Macrolitter in Groyne Fields

Short term variability & the influence of natural processes

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by

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Preface

Dear reader,

This thesis concludes my education in Civil Engineering at the Delft University of Technology. For this research I've spend three months doing fieldwork at the riverbanks of the Waal, an unforgettable experience. Being outside and observing seasonal changes from close by has made me look at the riverine environment in a way that I would never have from studying textbooks. For making this possible, I want to thank Margriet Schoor and Frank Collas. I also want to thank Riccardo Taormina, Willem Luxemburg and Tim van Emmerik for their support and feedback on my work. Finally, I want to thank Thom Verreijt, Lorraine Minnaar, Demi van Klink and Joep van Zuijlen for their assistance during fieldwork. Without these people I could not have delivered this work.

Conceiving this work was a wonderful experience. I hope you will enjoy reading it as much as I enjoyed making it.

J. J. Grosfeld
Rotterdam, May 2022

Abstract

Plastic pollution and accumulation in the riverine environment is of increasing concern. While most research focuses on microplastic contamination, the dynamics of macrolitter remain largely unknown. Large scale riverbank monitoring initiatives in the Netherlands reveal that macrolitter hotspots occur at several locations. Unfortunately, current knowledge on how these hotspots emerge and how this is influenced by hydrology and meteorology remains limited. As most studies are based on data from seasonal monitoring activities, short term variability remains unknown. This study is the first attempt to monitor and analyse the variability of riverbank macrolitter within a single location for over a period of three months. Behaviour of individual items is tracked and macrolitter exchange between water and riverbank is studied with regards to hydrology and wind. Finally, a conceptual model on riverbank macrolitter dynamics is presented in favour of supporting future research design.

A remote groyne field in the Waal has been monitored 21 times within the period of November 2021 until January 2022. The location of macrolitter items was recorded using Real Time Kinematic positioning. This allowed for analysing spatial patterns throughout time. Additionally, photographs of items were made in order to categorise the items without removing them from the riverbank. The river OSPAR protocol was used for item categorisation.

The data shows that macrolitter primarily accumulates in the floodmarks. Rising water pushed items higher on the riverbank. Wind had a limited effect on item mobilisation as most items are wet and sandy. Analysis of item exchange between riverbank and water revealed that macrolitter deposition was observed at a relatively constant rate with minor deviations. Item uptake was heavily dependant on changes in water level. Uptake was initiated when the water level rises ($dH > 0$). The rate of uptake was higher with a larger water level increase. However, correlation was not statistically significant as riverbank morphology, substrate and vegetation may also influence uptake. After three months and two moderate discharge peaks, almost all items found on day 1 (estimated 99.6%) had been taken up. This indicates that under normal hydrologic conditions, the retention time of items within groyne fields is defined by the timing and magnitude of moderate water level fluctuations (assuming no accumulation under water within the groyne fields).

A conceptual model of riverbank macrolitter dynamics under natural processes is presented. Macrolitter can be stored in three domains: water, sediment and riverbank surface. Exchange within these domains occurs in four directions: in/out of sediment (storage/mobilisation) and in/out of water (uptake/depositions). Exchange is promoted by an interplay between item attributes, environmental processes and riverbank morphology. Future research on the interaction between these variables is needed in order to fully understand macrolitter dynamics.

Samenvatting

De vervuiling van rivieren met plastic afval is een wereldwijd groeiend probleem. Daar het meeste onderzoek zich richt op de verspreiding van microplastics is er nog veel onbekend over het voorkomen en de dynamiek van macroafval. Grootschalige monitoringsactiviteiten in Nederland hebben laten zien dat er afval hotspots ontstaan langs de oevers van de rivieren. Helaas is de huidige kennis over hoe deze hotspots ontstaan en wat de invloed van hydrologische en meteorologische variabelen is nog beperkt. Omdat de meeste studies zijn gebaseerd op data van monitoringsactiviteiten die eens in het seizoen plaatsvinden, is er nog weinig bekend over hoe rivierafval zich gedraagt in de korte termijn. Deze studie is de eerste poging om het gedrag van afval op korte termijn te monitoren en te analyseren. Dezelfde rivieroever is voor een periode van drie maanden bestudeerd. Het gedrag van individuele items is bijgehouden en de uitwisseling van afval tussen oever en rivier is bestudeerd en gerelateerd aan hydrometeorologische variabelen. Tenslotte is een conceptueel model voor afval op rivieroevers voorgesteld, welke gebruikt kan worden bij het opstellen van nieuwe onderzoeken naar dit onderwerp.

Een afgelegen kribvak in de Waal is uitgekozen om te bestuderen. In totaal zijn er 21 monitoringen uitgevoerd in de periode van november 2021 tot en met januari 2022. De locatie van afval items werden gemonitord met een Real Time Kinematic positioning systeem. Dit gaf de mogelijkheid tot het analyseren van de ruimtelijke verdeling van afval op de rivieroever. Aanvullend zijn er foto's van de items gemaakt zodat deze later gecategoriseerd konden worden middels het river-OSPAR protocol. De items zijn onaangeraakt gebleven gedurende het monitoren.

De data liet zien dat afval zich voornamelijk in de vloedmerken ophoopt. Rijzend water duwde de items hoger op de oever. Wind had slechts een beperkte invloed op het in beweging brengen van items. Dit kwam waarschijnlijk doordat de meeste items nat en zanderig waren. De analyse van de aanstranding en heropname liet zien dat het aanstranden van afval zich in redelijk constante mate voordoet. De heropname, daarentagen, is variabel en wordt geinitieerd door stijgend water (dH > 0). De mate van heropname was hoger ten tijde van sneller stijgend water. Alhoewel de correlatie niet statistisch significant was, Dit komt waarschijnlijk doordat morfologie, substraat en vegetatie ook invloed hebben op het wegspoel gedrag van afval. Na drie maanden, waarin zich twee matige afvoergolven hadden plaatsgevonden, waren bijna alle items waargenomen op dag 1 weggespoeld (ongeveer 99.6%). Dit impliceert dat (met de aanname dat er geen accumulatie onder water binnen het kribvak plaatsvind) de retentie van afval onder normale hydrologische omstandigheden wordt bepaald door de timing en intensiteit van gematigde afvoer fluctuaties.

