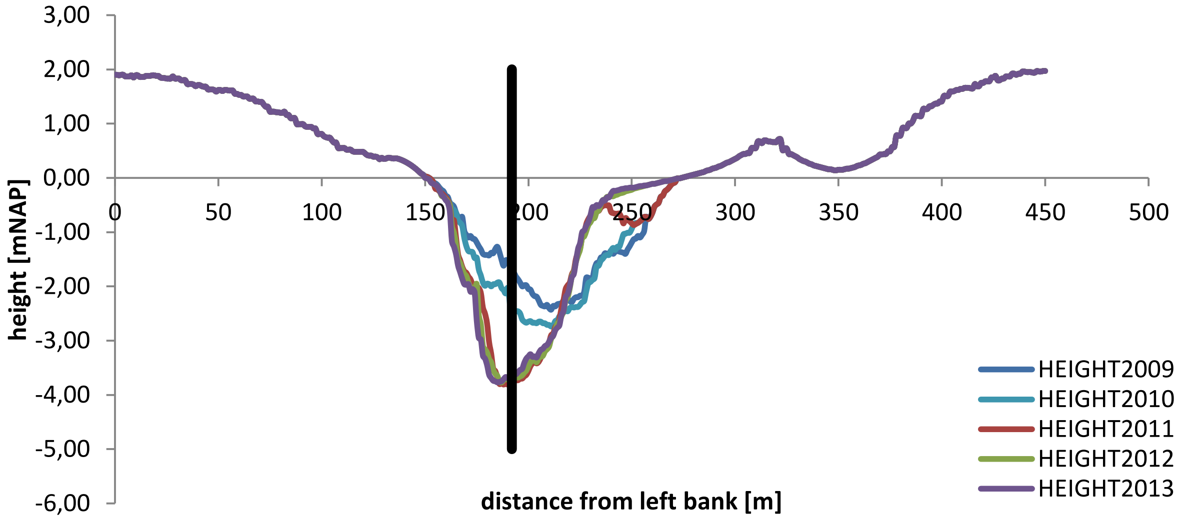


Figure 4.6: Channel development over time at the inlet (brug bandijk), vertical black line shows the location of the H-ADCP.

4.2 DEM and the basins volume

In order to check the calculated discharge volumes, the volume of the basin is needed. For this purpose the AHN ("Actueel Hoogtebestand Nederland) was used. The AHN is a file that contains detailed height information for the Netherlands. It is a digital height map with a resolution of 100 cm, and it is open data, allowing everybody to use it. The fieldwork area is also included in this file, giving us a detailed height map of the fieldwork area. Unfortunately the AHN does not indicate the depths of channels filled with water, causing it to miss data at the locations of the channels in the area. These channels however were measured in great detail for this project by RWS; using a multi beam echo sounder the bathymetry was monitored. The channels and their depths were monitored each year since 2009, this data has a resolution of 10 cm. Using ArcGIS the echo sounder data and the AHN were clipped, rasterized, adjusted and merged. This resulted in one detailed Digital Elevation Model (DEM) for the entire fieldwork area. Using volumetric calculations (surface volume function in 3D analyst, ArcGIS) the volume under a certain plane was calculated (Fig. 4.7). By setting several theoretical water levels as planes this allowed the calculation of the volume that is stored in the entire area at a specific water level.

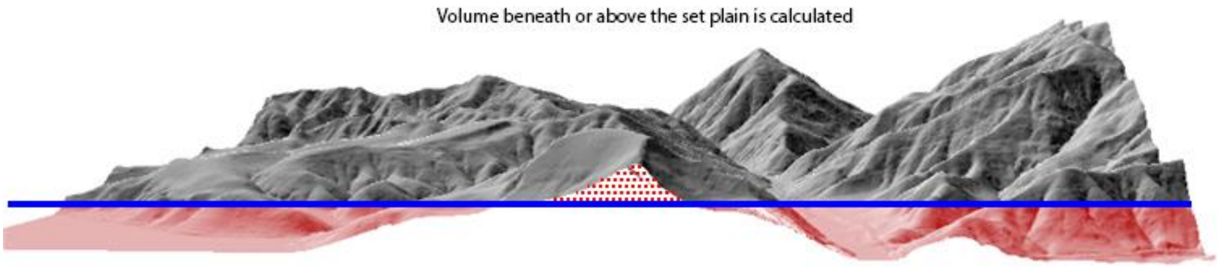


Figure 4.7: Surface volume function in 3D analyst, ArcGIS. Blue line shows the set plain and red area show the area of which the volume is calculated.

4.3 Boundary conditions

To find the influence of several external factors, the variation in discharge and retention of water in the area over time, was analyzed. To verify the reconstructed discharges from the H-ADCP data they were compared to the field measurements. A balance was created and as the system is a closed one, the balance over time should be zero. The area works as a retention basin where water is stored, the volume of the basin is therefore important used for checking the discharge and storage volumes. After checking the flow volumes it is possible to analyse the effect of each boundary condition, this was done by analysing the change in discharge caused by a changing boundary condition. The boundary conditions that are being considered are the tidal cycle, river discharge, wind direction and the Haringvliet barrier. Each of boundary conditions and their influence on the discharge were analysed separately. Two methods of analysis were applied; 1) a factor analysis where the influence of one factor over time is analysed and 2) an analysis using characteristic periods, where multiple periods were compared to each other. Each of the analysing steps is discussed in further detail to show what data is available, where it comes from and how it is used.

4.3.1 River discharge

RWS provides raw data of water levels (and discharges) from the rivers throughout the Netherlands (www.waterbase.nl). In this research the data from the river Rhine were used (several monitoring stations were used along the river Rhine). These data points are located from the Biesbosch area itself (Werkendam) upstream towards Lobith. Data from the stations: Werkendam Buiten, Vuren and Lobith were used (Fig. 4.8). These stations were chosen because together they allow the signal of the tide to be filtered out, leaving only data about the real discharge of the river and discharge controlled water depth. The discharge data from the station at Lobith was used in the sensitivity analysis for river discharge. The flood peak passing Lobith takes a little over one day to reach the research area, therefore discharge at t=1 is used in the calculations for t=2 with t in days. Note that in the analysis only discharges from the Rhine are used and no data from the Meuse is used. This is done because the Meuse's average discharge is small compared to the average discharge of the Rhine, and more importantly the water from the Meuse does not flow through the area. As seen in the overview map of the research area (Fig. 3.6) water from the Meuse can only cause set up south from the fieldwork area, and does not strongly influence the water levels in the Noordwaard. River discharge data is daily data, therefore it was only compared to the 24-hour or 25-hour average discharge in the area. In case of unexplainable measurements the Meuse river discharge was also analysed to rule out any unforeseen influence from that side.

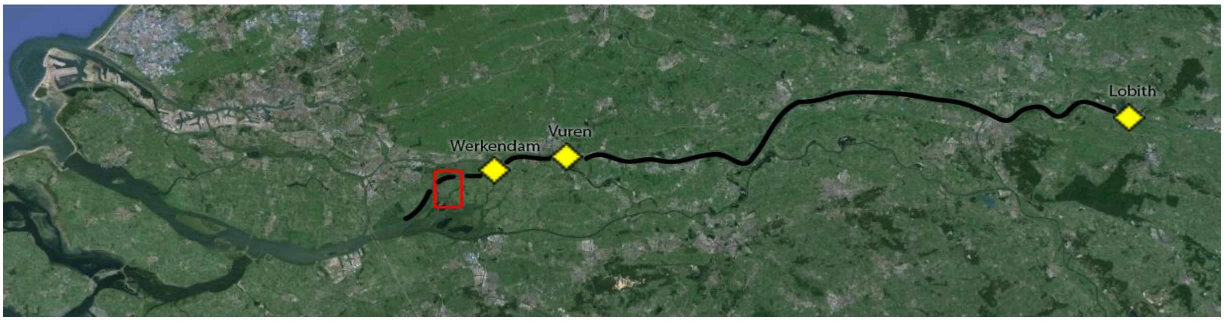


Figure 4.8: Locations of the discharge measuring stations along the Rhine.

4.3.2 Discharge regulation

RWS also keeps track of the discharge passing the Haringvliet barrier, which is an important factor in the water and flow balance. The Haringvliet barrier's main function is to protect the estuary against a high set up in the North Sea. It is also responsible for discharging all the river water into the North Sea. The Haringvliet is being closed when the discharge at Lobith drops below 1100 m^3/s, causing a set-up of water in the area. Haringvliet barrier data is daily data, providing an average discharge for 24 hours, and only available in the years 2011-2013. Unfortunately discharge data of the Haringvliet barrier is only available up to 2014. This makes it impossible to use in the analysis for data from the years 2014 and 2015.

4.3.3 Tidal cycles

Astronomical tide calculations were obtained from RWS to provide a theoretical water level at Werkendam Buiten exclusively caused by the tide. This is used in the analysis as a basic water level which provides information about the tidal components and the spring/neap tide cycle. In figure 4.9 the tidal wave is being visualized, showing the propagation of the tide through the Rhine-Meuse delta. Arrows show the direction of the wave and the colours indicate the phase in hours difference from Hoek van Holland (the inlet). Red colour indicates a time difference of +6 hours and the blue colour indicated a time difference of -6 hours. The figure shows that the tide is coming into the Biesbosch from two sides, both upstream and downstream, making it a complicated tidal environment.

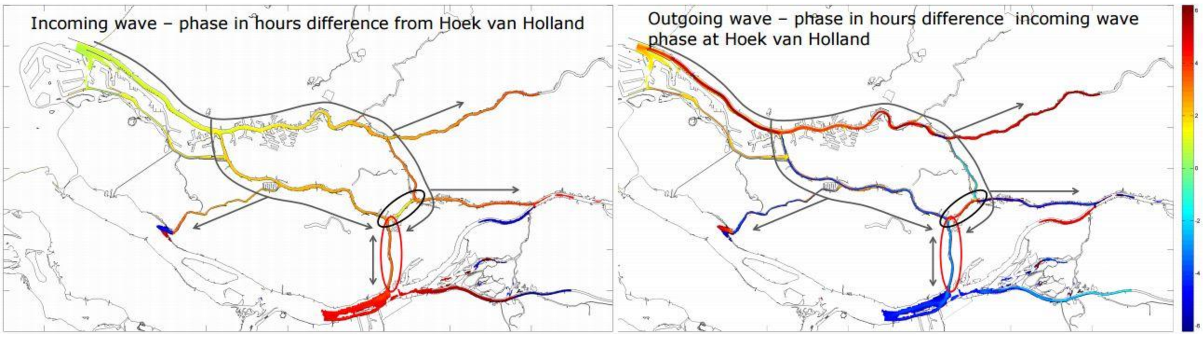


Figure 4.9: The incoming and outgoing wave – phase in hours difference from Hoek van Holland. (Vellinga et al., 2015)

4.3.4 Wind and weather

The wind direction and force is collected by the KNMI. Since no measuring station is located in the Biesbosch area itself a combination of three surrounding stations was used. The stations: Rotterdam, Gilze-rijen and Herwijnen all provide data from wind direction and force on an hourly basis. The Biesbosch area is located in the centre of these three points, therefore the combination of these measurement points was considered to provide the best estimate for the research area (Fig. 4.10).

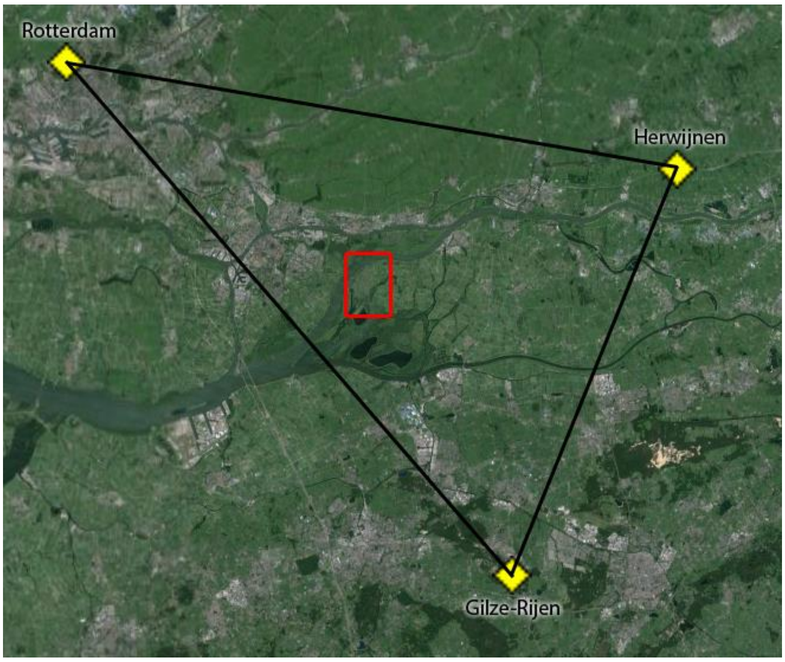


Figure 4.10: Location of the KNMI weather stations around the Biesbosch area.

4.3.5 Analysing methods

To analyse the influence of each boundary condition, two types of analysis were applied, a factorial analysis and an analysis using characteristic periods. These two methods will be (respectively) explained and discussed in further detail in the next section.

The first method of analysis is a factorial analysis, in which the influence of each boundary condition was analysed separately. This was done to determine the link between the boundary condition and the discharge going through the area, finding a relation between the two. Since the river discharge of the Rhine is expected to be the main driving force behind the flow through the area, this is the first factor to be analysed, followed by wind, tide and the Haringvliet barrier. The analysis is also a method used to find out how the different boundary conditions interact with each other.

To understand how the entire system works, three characteristic periods are compared to each other. One where the Rhine discharge is low, causing a closure of the Haringvliet barrier. One in which the Rhine discharge is average and one where the Rhine discharge is very high. These three scenarios are extremes and show perfectly how the area responds to certain conditions. For each period the external factors will be analysed to find out how they are influencing the discharge at that point in time.

The discharge in these periods is analysed in greater detail, focusing on the different boundary conditions and the reaction of the discharge. The periods consist of a time span of 5 days to be able to see ebb and flood cycles. How the area reacts on these changing boundary conditions was analysed by comparing the three periods. Using an overview sketch of the area and the water levels at several stations in- and outside the area the water balance was explained. This will be used to explain the direction and magnitude of the water flow going through and around the area.

5. Results

The results will be discussed according to the steps stated in the methods chapter, going from intermediate results to the final results. First discussing the size of the basin and how to determine the volumes going in and out, later the external factors are discussed and linked to the flow volumes to find out and explain what the main driving forces are behind the water balance.

5.1 The water balance

5.1.1 Storage volume of the Kleine Noordwaard

To put the volumes flowing in, out and through the area in perspective it is necessary to know the volume of the area itself and how much water the area can hold under different circumstances. The DEM for the entire area (Fig. 5.3), was created by combining the AHN (Fig. 5.1) and the bathymetry of the channels (Fig. 5.2). The DEM shows the deeper channels and higher dikes surrounding the area. It shows that most of the land that surrounds the channels has an elevation of approximately 50 cm + NAP. The average water level in the area is also somewhere around 50 cm + NAP, depending on the boundary conditions. This means that during normal water levels the channels are always filled, during ebb only the channels are filled and during flood a large part of the surrounding lands is inundated with a few decimetres of water. During high water levels, the surrounding lands are always flooded, varying between a thin layer (10 cm) of water and a large layer (+50 cm) of water. And during low water the surrounding lands are never flooded, as the water during flood never exceeds 50 cm + NAP, keeping only the channels filled. With this DEM a volume was calculated that shows the amount of water that can be stored in the area during a certain water level (Fig. 24).

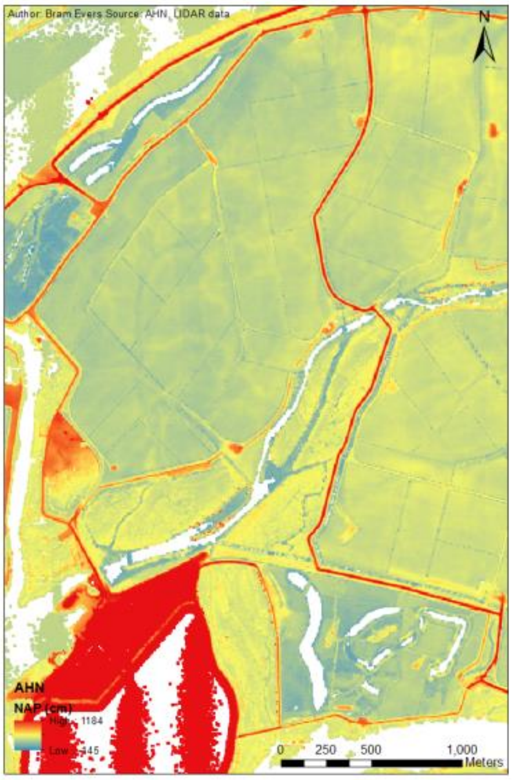


Figure 5.1: Digital elevation model of the Netherlands (AHN) showing height in meters +/-

Figure 5.2: Digital elevation model of the channels in the area showing height in meters +/- NAP.

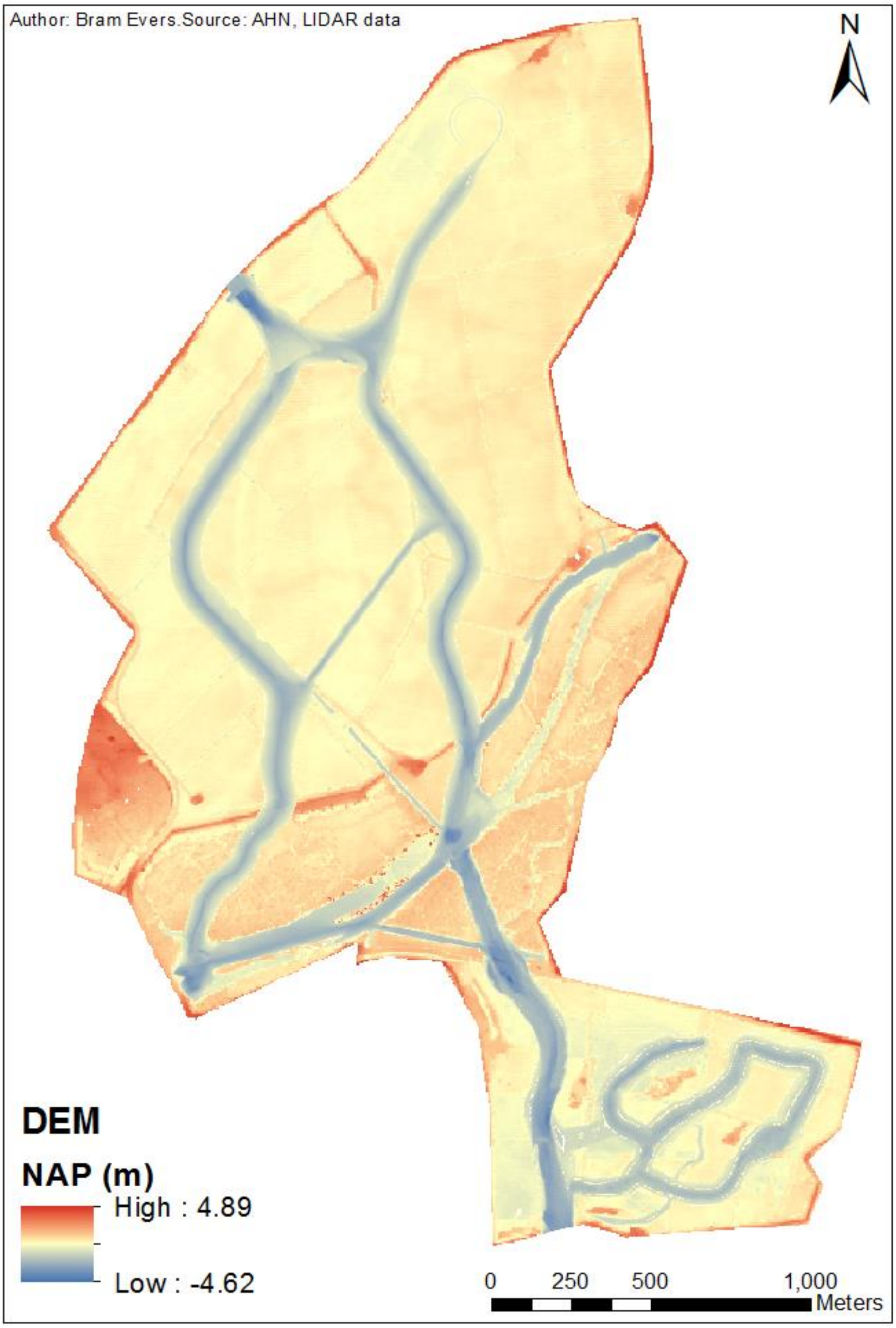


Figure 5.3: Digital elevation model of the research area, showing height in meters +/- NAP.

The graph in figure 5.4 shows the amount of water that the area can hold as a retention basin for a certain water level. When looking at the graph it is visible that first the channels are filled with water and that at approximately 0.5m +NAP (break point) the channels are starting to overflow and inundate the land. The graph before this break point is an exponential line as channels are getting wider near the top, so with each centimetre that the water level rises, an increasing amount of water is stored in the channels. After the breaking point the line is almost linear, this shows that for each centimetre that the water level rises above 0.5m +NAP, an equal amount of extra water is being stored. This is because the largest part of the area is a flat surface with only small height differences and because the area has a limited size due to the surrounding dikes.

The graph shows that a water level of 4m +NAP would result in a storage volume of 18.5 million m^3, of course such a water level is not realistic. The highest measured water level in our data set occurred during the 2015 high water peak, peaking at a water level of 1.88m +NAP (8.5 million m^3). The lowest measured water level in our data set is 0.05m – NAP during the drought of 2011 (1.3 million m^3). This means that during the data set the maximum available storage room for water is 7.2 million m^3 (high-low). This is however not the volume that is being stored during a peak discharge, as water levels before the peak are almost always higher than the lowest measured water level in the data set. Meaning that the actual volume that can be stored during a high water peak lies somewhere around 5 million m^3. As a reference value, the Rhine near Lobith transports 2000m3/s on average, which means it can fill up the area in a mere 45 minutes. The main reason for calculating the available storage volume however was to check how well the measurements are and whether or not we truly monitor a closed basin.

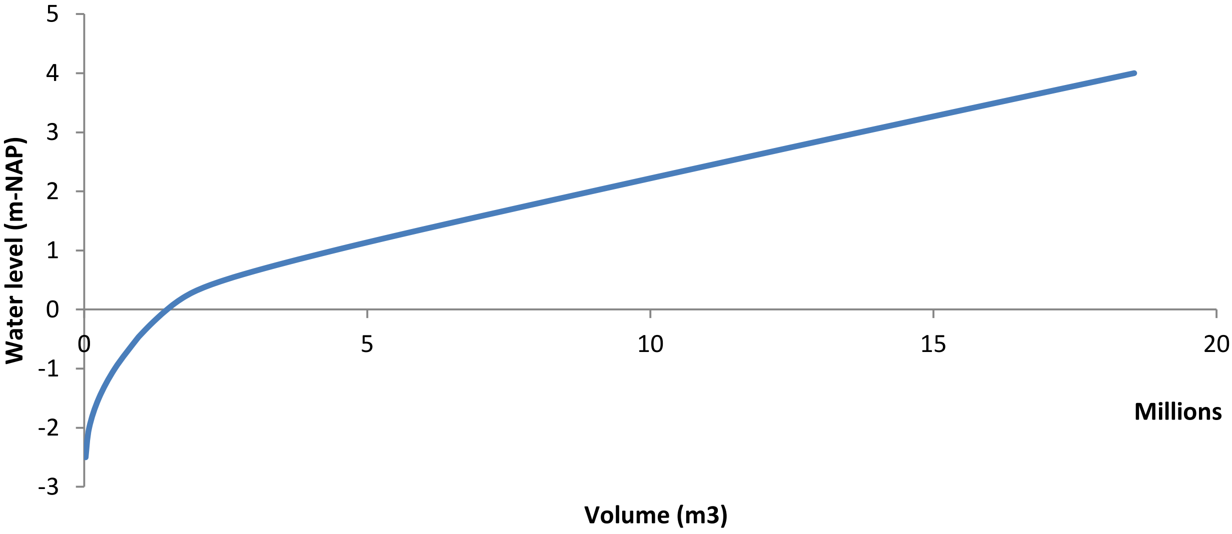


Figure 5.4: Amount of water that can be stored in the area at a certain water level.

5.1.2 Conversion of H-ADCP data to discharge

Part of the H-ADCP data is plotted in figure 5.5, it shows the raw data from the measurements to give an idea about the magnitudes of the flow. The H-ADCP measures speed in m/s, the graph shows the data for a period of 21 days. The blue line shows the measured velocity in the first cell in the X-direction (perpendicular to the channel) the red line shows the velocity of the first cell in the Y-direction (parallel to the channel). It shows the strong difference between ebb and flood speeds, which is the daily variation which reaches maxima of almost 1.0 m/s and shows minima of -0.2 m/s. The data also shows the spring/neap tide cycle which is visible in the fluctuating maxima (and minima) over the entire period. Near the end of the visible period negative flow velocities are observed.

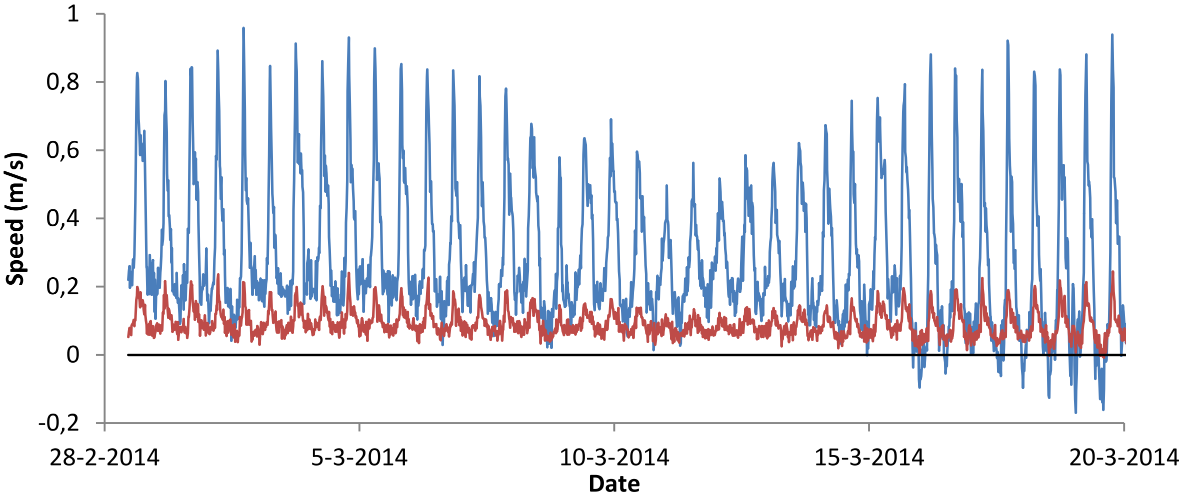


Figure 5.5: Raw data from the H-ADCP at the inlet (BrBan), showing the measured flow velocities in m/s for a period of 21 days. Red line indicates flow velocity measured in the Y-direction (parallel to the flow) and the blue line indicates flow velocity measured in the X-direction (perpendicular to the flow).

The first step in creating the volume balance is to correlate the real measured discharge to the discharge measured by the H-ADCP's. Figure 5.6 shows this correlation for BrBan (inlet) and figure 5.7 shows this correlation for Malta (outlet). Both figures show a linear relation between the real Q, measured by the ADCP from the boat, on the Y-axis and the H-ADCP Q, calculated from the permanent measuring devices at the in-and outlet, on the X-axis. The relation is assumed to be a linear one since it is used to correlate two measuring device and the scatter plot also indicates a linear relation. Also other relations, such as exponential and logarithmic resulted in a worse result.

When starting with the project it was expected that the flow direction should always be in the downstream river direction, a deeper analysis of the data however showed several cases of negative flow velocities. These negative flow velocities were consistent during typical conditions, making it impossible to be measuring errors. Therefore the correlations of both the in- and outlet were forced through (0.0). For the inlet the correlation did not change much (as it already had a natural path going through (0.0)). The outlet however was not going through (0.0), as the red dotted line shows (Fig. 5.7). Forcing the correlation through the origin therefore caused the correlation to become much lower as the R^2 decreased from 0.86 to 0.39. The end result however is better as it now acknowledges the negative flow velocities.