Een conceptueel model voor de dynamiek van afval op rivieroevers onder invloed van natuurlijke processen is opgezet. Hierin wordt voorgesteld dat afval zich in drie domeinen kan bevinden: water, sediment en landoppervlak. Uitwisseling binnen deze domeinen vindt plaats in vier richtingen: in/uit het sediment (opslag/mobilisatie) en in/uit het water (opname/aanstranding). De uitwisseling is een gevolg van interactie tussen item specifieke eigenschappen, hydrometeorologische processen en morfologische karakteristieken van de rivieroever. Meer onderzoek is nodig naar hoe sterk de rol is van deze variabelen op het gedrag van afval in het rivierenlandschap.

Contents

Acronyms

CDF Cumulative Distribution Function. 28, 48–50

CORS Continuously Operating Reference Station. 25

DEM Digital Elevation Model. 27

GPS Global Positioning System. 25

HDPE High Density Poly Ethylene. 10

IDW Inverse Distance Weighting. 28

KNMI Koninklijk Nederlands Meteorologisch Instituut. 28

LDPE Low Density Poly Ethylene. 10

PE Polyethylene. 5, 10

PET Polyethylene terephthalate. 5, 10

PP Polypropylene. 5, 10

PS Polysteryne. 5

PUR Polyurethane. 5

PVC Polyvinyl-chloride. 5

RTK Real Time Kinematic. 2, 23–25, 27, 29, 57, 59, 63

1 Introduction

1.1. Context

Plastics have been (and still are) a great benefit to society. Durability and low productions costs make plastics not only suitable as packaging for food and medicines, but also as engineering component in many products and construction work (Zalasiewicz et al., 2016). Unfortunately, its widespread use has lead to a global increase of plastic waste in the environment. This poses a threat to ecosystems and human health. Additionally, clogging of hydraulic structures and urban drainage sewer systems increases flood risk (van Emmerik and Schwarz, 2020).

The majority of studies on plastic pollution focuses on the marine environment. Current understanding of pollution in freshwater systems is limited. Evidence indicates that the microplastic concentration in freshwater ecosystems is comparable to that of marine ecosystems (Blettler et al., 2018), but the dynamics of riverine macrolitter (> 5 mm) remain largely unknown. It is often suggested that rivers act as pathways for litter from land to ocean (Lebreton et al., 2017; Schmidt et al., 2017). However, some recent studies propose the concept of rivers acting as storage reservoirs (Tramoy et al., 2020b; van Emmerik et al., 2022b), which are filled and emptied by extreme events. This leads to believe that most macrolitter never reaches the ocean.

The lack of quantitative data on riverine macrolitter is a major cause of current knowledge gaps. Expanding data availability by scaling up monitoring efforts is key in developing a better understanding of the spatiotemporal distribution of macrolitter. Additionally, more research is needed into the dynamics of individual items in a natural environment.

Current monitoring strategies mostly focus on either riverine transport or riverbank storage (Kiessling et al., 2021; Schone Rivieren, 2021; Tramoy et al., 2020a,b; van Emmerik and Schwarz, 2020). Widely used practices include quantification by visual observation of floating items from bridges and analysis of riverbank litter items through large scale cleanup initiatives. Each of these methods focus on another aspect of riverine macrolitter. Counting from bridges yields information on fluxes. Riverbank monitoring emphasises on item quantity and detailed item descriptions. Riverbank monitoring campaigns are often carried out twice a year, thus giving information on seasonal variability (Roebroek et al., 2021b).

Data shows that macrolitter hotspots can be identified along certain parts of the riverbanks (Schone Rivieren, 2021) (see figure 1.1). Though it is not certain why hotspots occur at these locations, various suggestions are made in literature. Kiessling et al. (2021) related an increase in riverbank macrolitter to proximity of polluting sources. Garello et al. (2021) suggest that hydrodynamic fluctuations are an important control in macrolitter variability, while Roebroek et al. (2021b) were not able to relate variability by hydrometeorologic processes. The conclusions of these studies differ. Although this could be explained by the fact that these studies were carried out in different parts of the world, it also indicates that the reasons behind hotspot formation are largely uncertain.

Developing better understanding of the factors that determine macrolitter accumulation along rivers is nec-

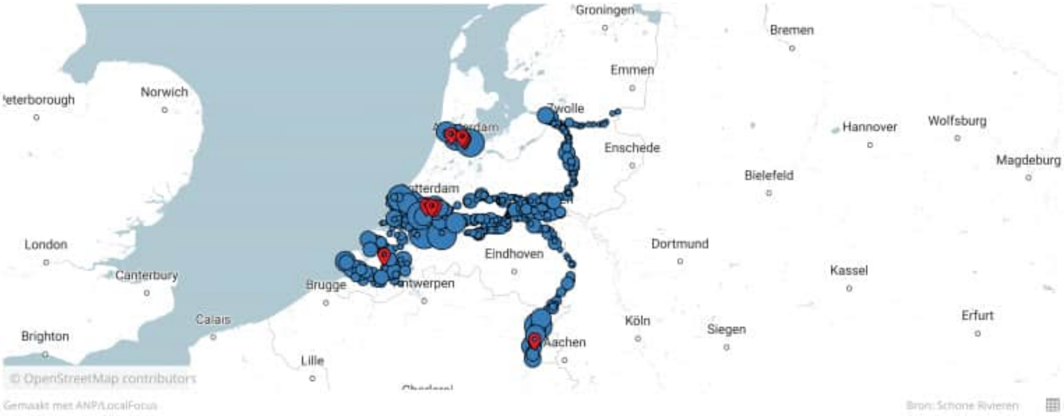


Figure 1.1: Macrolitter hotspots in the Netherlands. Red marks indicate locations with over 1 200 items found per 100 meter (Schone Rivieren, 2022).

essary to design efficient cleanup strategies. Monitoring and data acquisition are key in this effort. To this date, the short term (daily/weekly) variability of riverbank macrolitter has not yet been studied. This research is the first attempt to do so. By counting, identifying and localising every single item in a groyne field at the Waal several times per week for over three months, data on the transfer dynamics and the spatiotemporal variation of riverbank macrolitter is collected and analysed.