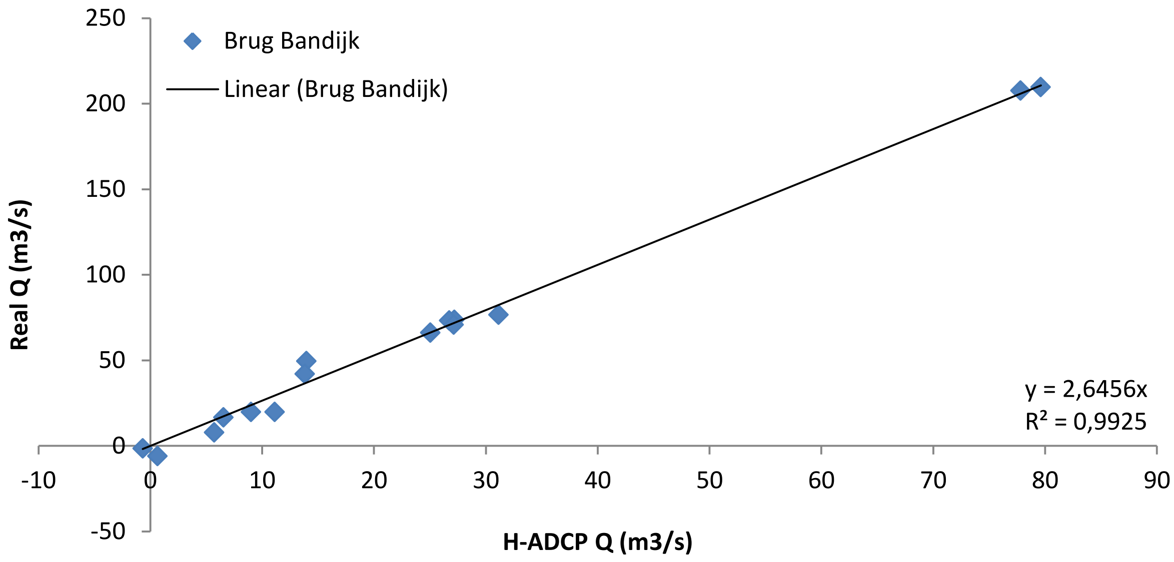


Figure 5.6: Correlation linking the real discharge to the H-ADCP measured one for the inlet (Brug Bandijk).

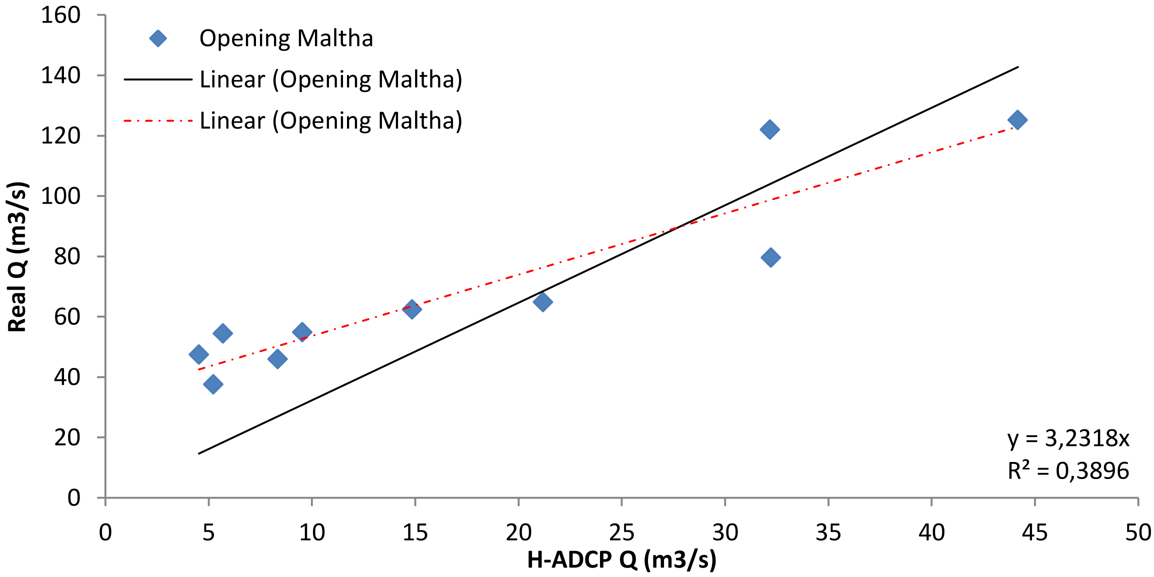


Figure 5.7: Correlation linking the real discharge to the H-ADCP measured one for the outlet (Opening Malta).

5.1.3 H-ADCP data converted to time series of discharge

The conversion is used to calculate real discharges from the H-ADCP dataset. The data set contains three periods in which the data is complete and reliable (table 5.1), resulting in three periods with a combined length of 484 days. Figure 5.8 shows the discharges during these periods. In all three figures the calculated Q (Y-axis) is plotted against time (X-axis). The flow volumes (Q) have been averaged over 25-hours. The 25-hour average has been taken to filter out the influence of tides and hence to determine the net daily flow into and out of the area.

Table 5.1: Used data periods, showing the date and number of days.

Period	**Start date**	**End date**	**Number of Days**
I	1/1/2011	16/7/2011	197
II	3/1/2014	17/5/2014	78
III	18/7/2014	11/2/2015	209

The figures (5.8) show the inflow (blue) and outflow (red) for the three periods. When looking at period I for example, it becomes clear that the in-and outflow are quite close to each other, alternating one another throughout the period. The inflow is a bit higher, indicating that the area is filling up, but at periods it is also visible that the outflow lies above the inflow, indicating that the area is draining. Ideally the in- and outflow should be in balance as it is a closed system with some space for storage in the middle. The figures also show that the volumes going in and out of the area are almost never constant but constantly changing, these changes in flow are caused by the external factors, which will be discussed later on. These observations are true for each period, not just period I. Each figure (period) will be discussed separately on the observed discharge.

Period I (Fig. 5.8) shows a large peak in the beginning where both the in- and outflow volumes reach up to 250 m^3/s. During this peak the inflow and outflow are equally large, and there is almost no variation caused by tide. This peak is caused by a large peak discharge coming from the river Rhine. After this high water peak the graph flattens out and shows almost no more fluctuation on such a large scale. The fluctuation nog takes place on a smaller scale, indicating other driving forces. The Rhine has a small discharge during this period and there are times at which the Haringvliet barrier is closed. The period actually consists of 3 smaller periods which are combined, which is visible as there are small gaps in between. During the 2nd period (2/15 - 5/01) the inlet is constantly measuring a higher flow volume than the outlet. This might be caused by a defect in the measuring devices, but there is no evidence for this assumption.

Period II (Fig. 5.8) is not as interesting as it takes place during a relatively calm period, in which the amount of water flowing through the Rivers is small. It shows higher discharges in the beginning and near the end with lower flow volumes in the middle.

Period III (Fig. 5.8) shows a lot of fluctuation in the amount of discharge, this is partly due to the fact that it is the longest period and because the river discharge varied a lot during this period. Near the end two strong peaks are visible, both caused by a large peak in river discharge.

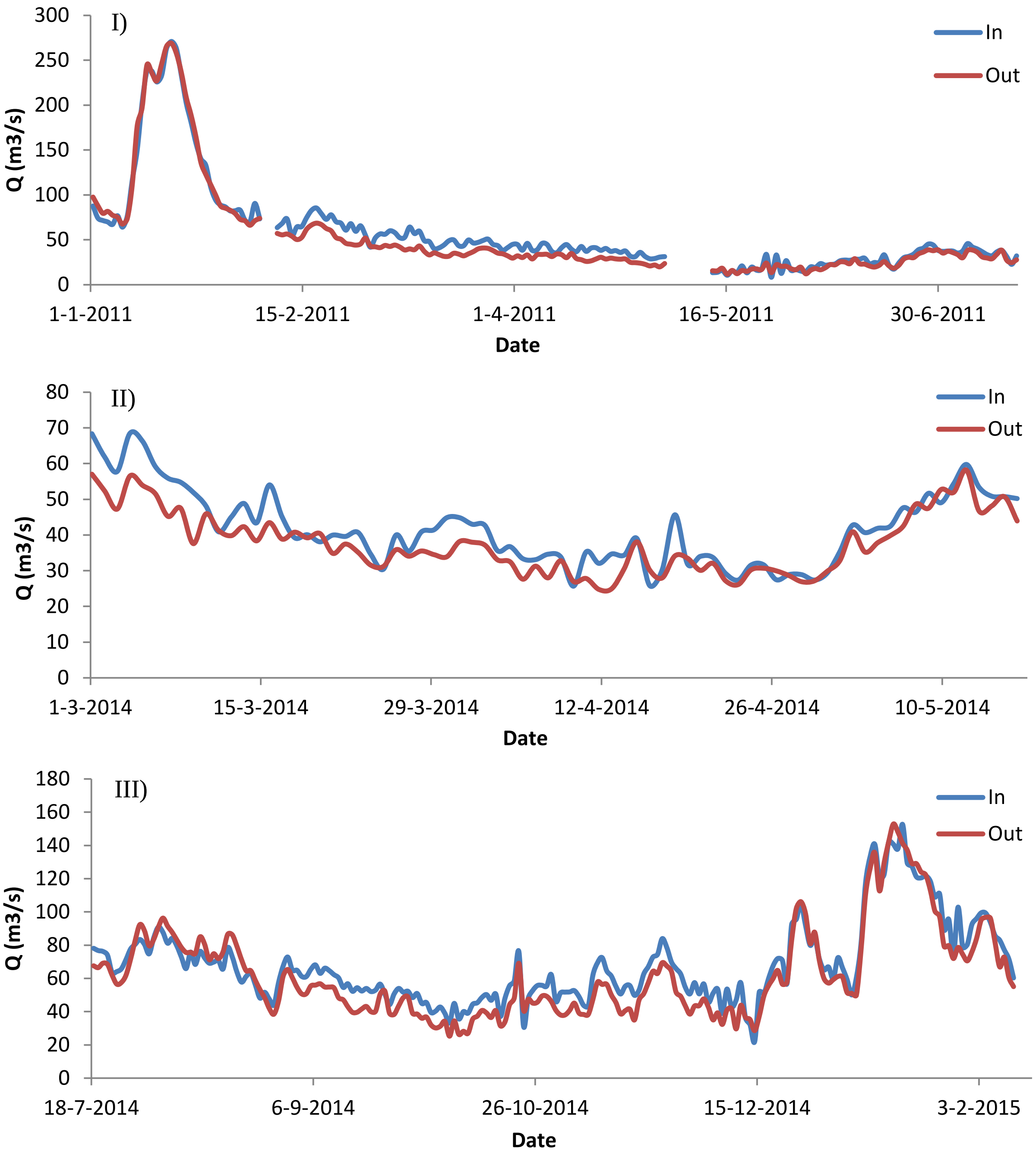


Figure 5.8: Discharge in m3/s for three different periods (I, II and III) at both the in-and outlet.

5.1.4 Cumulative volumes

The blue line in figure 5.9 shows the water volume stored in the area, resulting from the cumulative difference between Q-in and Q-out. Expected is a cumulative volume that equals 0 as the system is a closed one, the line however shows a progressive rise. Therefore the red line in this same figure is created, it also shows the cumulative difference between Q-in and Q-out but is balanced over the total period. Both lines are described in further detail, starting with the unbalanced or raw data.

Looking at the cumulative volumes it is clear that they are quite large and that the line only goes up. This suggests that the area is constantly filling up. This could be possible for a small period, but it cannot be true that the area is continuously filling up for almost 500 days straight. The amount of water that the area can store is approximately 5 million m^3, which is much less than the amount that is being stored according to the graphs below. According to the graphs the storage should be somewhere around 100 million m^3, which is a factor 20 larger than the amount the area can actually store. This shows us there is a problem, there is constantly more water flowing into the area than there is water flowing out of the area. When looking at the cumulative volumes the amounts of water are very extreme and nowhere near reality. When looking at how much more there is flowing in than there is flowing out (percentages), it is not that extreme. For the first period there is a difference of +14.5%, the second period has a difference of +10.7% and the third period shows a difference of 9.0%. This means that there is roughly 10% more inflow than there is outflow. When you add these numbers up for a long period of time, the volumes become extremely large, but the difference is not so extreme.

The fact that the inflow is larger than the outflow can be explained by a number of reasons. First of there are measuring errors, the H-ADCP's do not measure the entire channel, so it is possible that the flow works different under circumstances we have not measured yet. But overall this should be dealt with by the conversion factor of both the in- and outlet. Secondly it is possible that during high water there is a reversed current going out of the area near the inlet, there have been several strange measurements in the field at the side of the channel which can be explained by this reversed current. This would mean that part of the outflow is not measured, leading to a larger inflow than outflow. The most reasonable explanation however is that it is a stacking of systematic measuring errors, and a conversion factor between the H-ADCP and V-ADCP that is not perfect.

Since there is constantly more water flowing in than out and the error is around 10% it should be possible to balance this error out by adding 10% to the outflow for each measurement. This is what the red line indicates, and it shows an improvement of the results as the volumes are becoming less extreme and the area is not filling up endlessly anymore. However it does not solve the problem as it still shows volumes going from -30 million m^3 to + 30 million m^3. These volumes still add up to a storage of around 60 million m3, which is still a factor 12 too high compared to the storage that is actually possible in the area. The problem with this solution is that it adds up a set percentage to each time step, but in reality the amount that needs to be added is not the same. The origin of this problem probably lies in the conversion factor of the outlet (OpMal) (Fig. 5.7). The difference between the free line and the line forced through (0.0) is not the same along the line. Among the lower discharges the used correlation underestimates the real discharge while in the higher section it overestimates the real discharge. So in some cases there should be 20% added and in some cases the discharge is actually correct. Since discharges in the lower section occur more frequent than higher discharges, this increases the magnitude of the problem. As the largest difference between the free line and the line forced through (0.0) occurs at low discharge levels. The difference in the cumulative volumes can thus be explained but not solved.