1.2. Research scope and objectives

Macrolitter in a riverbank groyne field was studied for a three month period in order to observe the effect of natural processes. The study was conducted at a single location along the Waal river. A new method was designed using RTK positioning to measure the location of macrolitter items with high accuracy. Surveys were carried out every week, the timing of which was based on water level variations. A total of 21 surveys were done in which a new method of litter monitoring at riverbanks was tested. The study was carried out in two subsequent phases. The first consisted of in-situ data collection in a groyne field at the Waal river. Only macrolitter (>2.5 cm) items were recorded. The second phase consisted of an exploratory data analysis. The objective was to describe spatiotemporal variability of macrolitter both qualitatively and quantitatively and study the influence of hydrometeorologic variables. Observations made during surveys, as well as the monitoring method itself, were assessed in favour of supporting future research initiatives.

The main objectives of this study were defined as follows:

- Measure and analyse macrolitter at high spatiotemporal frequency for a single location
- Study the influence of hydrometeorologic variables on the quantity of riverbank macrolitter
- Develop a conceptual model on riverbank macrolitter dynamics which can support future research and modelling efforts

Although the study was carried out at a particular type of riverbank, namely a groyne field, the method and results may also be applicable to other situations.

1.3. Research questions

In line with the objectives of this study, the following research questions were answered:

1. What are the dynamics of macrolitter in groyne fields and which controlling processes can be identified using the newly developed approach?
2. What is the magnitude macrolitter exchange between river and riverbank and can this be explained by hydrometeorologic variables?
3. If the influence of hydrometeorologic processes could not be assessed, how should future research be designed?

1.4. Structure

The report starts with a literature review on the current state of knowledge on macrolitter in freshwater systems. A theoretical framework on controlling processes for macrolitter transport, retention and mobilisation is discussed. Additionally, an overview of hydrodynamic transport mechanisms for macrolitter is given by making parallels with sediment transport mechanisms. This provides a solid theoretical background on the subject and elaborates on different perspectives regarding macrolitter dynamics. Chapter 3 outlines the hydromorphological characteristics of the Waal and defines the study area in which monitoring takes place. Emphasis is given on sediment transport processes in the Waal, design of groyne fields and hydrologic behaviour. The monitoring method is outlined in chapter 4. Chapter 5 discusses the results in detail. The influence of hydrometeorologic variables on litter mobilisation and deposition is analysed. In chapter 6 a conceptual model on riverbank macrolitter is presented. This can be used as a framework for future research design. The final chapter provides the conclusions by answering the research questions.

In this report, the term macrolitter is used. However, the main pollutant of interest is plastic. Sometimes it is not clear whether an item contains plastic or not. Also, (pieces of) glass or tin cans can be found in the environment. This study uses a generally applied protocol for categorisation of macrolitter, called the river OSPAR protocol (found on the last pages). Non-plastic items are incorporated in this categorisation method and are therefore included in this study.

2

Theoretical Background

2.1. General types of plastics

Plastics are used for a wide range of applications and come in varying forms. Two main categories of plastics can be distinguished: thermoplastics and thermosets (PlasticsEurope, 2020). Thermoplastics are melt and form when heated and solidify after cooling down. The process of heating and cooling can be repeated for this type of plastics. Thermosets, on the other hand, are plastics which undergo chemical change after heating. This process cannot be reversed. The most common thermoplastics are polypropylene (PP), polyethylenes (PE), polyvinyl-chlorides (PVC), polyethylene-terephthelene (PET) and polysteryne (PS). Polyurethane (PUR) is the most common type of thermosets (PlasticsEurope, 2020).

Production of plastics begins with the manufacturing of small plastic pellets called "nurdles". Their small size (5 mm) allows for efficient shipping. Nurdles are transferred from production sites where they are molded (Hammer et al., 2012). They act as raw material for many plastic products. The largest use of plastics is in packaging, which is often in the form of single use products. Polymer types found in packeging are PEs, PPs and PETs. Plastics are also important building materials in construction, the automotive industry, electronic devices and household products mainly as PEs, PPs and PVCs. The demand of other sectors is spread out fairly even across different polymer types. Despite current efforts to recycle or reuse plastics, polymers still end up in the environment. Data shows that in 2018, 25% of all plastic waste in the European Union was sent to landfill (EuRIC AISBL, 2020).

Studies on macrolitter in the environment commonly differentiate items in size classes instead of polymer types. Items can be distinguished as macrolitter (>2.5 cm), mesolitter (5 mm - 2.5 cm) and microlitter (< 5 mm). It should be noted that these terms aren't used consistently in literature (van Emmerik and Schwarz, 2020). This study only considers items larger than 2.5 cm.

2.2. Macrolitter in freshwater systems

Consumption and use of plastic products occurs mostly inland. Industrialised and populated areas contribute to the input of plastics in the environment by solid waste disposal and littering (LI et al., 2016). A considerable amount of litter finds its way to the marine environment. Some studies suggest that riverine transport is the primary pathway (Lebreton et al., 2017). More recent literature indicates that litter remains trapped in rivers and estuaries. It accumulates on riverbanks and floodplains and may remain there for over decades (Tramoy et al., 2020b; van Emmerik et al., 2022b). Emission into the ocean can be traced back to waterways and (small) rivers located in coastal urban areas (Meijer et al., 2021).

Liro et al. (2020) have made a first attempt in constructing a conceptual model of macroplastic transport in freshwater systems. The route is divided into 5 phases: *input*, *transport*, *storage*, *remobilisation* and *output*. These phases are influenced by several anthropogenic and natural controls/processes. Anthropogenic controls are litter deposition and cleanup initiatives. Natural processes control the transport-storage-remobilization cycle of riverine macrolitter. Figure 6.1 depicts an overview of the concept and presents some examples of controlling processes.

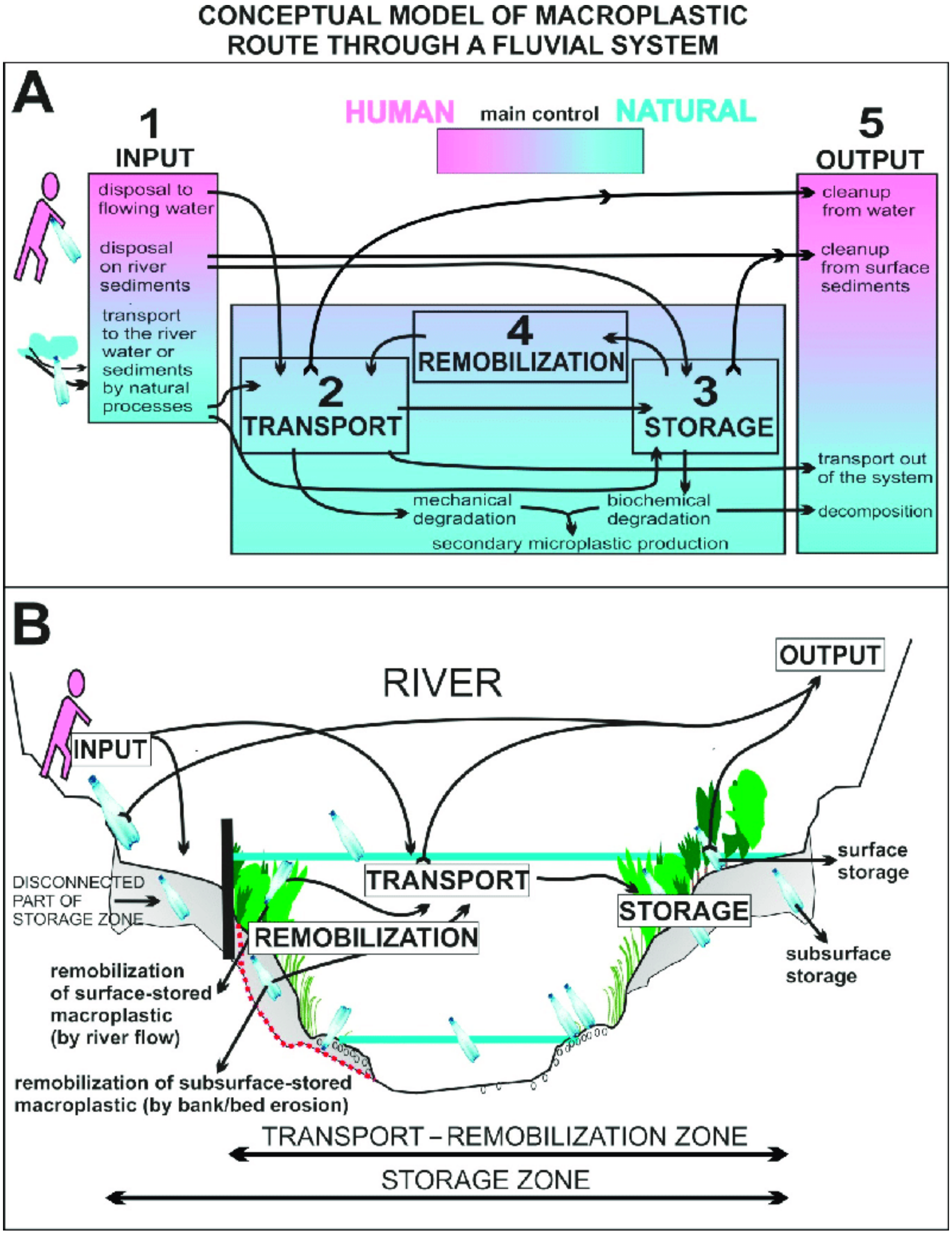


Figure 2.1: Conceptual model of plastic dynamics in the riverine environment as proposed by Liro et al. (2020) (Liro et al., 2020). The model depicts five phases of the macrolitter route through the riverine environment: input, transport, storage, remobilisation and output. Controls on each phase can be of either anthropogenic or natural origin. Anthropogenic controls are more dominant in the input and output phases while transport, storage and remobilisation are controlled by natural processes.

2.2.1. Input

Plastic input is defined as the placement of items within the region affected by fluvial processes. In many cases, litter hotspots at riverbanks are found close to its source (Kiessling et al., 2021; LI et al., 2016). Input of plastics is always anthropogenic. Areas with high population and/or industries contribute the most to environmental waste accumulation. In urban areas, litter is often spilled on the ground. Transport by wind can cause items to end up in rivers (Bruge et al., 2018). Also, rain events cause surface runoff which may carry litter to nearby streams (Moore et al., 2011). In rural areas, waste disposal due to recreational activities or accidental spilling of raw materials during transport are major inputs (LI et al., 2016). Manufacturing facilities, wastewater treatment plants and sewage overflow outlets have also been linked to increased litter quantities (Kiessling et al., 2021). Litter input is larger in low income countries with poor waste management (Lebreton et al., 2017). This stresses the importance of proper governance. It is key to develop efficient infrastructure for waste management and prevent illegal dumping in order to mitigate the input of litter into freshwater systems (Franz and Freitas, 2012).

2.2.2. Transport

Transport of litter is influenced by river hydrodynamics and intrinsic item properties. Litter concentration varies both in vertical and horizontal direction. The flux is highest in the middle of the river, where flow velocity peaks (Van Emmerik et al., 2019). Most items are not situated at the water surface but are vertically distributed in the water column. Items situated lower in the water column tend to travel shorter horizontal distances than floating items (van Emmerik and Schwarz, 2020). Density and degree of degradation decrease the buoyancy of items and affect their position in the water column (Van Emmerik et al., 2019). Additionally, turbulent mixing due to rough terrain results in vertical movement of buoyant items. In open waters, strong winds cause vertical mixing due to breaking surface waves and Langmuir circulations (Kukulka et al., 2012).

Discharge and river stage could be linked to litter concentrations (Castro-Jiménez et al., 2019). When the water level rises, the river is able to reach and mobilise items situated at riverbanks or previously disconnected floodplains. Likewise, the litter flux during extreme events like floods increases significantly. 10 year return period floods may tenfold litter mobilisation (Roebroek et al., 2021a). Not all studies find a relationship between discharge and plastic concentration though. Macrolitter flux in the river Saigon showed no clear relationship with discharge. Interestingly enough, litter transport seemed to be linked with water hyacinth abundance in the river (van Emmerik et al., 2019). In estuaries, the net travelled distance of items can be influenced by tidal waves. Flood tides cause mid-channel retroactive currents at the water surface which direct transport of buoyant items upstream. This effect is less profound during high discharge (Tramoy et al., 2020a). It seems that the relation between macrolitter transport and discharge is river specific. In the Rhine-Meuse delta strong correlations with transport and discharge were found (van Emmerik et al., 2022a).