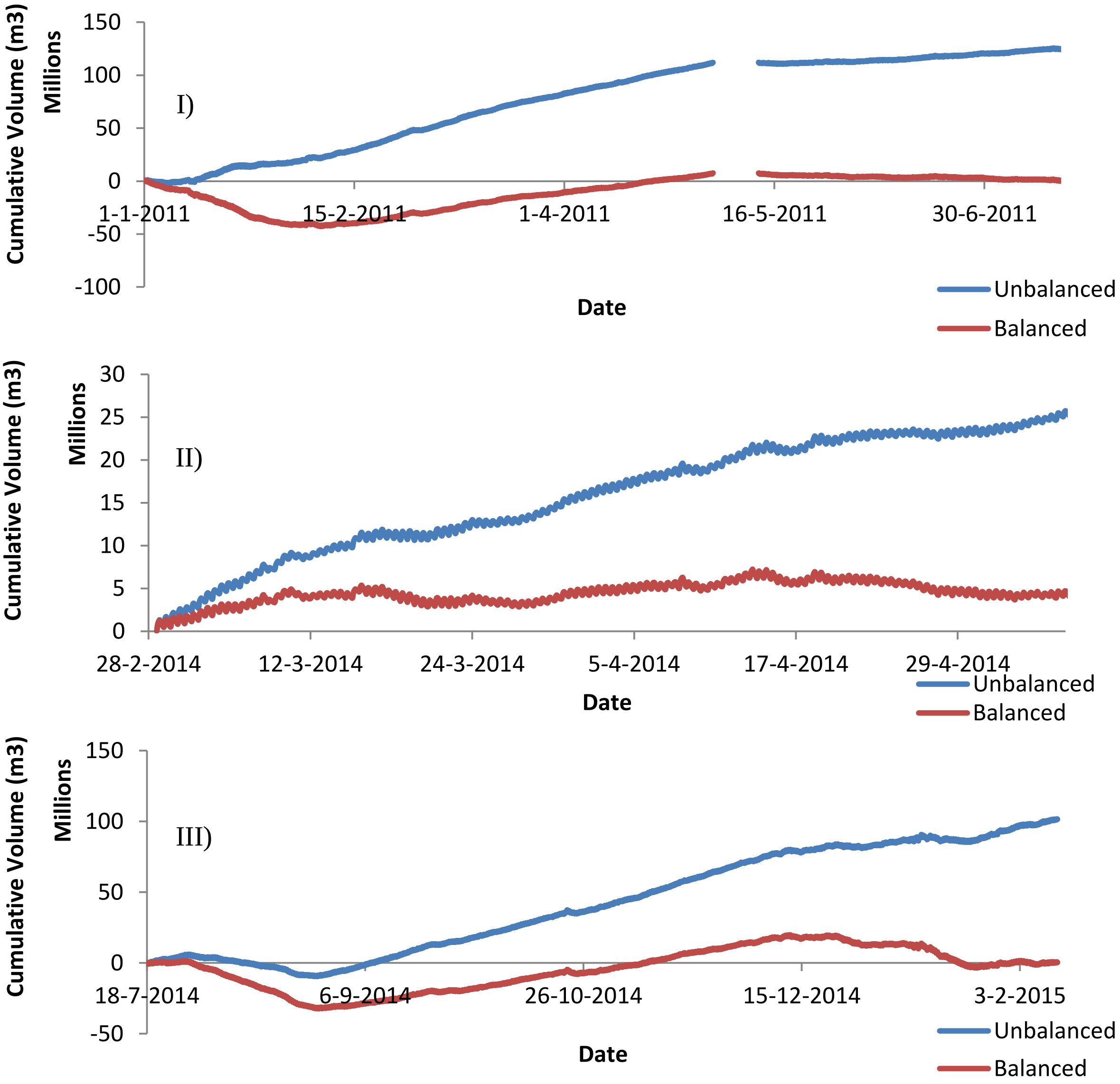


Figure 5.9: Cumulative volumes for the three periods (I, II and III) that are stored in the area, calculated by subtracting volumes going out from the volumes going in.

5.2 The boundary conditions

The flow volumes through the area are changing from time to time, going from a high discharge to a low discharge and back. The causes of these changes in the flow are the external factors; the discharge of the Rhine, the opening of the Haringvliet barrier, the tidal cycles and the wind. In this chapter these external factors will be highlighted and their effects on the flow will be analysed.

5.2.1 The discharge of the Rhine

The research area can in some ways been seen as a side channel of the Nieuwe Merwede, one of the branches from the river Rhine, the Q into the area comes directly from the Nieuwe Merwede. The discharge going in and out of the area is therefore plotted against the discharge of the Rhine to find a relation between the discharge of the Rhine and the discharge in and out of the area (Fig. 5.10).

Both Q-in and Q-out correlate well with Q-lb (Lobith), the correlations are close to very each other, showing only minor differences. This means that the discharge of the Rhine at Lobith strongly controls the discharge going in and out of the area. The correlation of the inlet (Bandijk) starts higher and ends lower than the line of the outlet (Malta). This is to be expected as in the end there should be a balance in water flowing in and out of the area, making it necessary for the lines to cross each other. It shows that in most cases there is more inflow than outflow, which is something that is also visible when looking at the discharge data in chapter 5.1.3. When discharge of the Rhine increases the balance shifts and the Q-out becomes larger than the Q-in. This might seem a bit odd, but can be explained by the Haringvliet barrier. The discharge through the Haringvliet barrier will increase when discharge of the Rhine increases, causing it to drain the area, creating a high downstream gradient. The discharge flowing through the area can thus be seen as a fraction of the discharge of the Rhine which is influenced by other boundary conditions.

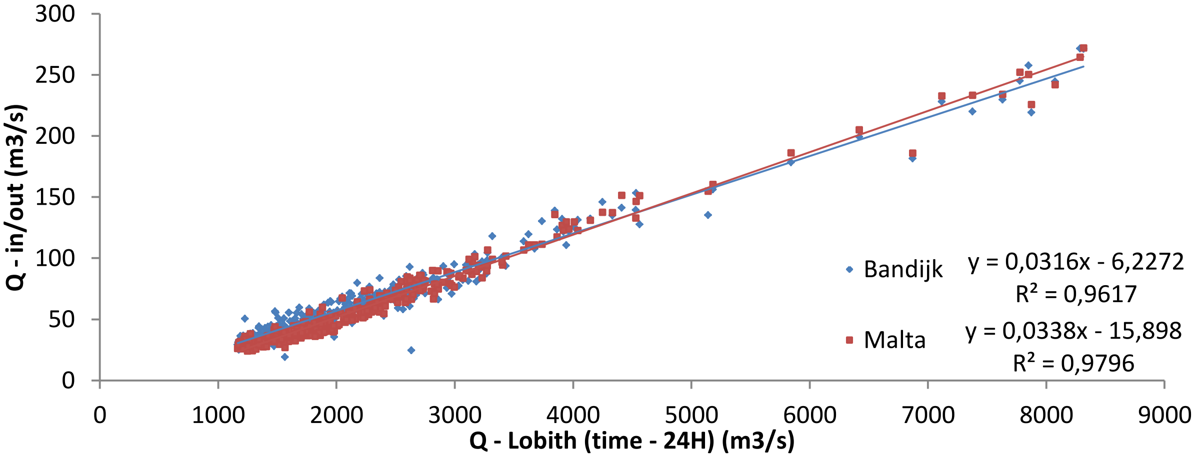


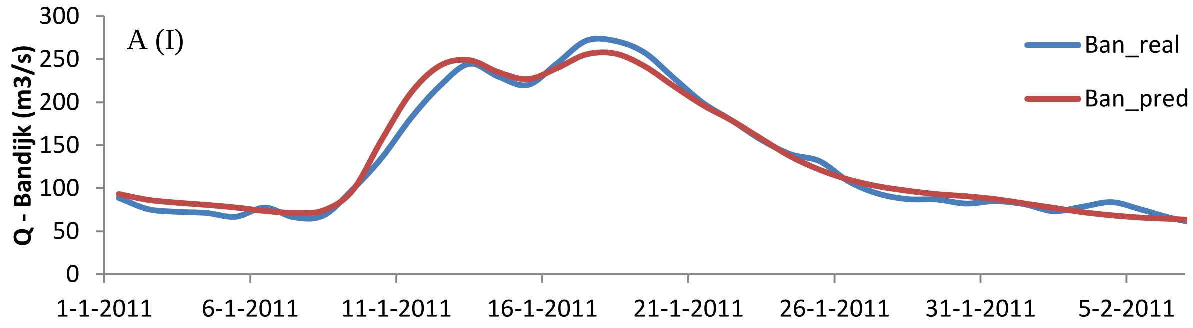
Figure 5.10: Correlation between the discharge through the area (inlet/bandijk and outlet/malta) and the discharge of the Rhine at Lobith.

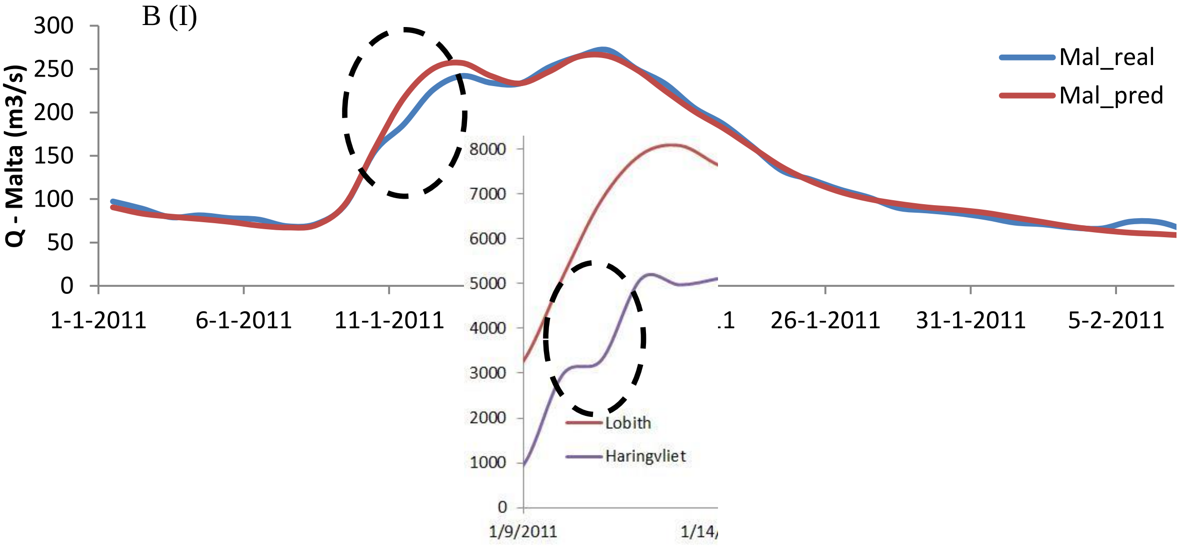
Using the correlation above a prediction can be made for the discharge that should go through the area. This prediction can be seen in figure 5.11, which shows the theoretical discharges in red and the actual measured discharge in blue for three periods. The first figure is the inlet (Bandijk) and the second figure is the outlet (Malta).

The predicted and measured Q show agreement for both the in- and outlet. The main line is the same but the actual measured discharge line shows more short term variability in its signal. These differences are due to the other boundary conditions; tide, wind and the Haringvliet barrier.

Figure 5.11b shows a remarkable difference between the in- and outlet, the highlighted part shows a breakpoint in the measured discharge, one which is not present in the predicted discharge. This breakpoint is very clear in the outlet discharge, and less obvious in the inlet discharge, but still present. The small graph placed next to this breakpoint shows the discharge of the Rhine (red) and the Haringvliet barrier (purple). The Haringvliet discharge clearly shows the same breakpoint, while it is not present in the Rhine’s discharge. The Haringvliet barrier discharge has a stronger influence on the outlet’s discharge than on the inlet’s discharge as the outlet is much closer to the Haringvliet barrier and the research area works as a buffer, damping the signal.

The short term variability surrounding the signal is mostly not present in the predicted discharge, but they are present in both the in- and outlet data. Most of this short term variability is caused by the influence of wind. When plotting the wind speed and direction under discharge graphs, the peaks and minima all line up almost perfectly, this will be discussed next. However, it can be concluded that the largest part of the discharge that goes through the area is based on the discharge that flows through the Rhine.





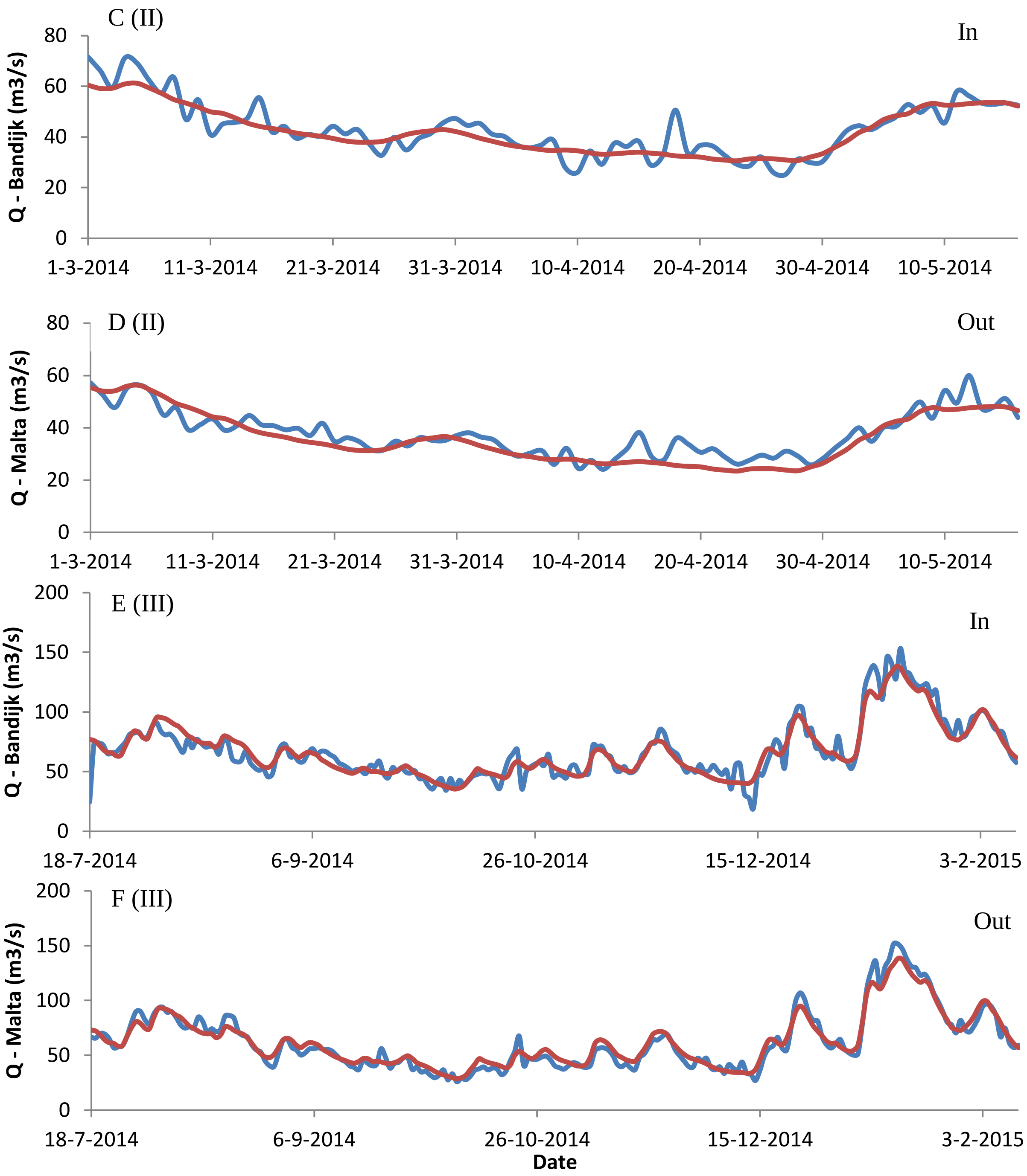


Figure 5.11: Predicted (red) and real (blue) discharges based on the Rhine discharge for both the in-(Bandijk) and outlet (Malta) for three different periods (I, II, III).

5.2.2 The influence of wind

Wind is an ever changing factor which hardly stays the same for a longer period of time, making it a difficult factor to analyse, as an increase or decrease in discharge is hard to tie to the changing wind. Figure 5.12 shows the wind speed (blue) and the wind direction (red) for period II which is plotted above. When looking at the peaks in both the wind and discharge graphs they seem to coincide. But not each peak in wind speed coincides with a peak in discharge, as it depends on the direction of the wind whether an increase in speed also causes an increasing discharge. And as figure 5.12 shows, the speed and direction of wind are constantly changing, being hardly stable. Looking at the wind influence on a qualitative scale, a strong connection is visible as the peaks in discharge often coincide with the peaks in wind speed. So there is a strong connection between the wind that blows and the discharge that flows, but it is very difficult to analyse this connection in a quantitative way.

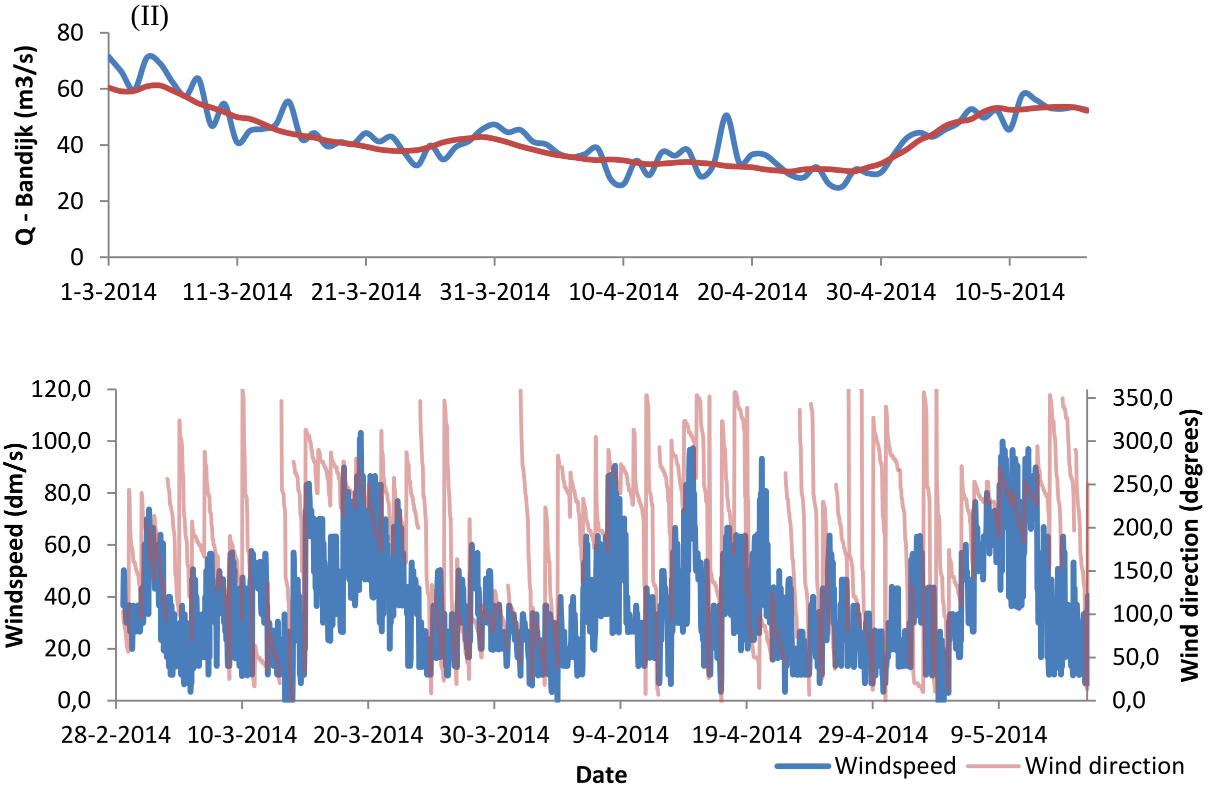


Figure 5.12: up: discharge in period II, down: Wind direction and speed for period II

The quantitative analysis that gave the best result is displayed in figure 5.13. This figure shows the percentage of time that an increase or decrease in discharge occurs when the wind comes from a certain direction. For this figure 25-hour data was used knowing that the wind has probably changed in that time span, but it is the only feasible way to filter out the tidal influence. Wind speed has been averaged over 25-hour period and wind direction is cut into 12 main directions. In the figure numbers in green mean an increase from that direction, numbers in red mean a decrease and = means there is a 50% chance of in- or decrease. For example when the wind comes from the West, there is a 60% chance that the discharge through the area will increase.

Wind coming from directions W and WNW mostly cause an increase in discharge through the area, respectively in 60% and 78% of the time. Wind coming from NNE and NEE cause a decrease in discharge, in respectively 60% and 77% of the time. Wind from directions S and SSE almost always cause a decrease in discharge, respectively in 69% and 80% of the time. This is to be expected when looking at the wind direction and the channels in the area. Wind from S and SSE causes water to stagnate as it works against the natural flow direction. Wind from NNE and NEE pushes water into the SW part of the area, making it harder to flow towards the exit, it also pushes water away from the entrance which causes a decrease in discharge. Wind from the W and especially the WNW push water towards the entrance and exit, working with the natural flow direction to increase the flow volumes. When looking at the map, one would expect to see an increase in discharge when wind is coming from the North. This cannot be observed from our dataset, probably because wind from that direction is quite rare, causing it to nearly always be mixed with other directions when looking at 25-hour periods. The increase or decrease of the discharge caused by wind effects is mostly small (around 5 m^3/s) but can reach up to a maximum of 20 m^3/s. Overall wind causes an increase when it has the same direction as the natural flow and it causes a decrease when it works against the natural flow.

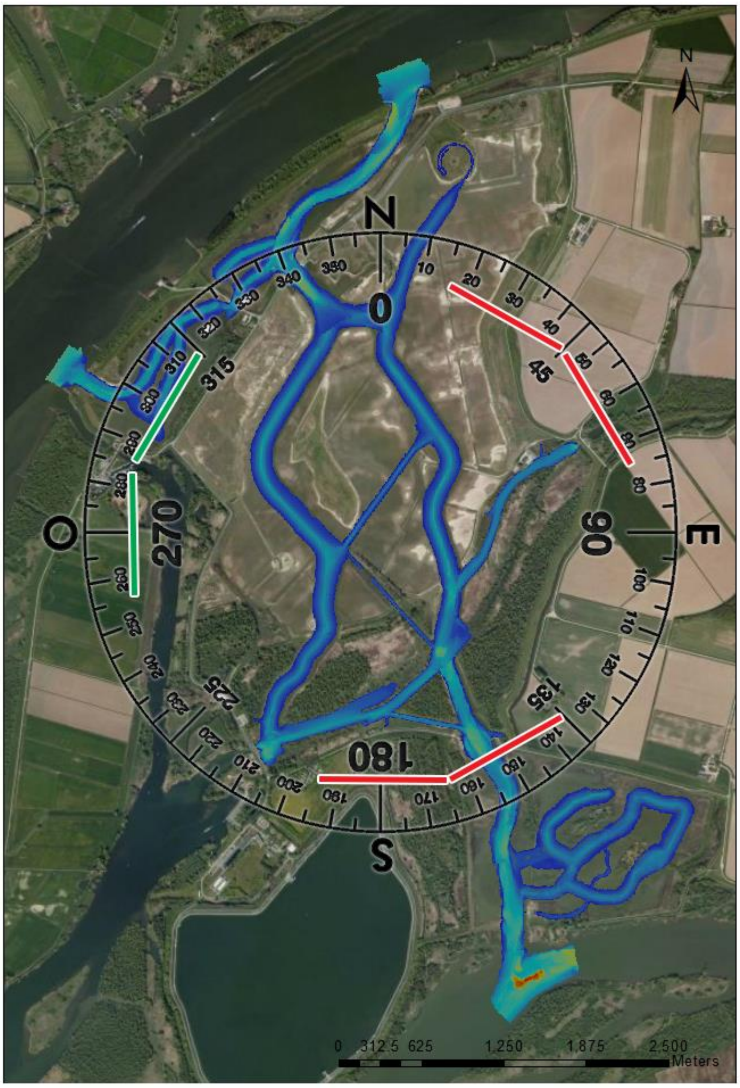


Figure 5.13: The effect of wind from specific wind directions on the discharge going through the area.

5.2.3 The tidal influence

Figure 5.14 shows the astronomical tide in the area, this is the tidal movement created by the astronomical influences, not affected by river discharges or other external factors. When looking at the graph it becomes clear that for the year 2014 the tidal range is slightly larger during the winter month than during the summer months. Next to this yearly cycle there is also a monthly cycle that creates spring and neap tides. The tidal range for a spring and neap tide is respectively 60 and 40 cm, giving a difference of approximately 20 cm. It therefore has an important influence on the observed discharges.

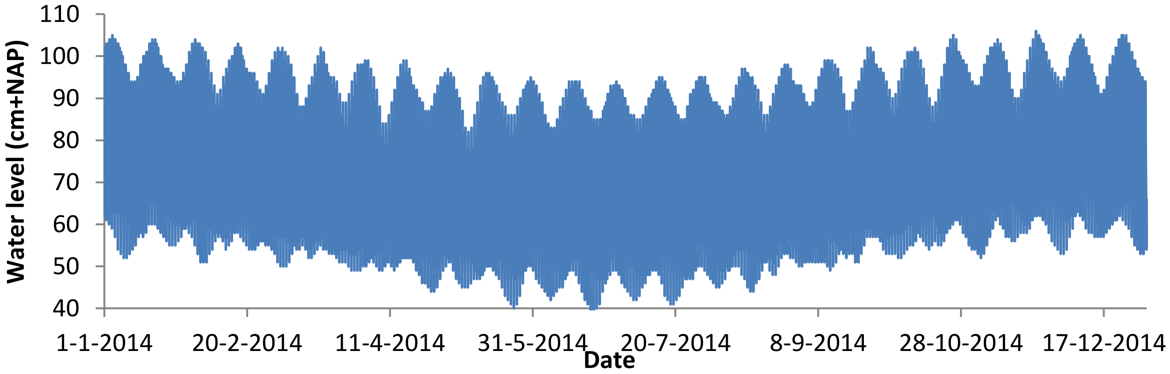


Figure 5.14: Tidal cycles at Werkendam for 2014, showing the neap and spring tide cycles.

As mentioned above, the area knows a semi diurnal tide which is flood dominated (Fig. 5.15). This causes high flow velocities between ebb and flood, and lower flow velocities between flood and ebb. This influences the flow going through the area as it influences the discharge going in and out, and thus the volume being stored. Water rises fast in the area causing the flow through the area to be hindered, which causes more storage. When the area was ebb dominated this would have caused the area to drain faster, which is the complete opposite effect of what is observed in the data. The amount of storage and the flow velocities through the area are strongly influenced by the tidal cycle.

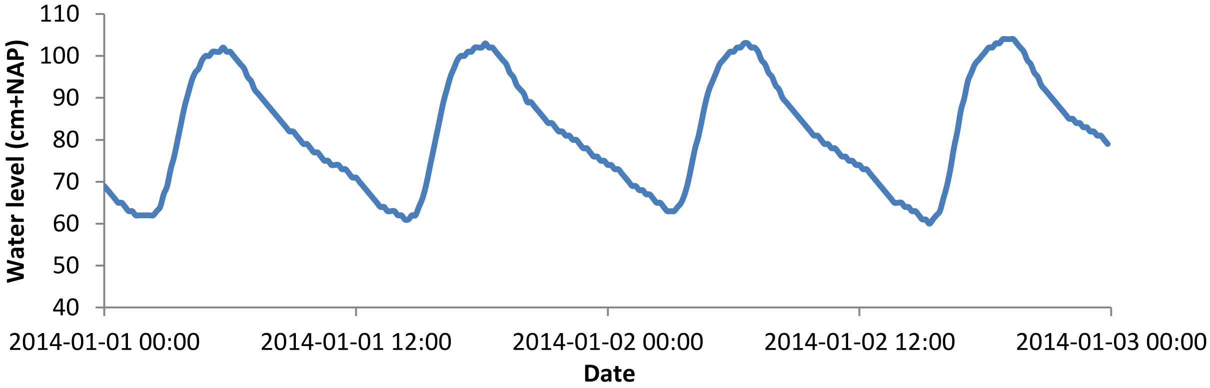


Figure 5.15: Zoom in on the astronomical tidal cycles, showing four tidal cycles in 2014 in greater detail at Werkendam.

In chapter 4.3.3 the propagation of the tidal wave is visualized and explained. The tidal wave reaches the area from both the up- and downstream side, which causes a tidal movement that is extraordinary. The tide is not moving from the outlet through the area towards the outlet but it is moving in a more complex way since the tide is sometimes entering the area from both the in- and outlet at nearly the same time. This changes the discharge going in- out- and through the area and the magnitude of these changes in discharge depends on the tidal range, which differs from day to day and month to month. This makes the tide a boundary condition that is very dynamic, thus having an unpredictable and hard to measure effect on the discharge.

5.2.4 Haringvliet discharges

The Haringvliet barrier is the last external factor that needs to be taken into account as it can change the water gradient through the area. Large discharges at the barrier cause the downstream area to drain, lowering the water levels, increasing the gradient between the in- and outlet. If the barrier is closed it causes water downstream to pile up, increasing the water levels and lowering the gradient between the in- and outlet. Of course the gradient is quite important as it determines how fast and how much water is flowing through the area. A daily estimate of the discharge of the barrier is calculated using models by RWS (Fig. 5.16). The graph shows the data for the 1st period, showing large discharges during the high water peak and later a closure of the barrier during the following low Rhine discharges.

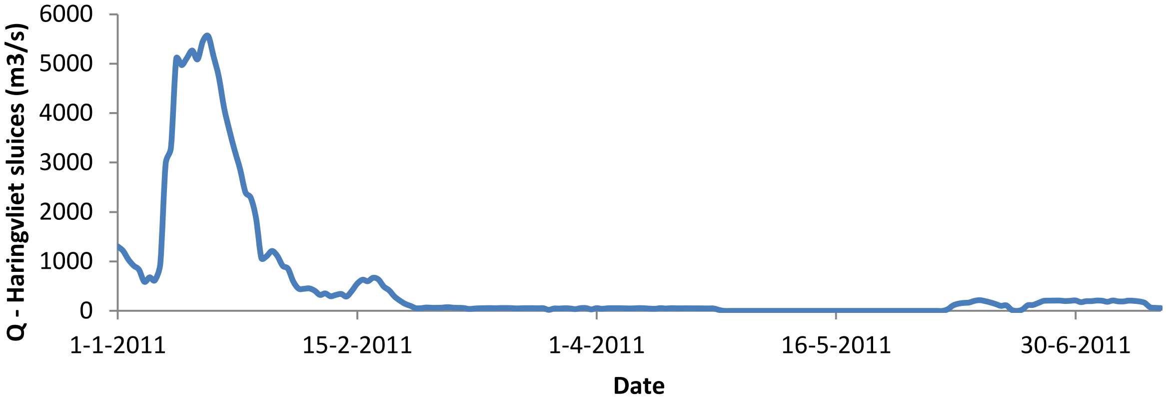


Figure 5.16: Discharge of the Haringvliet sluices for the first period (first half of 2011) showing both large discharges (16-1) and a closure of the sluices (21-5).