Tracer studies on floating items indicate that the travel distances are highly variable. Generally, travel distances before stranding are found to be relatively short. Studies conducted in the Waal an the Seine report this to be in the order of 10 kilometres (Goelema, 2021; Tramoy et al., 2020a). In smaller rivers, this is one order of magnitude lower. Tracer experiments conducted in the river Seine found the average travel distance to be 231 m after 24 hours (Newbould et al., 2021). All items eventually stranded somewhere.

2.2.3. Storage and Remobilisation

Transport is alternated by storage and remobilisation. Both Tramoy et al. (2020a) and Newbould et al. (2021) found that litter stranded more often at certain locations than others. In the Seine, accumulation was high at mildly sloped riverbanks located in the convex zone of a meander. Flow velocity and capacity is lower in the convex bank, where sediment deposition occurs. Macrolitter deposition is likely to behave similar. Mildly sloped riverbanks, either localised or stretched out, cause reduction in flow velocity and stream power. Other circumstances which promotes litter deposition are increased boundary resistance, flow divergence and flow seperation/obstruction. Boundary resistance can increase due to riverbed vegetation or coarse sediment. During overbank flow the capacity is reduced by the floodplain roughness. During overbank flow the cross sectional area of the stream increases. Consequently, the flow is less concentrated and stream power weakens. Finally, deposition can occur due to flow obstruction or separation. Flow separation occurs when the boundary layer detaches itself from the channel bed or banks, causing turbulent flow and recirculating currents. This is common in for example man made structures or natural irregularities like boulders (Charlton, 2007).

Some studies suggest that items can beach due to wind effects (Earn et al., 2021; van Emmerik et al., 2019) as horizontal positioning of floating items is affected by wind direction and may cause items to drift towards the riverbanks.

Litter can be stored in vegetation or sediment. Overhanging trees and riverbank vegetation act as traps (Liro et al., 2020; Newbould et al., 2021). Riparian vegetation can also act as a filter. Ecosystems are protected from pollution as litter is stored in vegetation. A study conducted in Italy found that vegetated riverbanks had a significantly higher concentration of litter. Floods are important in carrying items to vegetated areas (Cesarini and Scalici, 2022). Floods carry sediments too. When deposited, these sediments are able to cover debris at riverbanks or floodplains, thus disconnecting items from the fluvial processes (Liro et al., 2020).

Remobilisation occurs as the water level increases and reaches higher parts of the riverbanks or previously disconnected floodplains. Disconnected items stored in sediment can be remobilised when erosion occurs. The time-span of the storage-remobilisation cycle is determined by the hydrologic characteristics and trap effectiveness of the river (Liro et al., 2020). This cycle may last for centuries. The presence of old plastic litter items at floodplains is be primarily controlled by river-floodplain connectivity on the long term. On the short term, water level fluctuations or wind may be a main control of plastic mobilisation (Roebroek et al., 2021b; Tramoy et al., 2020a). Deposited riverbank litter is located at a certain elevation and may be mobilised when the water level is sufficient (Goelema, 2021). Water level fluctuations due to tidal influences remobilises quickly and makes stranding less likely. At locations without tidal influences the main drivers of storage and mobilisation are thought to be wind, boat induced waves and water discharge variations (Tramoy et al., 2020a). The effect of ship induced waves on mobilisation of litter depends on item size, distance to waterline and wave amplitude. Wave amplitude is positively correlated with the probability of plastic mobilisation. With increased riverbank slope or item size, mobilisation by waves is hindered (Climo, 2021).

2.2.4. Output

Macrolitter output can occur through natural transport out of the system. In low complexity river systems, the time span of the storage-remobilisation cycle is likely to be short. Low complexity rivers are channelised, have embanked riverbanks and often lack meanders. These characteristics favour fluvial transport and reduce the trap effectiveness of the system. Therefore, output may be higher in low complexity river systems. Natural, wide river systems with riparian vegetation and floodplain zones have lower emission rates as the storage-mobilisation cycle is more profound and lasts longer (Tramoy et al., 2020b).

In systems with long lasting storage-mobilisation cycles, macroplastics can degrade and fragment into microplastics. Plastics are designed to be durable, therefore degradation takes place over great time spans. Degradation can occur chemically and mechanically. As chemical degradation is accelerated by UV-light, temperature and oxygen, its potential is very location specific (Weinstein et al., 2016). Because the majority of plastics is susceptible to photo-oxidative degradation, UV light is an important controlling variable. Optical properties of plastics alter which causes a yellowing effect. Also, strength, mechanical integrity and extensibility decrease (Singh and Sharma, 2008). UV light is less efficient when items are submerged or when biofilms form on the surface of items, hindering UV light (Weinstein et al., 2016). Degredation, once initiated, can continue in the absence of UV light under the influence of temperature dependent thermo-oxidative reactions (Weinstein et al., 2016). Subsequent fragmentation of plastics is likely to occur mechanically. Strong flow, wave action and abrasion with rough surface are driving factors (Andrady, 2017).
Litter may also exit the system by human effort. Frequently visited areas are likely to be cleaned. Volunteers often participate in large scale riverbank cleanup initiatives (Schone Rivieren, 2022).

2.3. Physics behind macrolitter transport in water

Literature on the physics behind macrolitter movement in water is scarce. This section provides an overview of the general principles behind sediment transport in fluvial systems and discusses the state of knowledge on the behaviour of plastic in water (for both micro- and macroplastics). Equations presented in this section are not directly used in analysis. However, they serve as background knowledge and provide for better understanding of the underlying physics/processes. Research discussing the behaviour of litter presented in this section solely focus on plastic litter.

2.3.1. Buoyancy

Objects immersed in a fluid experience an upward force exerted by the fluid counteractive to the weight of this object. According to Archimedes' principle, the upward force exerted on a body is equal to the weight of the volume of water displaced by the body. This causes objects with a lower density than water to float and objects with a higher density to sink. If a submerged object has the exact same weight as the fluid it displaces it will remain stationary. The force exerted on an object is defined by:

$$F_b = -\rho g V \tag{2.1}$$

In which:

$$\begin{aligned} F_b &= \text{buoyant force [N]} \\ \rho &= \text{fluid density [kg/m}^2\text{]} \\ g &= \text{acceleration due to gravity [m/s]} \\ V &= \text{volume of displaced fluid [m}^2\text{]} \end{aligned}$$

An object floats when the downward force due to its mass is in equilibrium with the buoyant force, determined by the volume of displaced water. Generally speaking, only density of the object determines whether it floats or sinks.