When comparing the Rhine discharge to the discharge of the barrier both signals are very much alike. Since the discharge of the barrier is an indirect effect of the discharge of the Rhine a relation between these two has been established (Fig. 5.17). Over 5 years of discharge data has been plotted in this graph, immediately showing a solid relation. The line crosses zero at a Rhine discharge of 1100 m^3/s, which is the point at which the barrier closes. This is in accordance with the management rules of RWS, which state that during river discharges up to 1100 m^3/s at Lobith the barrier is closed off completely. The relationship is a linear one, which seems to overestimate the barrier discharge when the Rhine discharge is high. The relation is not perfect but clearly there, which allows us to approximate the discharge of the Haringvliet for years that have not been modelled by RWS yet. However, this relation only creates a scaled discharge of the Rhine, which does not show any unexpected discharges and deviations.

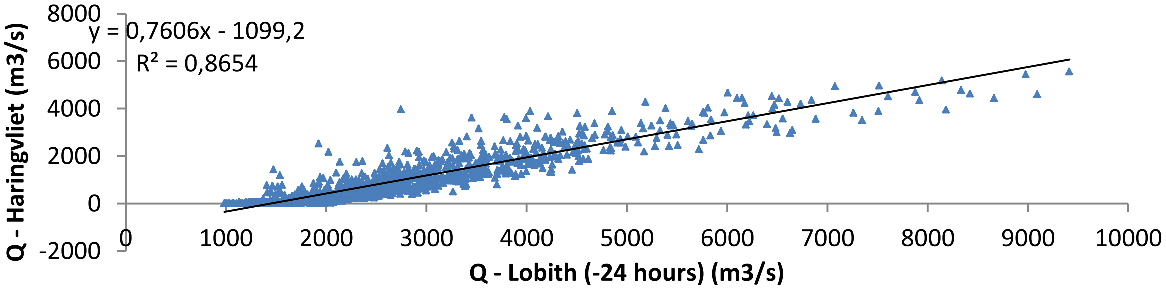


Figure 5.17: The relation between the discharge of the Rhine at Lobith and the discharge of the Haringvliet sluices.

5.3 The combined effect of the boundary conditions

In this section the intermediate results will be linked together to explore how the flows are controlled by the boundary conditions. This will explain the driving forces in the flow balance and why sometimes negative discharges are observed. To do this, three characteristic periods are analysed into further detail. The periods are based on the discharge of the Rhine, the accompanied Haringvliet response and the tidal wave. The following characteristic periods are analysed; high Rhine discharge, low Rhine discharge and average Rhine discharge. For each period the discharge in the area and all of the boundary conditions are plotted for a time span of 5 days, followed by an explaining overview for the area.

5.3.1 High Rhine discharges

High Rhine discharges occurred twice in our data set, both showing similar results, the event analysed is the high water peak of January 2011. Figure 5.18 shows a very high Rhine discharge at Lobith that varies between 8300 m^3/s and 6400m^3/s. As a reference value; 6800 m^3/s is a discharge that occurs roughly twice a year at Lobith. The Haringvliet barrier responses to this large Rhine discharge by discharging 5000 m^3/s into the North Sea.

The tide causes a water level variation of 20 cm between ebb and flood. This is much lower than the average 50-60 cm that occurs during springtide which is indicated by the red dotted line in the graph. The water levels react strongly on the discharge levels of the Rhine as the highest water levels coincide with the highest discharges and not with the springtide period.

The wind during this period is actively changing and showing relatively high speeds of up to 6 m/s which is above average. The direction however is coming from opposing directions, causing the effect of the wind to change rapidly, having an unknown influence on the discharge.

The discharges in the area are high both at the in- and outlet, showing a large phase difference between the in-and outlet, this is also observed in the other periods with a high river discharge. Water flowing into the area reaches a higher Q (400 m^3/s) and shows a very clear ebb and flood alternation. Water flowing out reaches a less high peak discharge (350 m^3/s) but shows a wider peak and a lower minimum flow. The in- and outflow show a remarkable phase difference, the outlet reaches its maximum discharge 2,5 hours before the inlet reaches its maximum discharge. There is a fast drop from the maximum discharge to the minimum discharge in both the in- and outlet. In combination with the phase difference this causes situations in which the inlet is having its largest flow while at the same time the outlet has its smallest flow. This causes large (temporary) storage of water in the area. On the long term more water is flowing in than out of the area, causing long term storage.

This is confirmed when looking at the cumulative volume, which overall increases over time and shows fast increases in volume followed by slower decreases in volume on a diurnal basis. This causes the area to fill up, working like a retention basin. The cumulative volume reaches values of over 8 million m^3, which is even more than the area can store during optimal conditions.

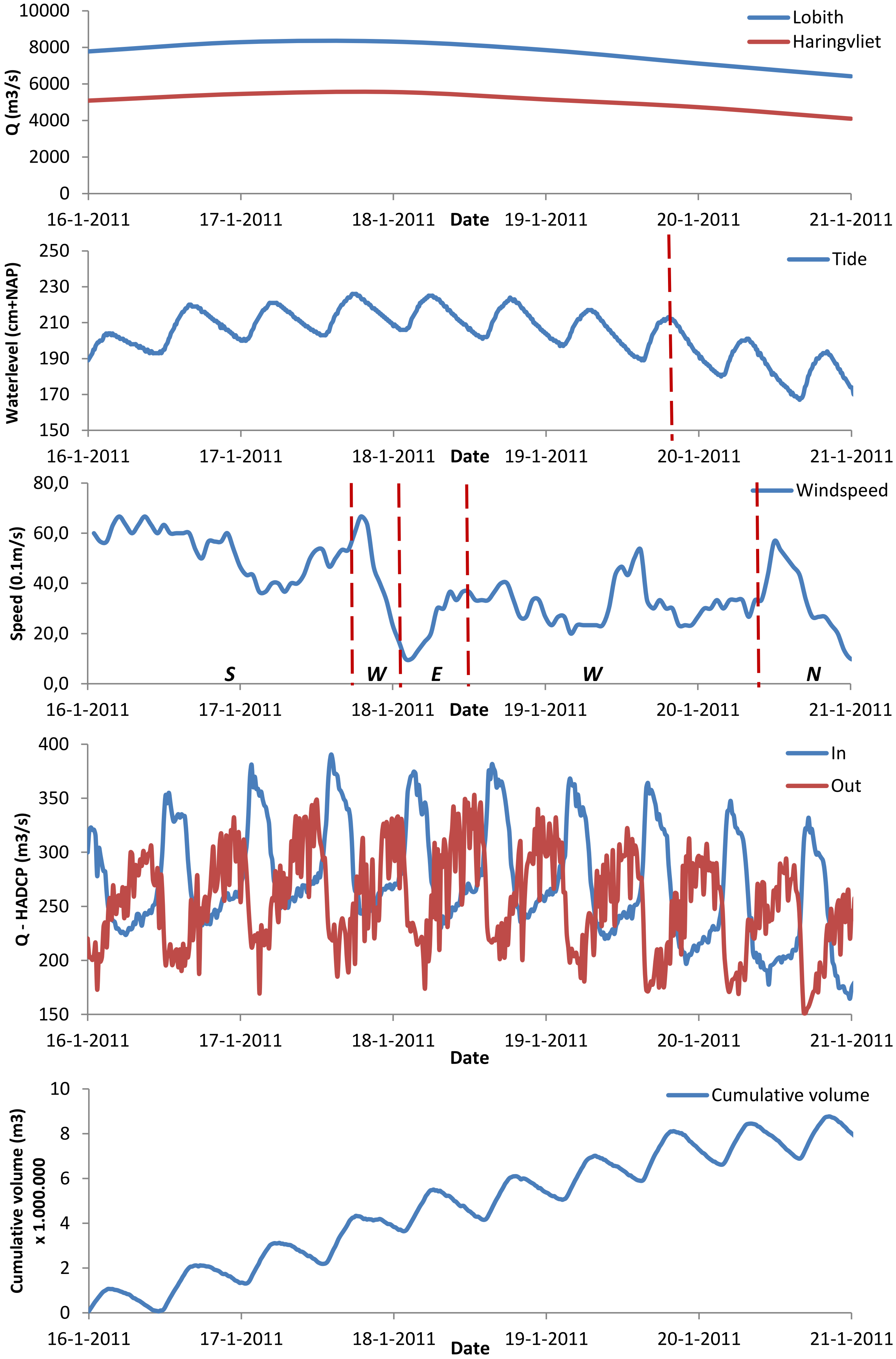


Figure 5.18: Showing the discharge of the Rhine and the Haringvliet sluices (1), water level at Werkendam (2), wind speed (3), discharge in the area (4) and the cumulative volume for the area (5) for a period with a high Rhine discharge.

5.3.2 Low Rhine discharges

When discharge in the Rhine is low (fig. 5.19), the Haringvliet barrier closes. Rhine discharge at Lobith is flowing steady at almost 1000 m^3/s, which is lower than the average 2200 m^3/s. The Haringvliet barrier closes at any discharge beneath 1100 m^3/s, creating the graph from figure 35. The Haringvliet barrier is closed during the entire period, preventing water from discharging into the North Sea, thus reducing the gradient through the area as water downstream is piling up. This causes higher water levels downstream of the area and upstream of the area water levels are low due to the small discharge of the Rhine.

The tidal influence is quite large as the period lies very close to the springtide (red line), causing large variations in water levels around the area. The water level variation between ebb and flood is almost 50 cm, which is more than the average 40 cm. Overall water levels are very low, varying around 40 cm +NAP, this is caused by the low Rhine discharge. Water levels are slightly increasing over the period, which is a combined effect of the slight increase in Rhine discharge and getting closer to springtide.

The wind is constant in direction but varies in speed, almost showing a day and night variation. During day winds reach up to 8 m/s which is above average and during night it drops to 2 m/s which is below average. The direction primarily comes from the North West, later shifting to the North East. This means that during the larger part of the period the wind should have a small increasing effect on the discharges, creating a larger flow through the area.

Discharges through the area become very low, even negative discharges occur, meaning water is flowing in the upstream direction. The inlet shows a large variation between ebb and flood, going from a strong flow into the area (100 m^3/s) to a flow out of the area (25 m^3/s) in a very short time span. This produces a very small high peak and a larger (longer) minimum flow. The outlet varies much less, going from only a light flow out (50 m^3/s) to a very small flow in (10 m^3/s), being more constant. When looking at the flow volumes at the inlet sometimes an agger (double tide) is observed, during the decrease in discharge there is a point at which the decrease ceases and increases again. This agger is caused by the interaction of the different tidal harmonics in the area. It is remarkable that this is only observed at the inlet and not at the outlet. Tide seems to have a larger influence on the inlet than it does on the outlet. During this period a phase difference is also observed but in this case the inlet reaches its maximum an hour before the outlet reaches its maximum. This is a phase difference that is the other way around and much smaller than the phase difference observed during the period with high Rhine discharges.

The cumulative volume is quite constant, starting and ending a bit higher with a little minimum in the middle of the period. This means that despite the negative flow, over the entire period just as much water has flown into the area as there has flown out of the area. The magnitude of the total storage volume (difference minimum and maximum) is approximately 1 million m^3. This is a realistic storage volume which coincides with the calculated storage volume of the area.

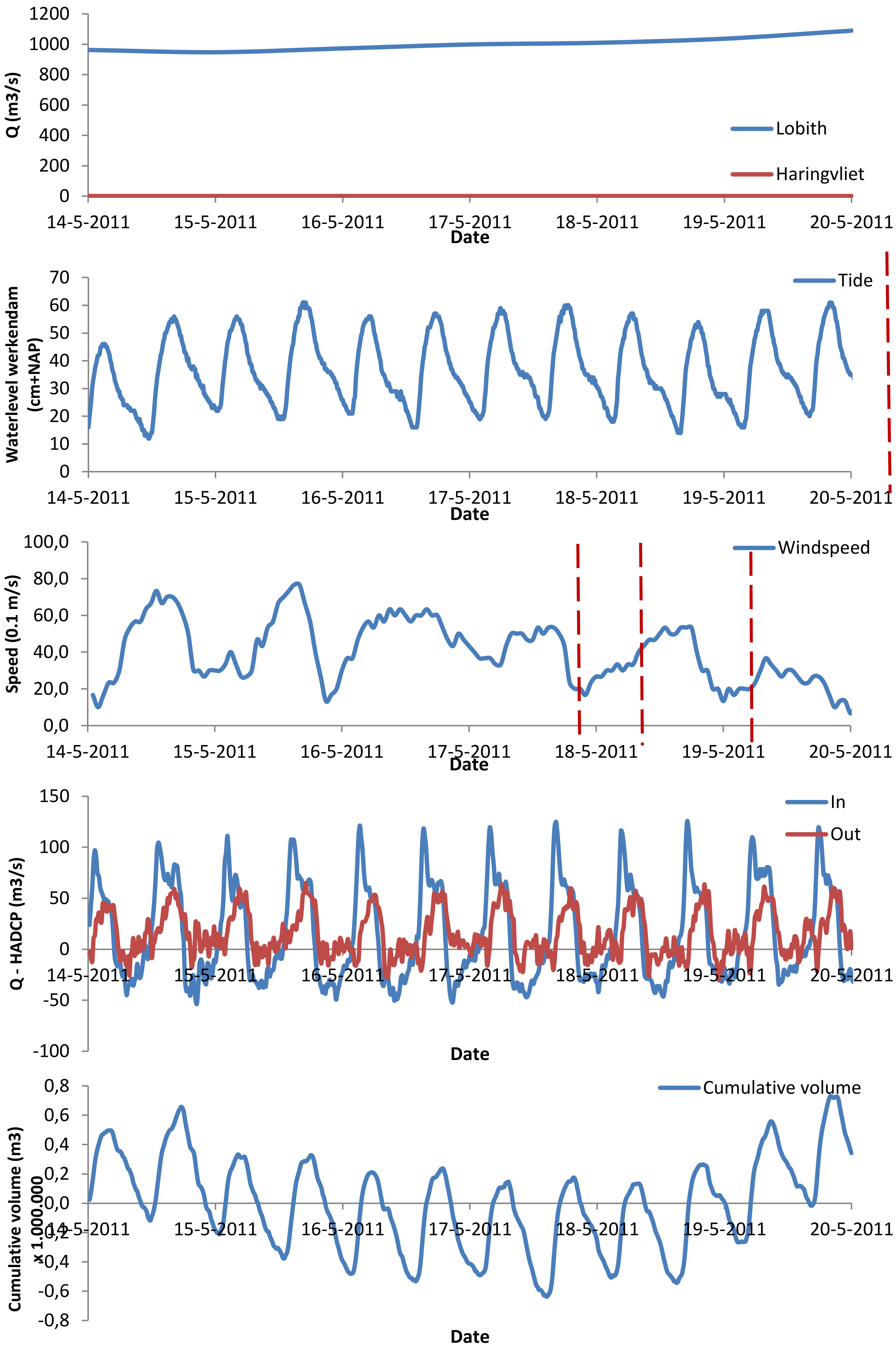


Figure 5.19: Showing the discharge of the Rhine and the Haringvliet sluices (1), water level at Werkendam (2), wind speed (3), discharge in the area (4) and the cumulative volume for the area (5) for a period with a high Rhine discharge.