2.3.2. Settling

The behaviour of sinking objects is more difficult to predict. The settling rate depends on density, size, shape, roundness and surface texture of an object. Additionally, fluid density and viscosity are of influence (Dietrich, 1982). A settling object accelerates due to gravity. A resisting force (drag force) acts on the object generated by the fluid's resistance to deformation. The drag force consists of two components. The first component is drag due to friction caused by shear stress exerted on the body (friction drag). The second component is caused by differences in pressure across the body (pressure drag). Shape and orientation of the body are important controls on pressure drag while texture and roughness determine friction drag.

Settling velocity is commonly determined for small grains or particles. Forces acting on a settling particle are defined as the force due to weight of the particle F_g and the resistant force F_D (Dietrich, 1982):

$$F_g = (\rho_s - \rho) g V \tag{2.2}$$

In which:

$$\begin{aligned} \rho_s &= \text{particle density [kg/m}^2\text{]} \\ \rho &= \text{fluid density [kg/m}^2\text{]} \\ g &= \text{acceleration due to gravity [m/s]} \\ V &= \text{volume of the particle/displaced fluid [m}^3\text{]} \end{aligned}$$

and

$$F_D = C_D \rho \frac{w_s^2}{2} A \tag{2.3}$$

In which:

$$\begin{aligned} C_D &= \text{dimensionless drag coefficient [-]} \\ \rho &= \text{fluid density [kg/m}^2\text{]} \\ A &= \text{cross sectional area of the particle [m}^2\text{]} \\ w_s &= \text{particle velocity relative to fluid [m/s]} \end{aligned}$$

The terminal velocity is defined as the settling velocity for which $F_g = F_D$, which results in:

$$C_D = \frac{(\rho_s - \rho) g V}{\rho \frac{w_s^2}{2} A} \tag{2.4}$$

Thus the settling velocity can be computed when the coefficient of drag is known. The coefficient of drag is a result of friction drag and pressure drag, which are determined by inertial and viscous forces. These factors are incorporated in the dimensionless Reynolds number (Re). The dependency of C_D on Re is often determined experimentally for different shapes sizes, density, roundness (Dietrich, 1982). However, for large items like macrolitter it is more difficult to predict the terminal velocity. Items can roll, fold or fill themselves with water, influencing its properties. Current knowledge on the settling behaviour of macrolitter is discussed in the next section.

2.3.3. Vertical positioning of macrolitter

The vertical positioning of macrolitter is difficult to predict. Its exact behaviour remains largely unknown. Positively buoyant items have been found in large quantities at the ocean's floor, indicating that other factors can determine the vertical positioning (Int-Veen et al., 2021). Strong flow and turbulence can increase the amount of suspended items in a river (van Emmerik et al., 2019). Near-neutrally buoyant macroplastic foils can be distributed homogeneously throughout the water column. Accumulation of sediment on or in items can also affect buoyancy (Al-Zawaidah et al., 2021).Buoyant macroplastics can sink due to biofouling, which increases the density of an object. As the amount of biofouling is a function of an item's surface area and buoyancy is a function of an item's volume, items with a large surface area to volume ratio tend to sink faster due to biofouling (Fazey and Ryan, 2016).

Terminal rising and settling velocities play an important role in the distribution of macrolitter in the water column and the processes behind litter sedimentation at riverbanks (Kuizenga et al., 2021). As macrolitter items come in many different shapes, sizes and densities, their behaviour varies a lot. Unfortunately, research on the rising and settling velocities of macroplastics is limited. Waldschlager et al. (2020) (Waldschlaeger et al., 2020) studied the rising and settling velocities of particles ranging in size between 0.5 to 30 mm. Settling velocities were reported to be between 0.16 and 2.98 cm/s and rising velocities were between 0.18 and 19.85 cm/s. The terminal velocity for pellet, foam and fragment shaped particles could be predicted by predescribed formulas. Film shaped particles, however, could not predicted. Films show variable behaviour due to deformation under transport conditions. Both rising and settling velocities of films were lower than that of pellets, foams and fragments. Larger particles (> 5 mm) were harder to predict.

Kuizenga et al. (2022) (Kuizenga et al., 2021) did further study into the rising and settling of foils. Various polymer types showed different behaviour. PET had the largest settling velocity (2.9 - 3.7 cm/s). PE and PP had significantly lower settling velocities (0.01 - 0.4 cm/s and 0.2 - 0.6 cm/s respectively). For PET foils it was found that the settling velocity decreased with increasing size. This may indicate that they are influenced by turbulent movements. This is supported by Zaat (2020) (Zaat, 2020), who did a flume experiment in order to determine the vertical distribution of macroplastics (> 25 mm in this case) in the water column. The experiment was carried out for HDPE and LDPE plastic bags. Both materials have positive buoyancy. It was found that turbulence intensity decreased the surface share of HDPE plastics to 25 % (with a flow velocity of 0.50 m/s).

The behaviour of large litter items is highly variable. Plastic bottles or food packages are likely to float due to their ability to capture air. Also, clean items which have not been affected by biofouling are more likely to be buoyant. When sediment accumulates at items, or when items degrade or get affected by biofouling, buoyancy decreases. Soft, film shaped items which may be positively buoyant are likely to submerge due to turbulent flow.

2.3.4. Horizontal transport of macrolitter

Due to the lack of literature on horizontal macrolitter transport mechanisms, horizontal macrolitter transport is assumed to behave according to the same principles as defined for sediment transport. As with vertical transport, horizontal transport depends on the balance between driving and resisting forces. In this case, the driving force is exerted by the fluid on the body. The driving force is comprised of a drag force and a lift force. The drag force is the effect of the flow of fluid along the object. It is thus orientated in the same direction as the stream flow. The lift force is an upward acting force caused by pressure differences above and below the body, a phenomenon explained by the Bernoulli principle (Charlton, 2007).

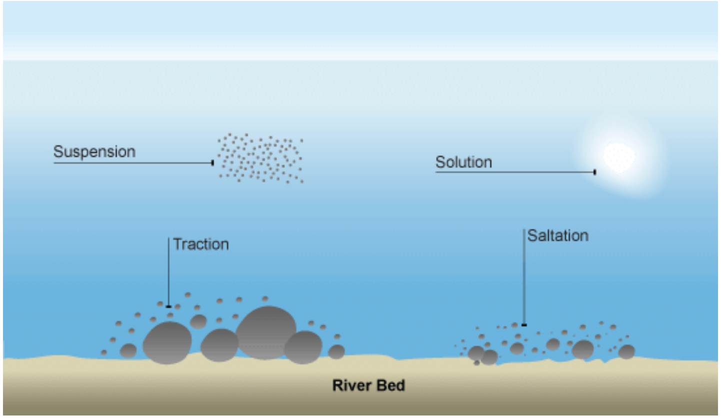


Figure 2.2: Four transport modes of sediment in rivers are distinguished (image source: Afzal, 2013 (Afzal, 2013)). Traction, suspension and saltation are applicable for macrolitter.

High density objects at the riverbed can be transported by traction or saltation. Traction is horizontal movement by dragging or rolling on the riverbed. An object is set in motion when a critical bed shear stress is achieved. This bed shear stress is defined as the Shields parameter and depends on bed roughness and particle size. Transport by traction is often slow and sporadic. Saltation occurs when items at the bed are lifted. Horizontal movement takes place in short jumps. The lift force decreases when items move upwards, causing them to fall. Lighter objects are transported by suspension. Suspended particles are carried by turbulent eddies, which prevent the items from settling or rising. The main transport processes are that of advection and turbulent diffusion. Advection is transport with the stream flow. Turbulent diffusion is mixing due to turbulent eddies, which is also in horizontal direction (Charlton, 2007). The mode of transport for particular item types is expected to play a role in the spatial distribution of macrolitter and may determine item pathways and probability of beaching.

2.3.5. Transport in the littoral zone

The littoral zone of the Waal consists of sandy beaches subject to waves induced by navigation. It bears some similarities with coastal zones. Therefore, sediment transport processes as they occur near the shoreline are deemed relevant to discuss. Waves may play an important role in macrolitter uptake and deposition in the littoral zone of the Waal riverbanks climo2021inland. The littoral zone consists of several sub-zones, which are defined by wave dynamics (see figure 2.3). The surf zone is the area where incoming waves become asymmetrical and tend to break. It is shallow and characterised by turbulent flow. Incoming waves slow down and increase in height as they approach the shore and the depth decreases. When the ratio between height of the wave and the wavelength exceeds 1:7, the wave breaks. The area at which breaking waves are projected on the shore is called the swash zone (Brew et al., 2005).

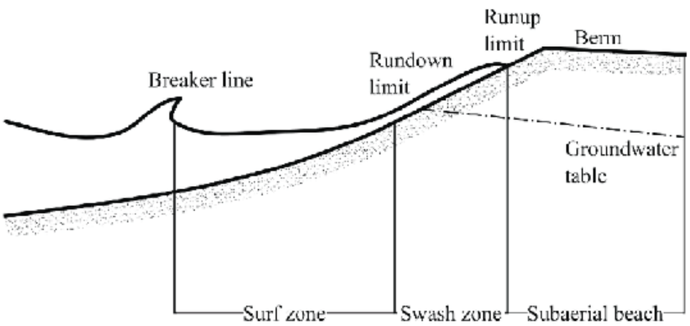


Figure 2.3: Cross-sectional view of wave propagation in the littoral zone (Lanckriet, 2014). The image depicts three sub-zones in which different wave dynamics take place. Although the figure is taken from literature which applies to coastal wave dynamics, it is assumed that wave action occurring in the Waal is similar.

Currents caused by waves are important controls on the sediment budget (Horn and Mason, 1994). Influence of waves on sediment in the littoral zone is commonly studied in coastal morphology. However, for intensely navigated rivers, waves also affect the morphology of riverbanks (Duró et al., 2020). Processes controlling sediment dynamics also control litter dynamics in the swash zone. The main processes inducing transport are swash and backwash (Brew et al., 2005) (Horn and Mason, 1994). Swash and backwash refer to the onshore motion and offshore motion of the water. Swash carries sediment in the direction of the wave propagation, after which backwash carries sediment down again. The backwash is directed in alignment with the steepest slope, often perpendicular to the shoreline (Brew et al., 2005) and less energetic than the swash (Luccio et al., 1998). In coastal areas it is often the case that all waves approach the coastline with the same oblique orientation. The resulting direction in which sediment transport occurs is therefore along the shoreline. This phenomenon is called longshore drift (see figure 2.4)(Brew et al., 2005).

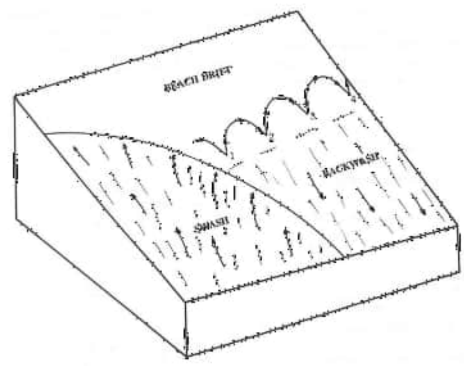


Figure 2.4: Swash and backwash. Swash is directed along the path of wave propagation while backwash is directed along the steepest slope (Brew et al., 2005). Macrolitter transport mechanics by swash and backwash may determine the rate of deposition and uptake for different types of items.

Transport in the swash zone occurs both by suspension and by bed load. A study by Horn et al. (1994) (Horn and Mason, 1994) found that bed load is the dominant transport mode during backwash, while suspension is slightly more important during swash. Larger items are mobilised with swash when the threshold for the initiation of motion is exceeded (Luccio et al., 1998). More heavy particles tend to accumulate in the breaking zone due to the balance between wave forcing and return flow. Lighter particles are advected across the surf zone. The shape of the particles influences whether they are carried back by the return flow. For example, sheet shaped microplastic particles are less prone to beaching compared to pellet shaped particles (Forsberg et al., 2020). It is expected that the susceptibility for transport by swash and/or backwash of a single items influences the rate of deposition and uptake.