5.3.3 Average Rhine discharges

The Rhine discharge is quite constant, with an average discharge of 1800 m^3/s at Lobith (Fig. 5.20), which is slightly under the yearly average of 2200 m^3/s. The discharge at the Haringvliet is also stable, unfortunately it is not included in this graph as this data is not yet available. The Haringvliet is discharging the amount of water that is being delivered by the river, creating a stable gradient over the area.

The tidal range is relatively small, as neap tide is present in this time span (red line). The water level varies around 70 cm, the difference between ebb and flood is 40 cm. This is exactly the same as the astronomical tidal range during neap tide. The water level shows a little variation, following the variation in Rhine discharge.

Wind speeds are also relatively stable, with a wind direction coming almost constantly from the South West. This should have no real negative or positive impact on the discharges in the area (chapter 5.2.2). Wind speeds are above average with 8 m/s, showing no extraordinary features.

During these average conditions the discharge at the outlet is very stable, showing little peaks (80 m^3/s) and minima (20 m^3/s) but mostly periods in which there is almost no variation in discharge (50 m^3/s). The Inlet on the other hand shows more variation. Looking at the discharge at the inlet a large peak can be seen (150 m^3/s), with in most cases a very clear agger, where discharge really drops and increases again. The minima are also quite low (10 m^3/s), sometimes even very small negative discharges are reached. The phase difference between the in- and outlet is visible and nearly the same as during low Rhine discharges (approximately 1 hour difference and inlet reaches maximum before outlet).

This leads to a cumulative volume that in the end is very stable, in the beginning the area is draining a bit, after which it fills up, draining again and in the end filling up again. The volumes are not very large which is expected as the discharge near the in- and outlet is not very large either. The storage in this period is 1.2 million m^3, which is very possible when comparing it to the calculated storage of the area.

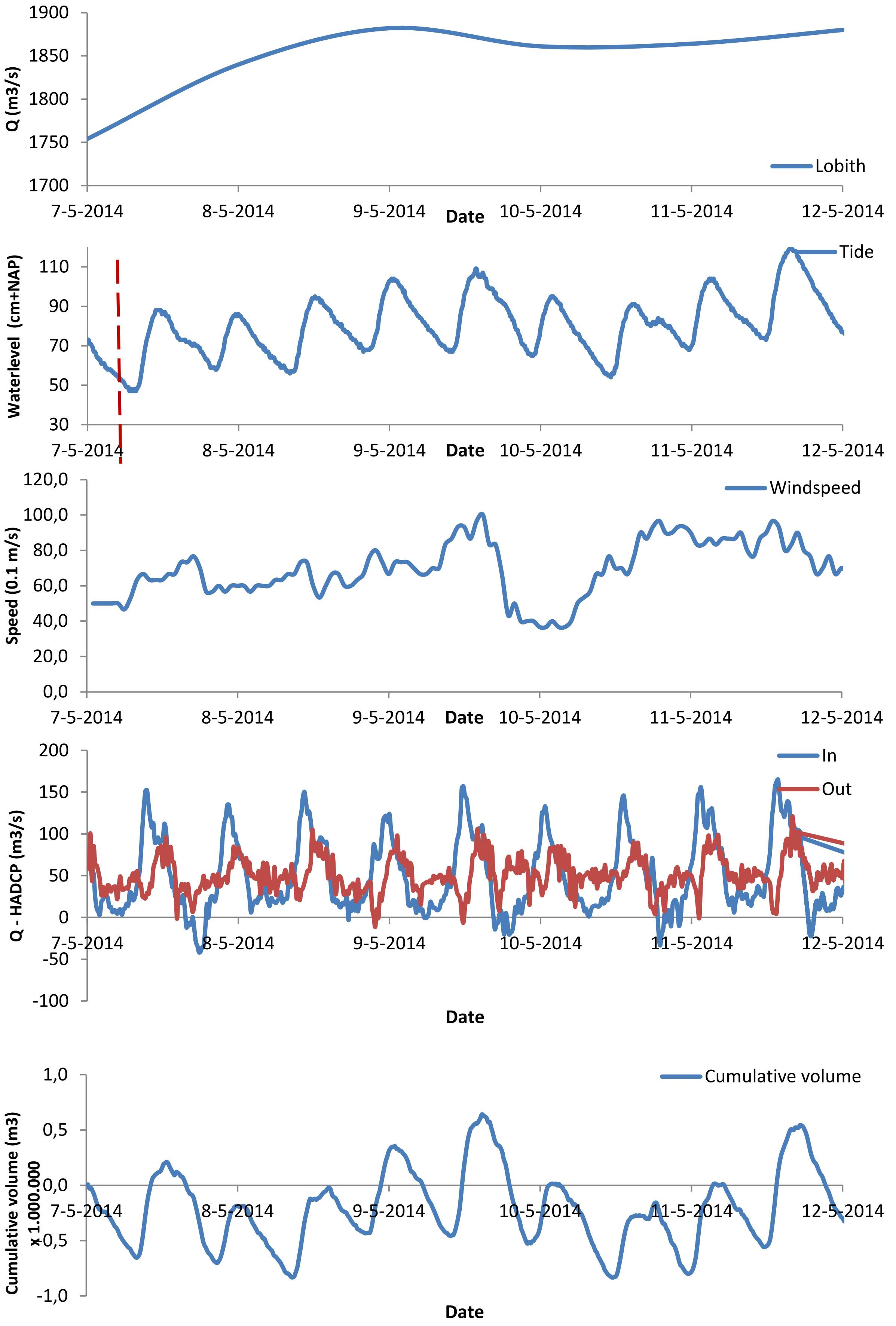


Figure 5.20: Showing the discharge of the Rhine and the Haringvliet sluices (1), water level at Werkendam (2), wind speed (3), discharge in the area (4) and the cumulative volume for the area (5) for a period with a high Rhine discharge.

5.3.4 An overview of the water flow during three characteristic periods

The previous part shows how the discharge changes and what the external factors are doing during the characteristic periods. This detailed analysis brings up some questions about the water flow through the area. Is it true that there sometimes occurs a negative flow and how can this be explained? This is going to be answered by looking at the water level variations, around and in the area, explaining the direction of the flow.

The three periods are being explained by a sketch which shows the water level variation at both the in- and outlet with an overview of the area in between. The red arrows show the direction of the flow at that location and the curved lines indicate tidal influence.

The first period (Fig. 5.21) shows a high Rhine discharge, this means a constant high water level upstream. The tidal range therefore has relatively less influence as it is damped. High discharge from the Rhine also means a high discharge at the Haringvliet barrier, causing drainage downstream. Combined this means high water levels upstream, low water levels downstream and a damped tidal range, meaning a constant gradient in the downstream direction, causing water to flow rapidly through the area in the downstream direction. Figure 5.22 shows an enlargement of the water levels and the discharges at the in-and outlet for high Rhine discharges, where Werkendam is an upstream station, Moerdijk is downstream, Ban is the inlet and Mal is the outlet. It explains the sketch and shows the real water levels and thus gradients over the area.

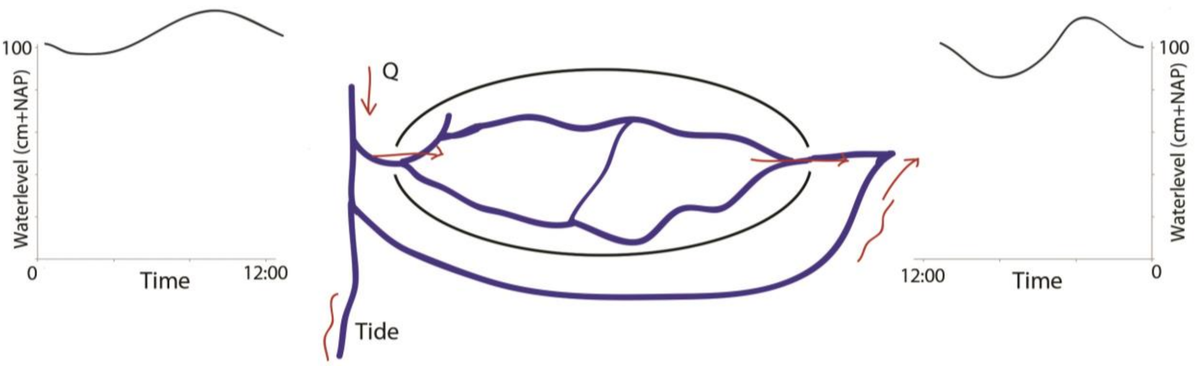


Figure 5.21: An overview of the area and the water flow during a high Rhine discharge, showing the schematic water levels at the in- and outlet.

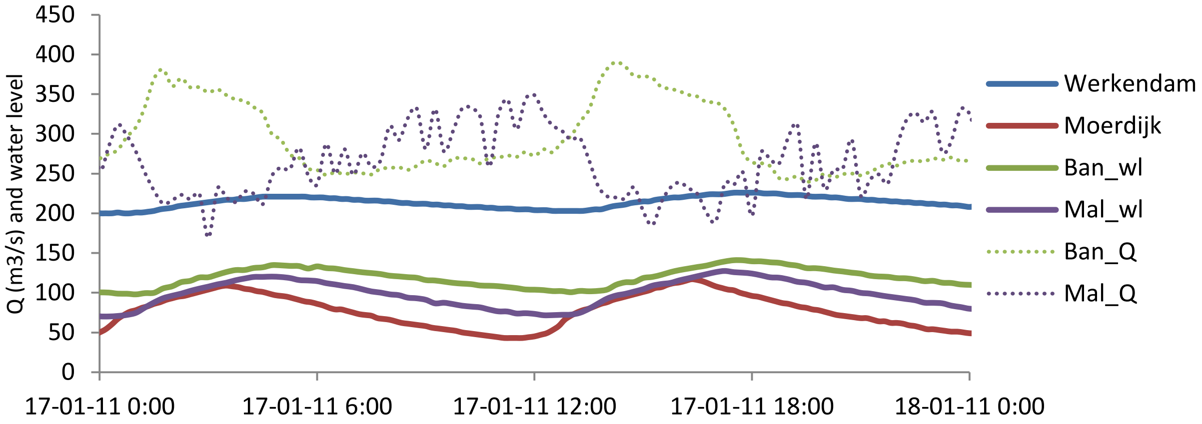


Figure 5.22: The real water levels at Werkendam (upstream), Moerdijk (downstream), Bandijk (Inlet) and Malta (outlet) and the discharges measured at the in-and outlet during a high Rhine discharge.

During low river discharges (Fig. 5.23) something odd occurs, the Haringvliet barrier closes and water is not allowed to flow freely through the area anymore. The tidal range becomes more important as there is no constant high water created by the river anymore. Water is piling up downstream, and water levels rise, causing the downstream gradient to disappear. Since the Haringvliet is closed, the only way for the tide to reach the area is through the branch of the river. Tidal movement now has two ways to reach the outlet, through the river itself or through the area. These two routes do not take the same amount of time, causing the water levels to vary around the area. This causes situations in which the downstream water level is higher than the upstream water level, due to tide, creating a reversed flow in the upstream direction. And it causes 'normal' scenarios in which the upstream water level is higher than the downstream level, creating a flow that is directed in the downstream direction. This explains the change in flow direction at both the in- and outlet that is observed in the data. However there are also times at which the flow is going into the area at both the in- and outlet at the same time and vice versa. This also caused by rapid tidal movements around the area which causes the water level in the area to be the highest and lowest compared to the water levels outside of the area. This is only observed at the turning points of the tide and only during a very short time. When river discharge is low, the tide is the most influencing factor on the flow directions. Figure 5.24 shows an enlargement of the water levels and the discharges at the in- and outlet for low Rhine discharges. It explains the sketch and shows the real water levels and thus gradients over the area. In this case the gradient between the 4 stations is important, a high gradient between upstream and downstream means a flow through the area, even though the water level within the area are equal or even the other way around. Water will always follow the largest gradient. This water flow going against the normal direction is also observed during other studies at the river junction near Werkendam (Vellinga et al., 2014). Their research shows that when the southwest branch does not deliver tidal energy, the tidal movement there is completely controlled by the other two branches, creating reversed flow patterns. The water flow through the research area shows this reversed pattern as well.

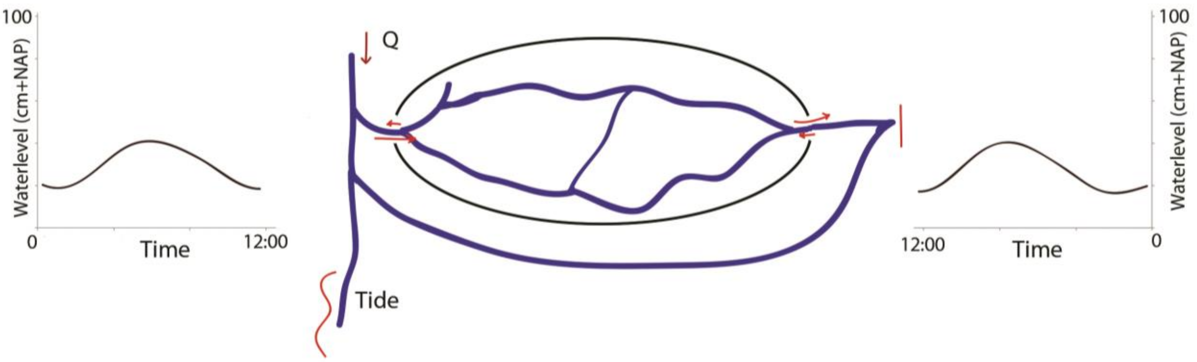


Figure 5.23: An overview of the area and the water flow during a low Rhine discharge, showing the schematic water levels at the in- and outlet.

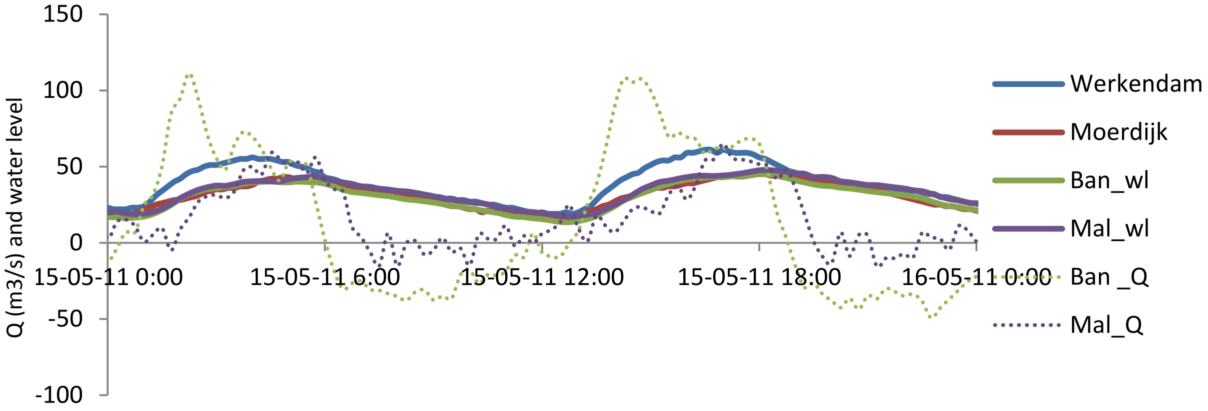


Figure 5.24: The real water levels at Werkendam (upstream), Moerdijk (downstream), Bandijk (Inlet) and Malta (outlet) and the discharges measured at the in-and outlet during a low Rhine discharge.

The water levels measured by the divers in the last period of 2011 seem to be incorrect (Fig. 5.24). The levels of the inlet are constantly lower than the levels at the outlet, in hindsight this is probably caused by a construction error. The diver at the inlet is probably placed 7 cm lower than documented, meaning that the water level at the inlet should be 7 cm higher than the figure shows. This makes the explanation of the water flow more understandable as it causes the water levels at the inlet to increase, creating a shifting gradient going both ways through the area. This falls in line with the shifting water flow through the area. It does cause another problem, a problem with the calculated discharges as the wetted perimeter of the channel increases. This increase is roughly 0.07 * 100 = 7m^3 (h*w), when multiplied with an average flow velocity of 0.10 m/s this comes down to an increase of 0.70 m^3/s when looking at the discharge. This is less than 2% of the total average flow during that period and can therefore be neglected. An increase in the water level of 7 cm at the inlet (ban) creates a situation in which the gradient over the area is not always negative but shifting from positive to negative due to the tidal influence. The suspected error in the documentation of the diver construction therefore supports and improves the found results.

When river discharge is average there is a constant high water level upstream and a constant high water level downstream caused by the discharge of both the river and the Haringvliet barrier (Fig. 5.25). This causes a gradient over the area from upstream to downstream, causing the flow to go through the area in the downstream direction. The tidal influence however is much larger when river discharge is average than when it is very large as the tidal signal is not being flushed out. This causes water levels to vary around the area, which at times causes the gradient to become very small, nearly causing the flow direction to change. This tidal effect however is mostly not strong enough to reverse the flow, whether it is spring or neap tide therefore has a large impact during otherwise average conditions. Figure 5.26 shows an enlargement of the water levels and the discharges at the in-and outlet for the average Rhine discharges.

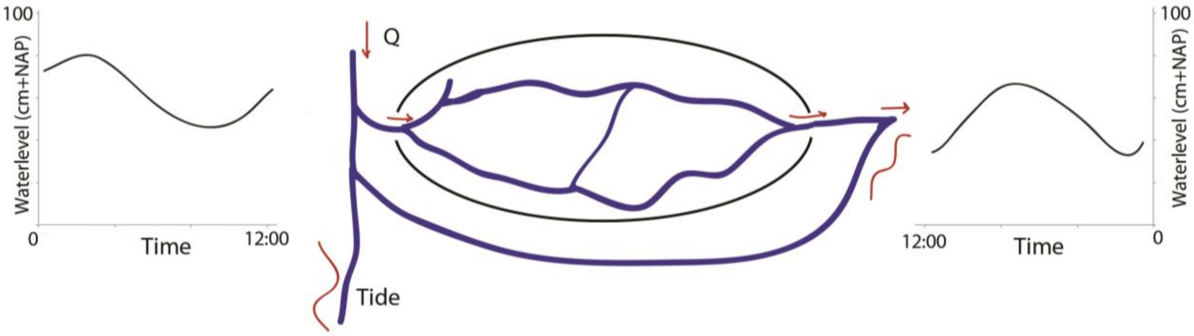


Figure 5.25: An overview of the area and the water flow during an average Rhine discharge, showing the schematic water levels at the in- and outlet.

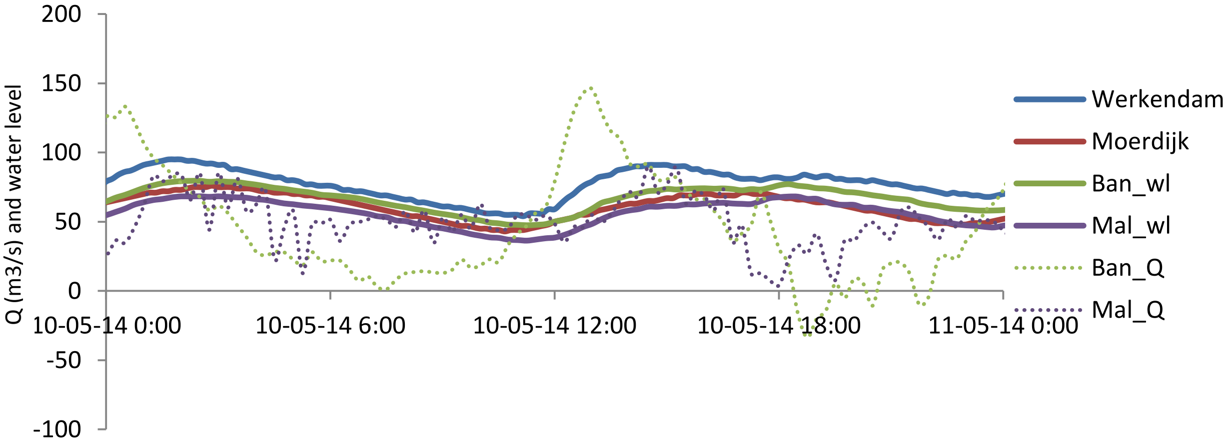


Figure 5.26: The real water levels at Werkendam (upstream), Moerdijk (downstream), Bandijk (Inlet) and Malta (outlet) and the discharges measured at the in-and outlet during an average Rhine discharge.

6. Discussion

The found results are very dependent on the used research method and thus on the certainty of the results. The used measuring method for the discharges only measures part of the channel, even though the H-ADCP's are placed strategically near the thalweg of the water they still have a large blind spot. Only 20% of the channel is actually being monitored and measured. The other 80% is being calculated by using the correlation. This creates an uncertainty as we cannot be completely sure that the discharge that is being measured always represents the full discharge.

The correlation plays an important part in calculating the real discharge, for the Bandijk (inlet) this relation is almost perfect and therefore very reliable. For the Opening Malta (outlet) however this is more complicated. The choice has been made to use a linear relation and force the relation through (0,0), which has been explained in chapter 5.1.2. But this still causes an uncertainty in the discharge at the outlet, especially when discharges are relatively low (around 40 m^3/s). The used correlation line is least reliable in this low region of the graph, causing discharges that are low to often be underestimated. This is probably the main reason for the $^+/_-$ 10% difference in volumes flowing in and out of the area.

The results show a changing water balance that strongly depends on the boundary conditions. The flow at the in- and outlet and the storage interact in a different way when the discharge of the Rhine changes. The discharge of the Rhine can be seen as the controlling boundary condition, which on its turn changes the influence of the other boundary conditions. During high discharges the area works as a side channel and buffer, storing water but mostly discharging it. During low discharges the area works more as a small tidal basin with water flows going both in and out of the area in both up- and downstream directions. The tidal wave can reach the area from two ways, coming in from either the downstream or upstream direction and sometimes at the same time. This means that there is a point where these two "tidal waves" reach each other. The meeting point of the tides is changing when the Rhine discharge changes when looking at the phase differences and the tidal fluctuation of the outlet (chapter 5.3). This causes a changing gradient over the area and thus a changing flow through the area.

The area works like a buffer, damping out incoming signals. When the tidal wave comes in from the upstream direction, a large tidal variation in the discharge is observed at the inlet, while at the same time the outlet shows almost no tidal variation. This effect is most clear when discharge of the Rhine is average. Tidal signal coming in is strong, while the signal going out is much weaker. This is caused by the dispersion of the signal as the tidal wave flows through the shallow channels in the research area it loses energy, resulting in a dampening of the signal.

In research of Vellinga et al., 2014 similar results have been found. They measured the tidal movement at several river junctions in the Rhine-Meuse river delta network, including the junctions up- and downstream of our research area. The measured flow velocities at the upstream junction are shown in figure 6.1; it shows opposing currents in the side channel adjacent to the research area.

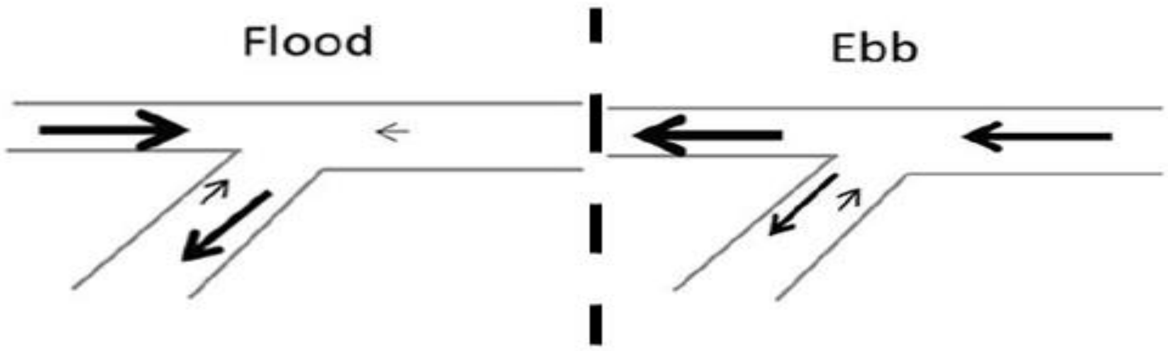


Figure 6.1: Sketch of the measured flow direction and magnitude at the river junction near Werkendam, the South-East branch is the Nieuwe Merwede, the river that flows parallel to the fieldwork area. (Vellinga et al., 2014)

During preceding research (MER) in the research area no attention has been paid to the flow direction. It might be possible that the depoldering of the research area has created or increased the magnitude of the observed reversed flow. This however cannot be concluded with any certainty since there is no record of flow direction before the area was depoldered. Reversed flows often occur in deltas, as ebb and flood tidal flows alternate each other. However there are no records found of reversed flows at other locations that are so far upstream.

Since all external factors are influencing each other it is difficult to isolate the effect of one factor. For the Rhine discharge this was possible as this is the most controlling factor. The other factors are so intertwined and hard to isolate that it became almost impossible to isolate their effects. The effects of the Haringvliet barrier were also hard to analyse because the data for 2014/2015 were not available. Future research might be able to shine a light on these factors but it needs a very detailed research focussed only on one factor.

Further research is needed to give meaning to the water balance when it comes to sediment concentrations and transport. This research only focussed on the water balance, how does the water flow in this area and what controls these flows. This can be put into a broader prospect when also looking at the sedimentation and erosion processes that are being driven by the water flow. Future research can and will go further where this research has ended.

7. Conclusion

The water balance of the Kleine Noordwaard is not as straightforward as it may seem. The area functions as a side channel, transporting water towards the Haringvliet but it also works as a small retention basin. The water flow through the area is mainly controlled by the discharge of the Rhine, the discharge of the Haringvliet and the tidal wave coming in from the North Sea. Wind controls whether water is being set up or set down, and with that if the flow is decreasing or increasing. The area also works as a buffer, it dampens the incoming signals. The Haringvliet discharge and the Rhine discharge determine how the gradient over the area is, the tidal wave then runs around the area creating an increase or decrease of this gradient.

The water flow through the area can be seen as the combined work of the Rhine and Haringvliet discharge which is transformed by the tide. In this case three characteristic situations explain the water flows through the area and their controls.

- The **first** situation is a high discharge at both the Rhine and the Haringvliet, causing the upstream water level to be very high and the downstream water level to be very low. This creates a large gradient over the area, so water will flow rapidly through the area. The tide in this case can only increase or decrease the gradient a little, but relative to the gradient caused by the discharge this is only an adjustment of the flow speed. Therefore during these conditions water is always flowing fast in the downstream direction and it is being sped up and slowed down a little by the tide.
- The **second** situation is an average discharge at both the Rhine and the Haringvliet, this causes average water levels upstream and downstream. The water levels upstream are always higher than the water levels downstream, causing a gradient over the area. Water will therefore always flow in the downstream direction. Then the tide comes in and adjusts these water levels, since the difference is not as large as in the first scenario the tide has a greater influence (relatively seen). This causes water levels to fluctuate stronger around the area, influencing the water flow through the area. Water will always flow in the downstream direction but there are moments at which the tide increases the water level downstream, causing the gradient to decrease and slowing down the flow to almost zero.
- The **third** situation is a low discharge at both the Rhine and the Haringvliet, in some cases the Haringvliet is closed, causing discharge to be zero. In this case water levels upstream are relatively low and water levels downstream area relatively high, due to water piling up. This causes the gradient over the area to become very small. Tidal influence therefore has a relatively large influence on the water levels around the area. Such a large influence in fact that it can create a higher water level downstream than upstream, creating a reverse flow at times. Since the area also stores water there are even small periods during the turning of the tide at which water levels in the area are higher than around the area, creating a flow out of the area at both the in- and outlet. Overall water is still flowing downstream but due to the tidal wave coming in the water flow can change its direction, going upstream.

The gradient over the area is being controlled by the discharge of both the Rhine and the Haringvliet and the tidal wave transforms this gradient. How much influence the tidal wave has on this gradient depends strongly on how large the gradient is. High gradients are only slightly changed while low gradients are suspect to a much larger change.

8. References

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Abbreviations/Institutes

KNMI, Koninklijk Nederlands Metereologisch Instituut, Royal Dutch Meteorological Institute

SBB, Staatsbosbeheer, State Forestry Service

RWS, Rijkswaterstaat, National Water Authority