3
The Waal

The study is conducted at a groyne field of The Waal. The Waal is a distributary branch of the Rhine river in the Netherlands. About 10 kilometers from the Dutch-German border, the Rhine bifurcates into the Pannerdensch Canal and the Waal (Asselman et al., 2020). The Waal accounts for approximately 66% of the total discharge of the Rhine measured at Lobith (Van Vuren et al., 2005). This number may vary depending on the total discharge. Its size makes the river very suitable for inland navigation. In order to keep the river navigable, groynes have been placed along the riverbanks (Reeze et al., 2017). Riverbank morphology is thereby characterised by sandy beaches (Ten Brinke, 2003). This chapter discusses the history, morphology and hydrologic characteristics of the Waal.

Figure 3.1: The Waal is one of the main branches of the Dutch Rhine and accounts for 66% of the total discharge. Image source: (Siepman, 2022).

3.1. Background

The Rhine delta has a long history flow regulation and training, dating back to Roman times. The Romans began constructing dikes and creeks for agricultural purposes. As the population in the area grew over the following ages, more creeks were constructed in order to turn the wetlands into arable soil. The lowered groundwater table initiated the process of bottom subsidence. In the lower parts of the Rhine delta, land subsidence resulted in the necessity of flood protection against tidal waves. Around 1500 AD, dikes and dams were constructed and eventually polders emerged. Dikes also emerged in the upstream areas. As the branches of the Rhine became more regulated, the need for controlling erosion increased. Around the 1800s, groynes and dikes emerged along the riverbanks. This caused sediment to be captured and prevented riverbank erosion. The groynes also appeared to be beneficial for inland navigation (Havinga, 2020).

Currently, the Waal is the most heavily navigated river in the Netherlands. River traffic mainly consists of commercial shipping. Commonly, loaded ships navigate in the upstream direction while unloaded ships navigate in the downstream direction. Upstream transport often navigates close to the southern riverbank while downstream transport navigates along the north side. Vessels induce waves and currents which influence sediment resuspension (Reeze et al., 2017). Ship induced waves can also mobilise litter items at riverbanks (Climo, 2021). The hydrodynamics of vessel induced waves is further discussed in section 3.3.3

3.2. Hydrology and Morphology

3.2.1. Discharge

The hydrological behaviour of the Rhine is characterised by having a peak discharge during summer months. The mean yearly discharge can very a lot. The Rhine is fed by both meltwater and rainwater. Although the share of rainwater is larger than the share of meltwater, the river discharge commonly remains high until August do to the melting of snow during spring and the melting of glaciers during summer. The chance of low hydrologic conditions to occur is highest from August to November. Discharge often rises again in December and January. This hydrologic behaviour remains similar throughout the years, although the mean yearly discharge varies a lot. According to records from 1901 to 2016, the mean discharge of the Rhine is 2 225 m^3/s at Lobith. This commonly varies between 1 160 m^3/s (10^{th} percentile) and 8 600 m^3/s (90^{th} percentile) (Reeze et al., 2017).

As mentioned before, the Waal is the largest branch of the Rhine. The water level of the Waal is regulated by the weirs at Driel. These weirs are not situated in the Waal itself, but can regulate the discharge indirectly. In favour of navigability, the Waal is free from obstructions (with the exception of the most downstream part, commonly not referred to as the Waal but as the Nieuwe Maas). During low hydrologic conditions of the Rhine, the weirs at Driel are set to increase the relative amount of discharge to the Waal to approximately 82%. This share decreases with rising discharge levels to a minimum of approximately 63% (Reeze et al., 2017). During mean discharge at Lobith the water level gradient of the Waal until Zaltbommel is 10 cm/km. Downstream of Zaltbommel, the water level is affected by tides from the North Sea (with an amplitude of approximately 20 cm at Zaltbommel).

3.2.2. Sedimentation and erosion

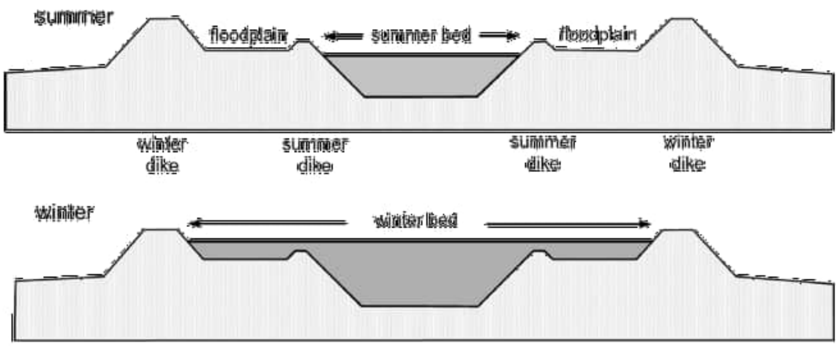


Figure 3.2: Cross-section of riverbanks and floodplains (Disco, 2009). Typically, Dutch riverbanks are characterised by summer dikes and winter dikes with floodplains in between. During periods of high discharge, the summer dikes are submerged and the floodplains are inundated.

Sediment is transported through the fluvial system, varying from fine to coarse material. Fine silt floats in the water column and may be carried over large distances during high water levels. Silt is often deposited in the floodplains, where it is unlikely to be resuspended again (Reeze et al., 2017). As mentioned before, groynes are placed along the riverbanks in order to keep the river navigable. Sediment is trapped between the groynes, resulting in beaches along the riverbanks. Consequently, beaches are generally mildly sloped. The bed slope steepens outside of the groyne fields (Ten Brinke, 2003). The riverbanks of the Waal remain morphologically active. Over long periods of time the riverbanks experience both sedimentation and erosion. When the mean discharge in the Rhine is relatively low, beaches in groyne fields tend to erode and sediment is transported from the riverbanks to the summer bed. Sedimentation occurs during periods of high discharge (occurring once every 5 years) as sediment is transported from the summer bed to the riverbanks (see figure 3.2). According to a study by Ten Brinke (2003), resuspension and deposition of sediment at the riverbanks seem to be in balance when looking at a timescale of decades. However, some of the groynes have been lowered since. This may have altered sediment resuspension and deposition (Van der Wal et al., 2010).

3.3. Design and Hydrodynamics

3.3.1. Meanders

Meander bends are commonly found in natural rivers. They are a consequence of complex interaction with riverbed sediment, vegetation, flow and bank material (Kasvi et al., 2017). Meanders appear as sinusoid patterns and can be described by wavelength, amplitude, radius of curvature and sinuosity (Howard and Hemberger, 1991). The inner banks are characterised with point bars, which consists of accumulated sediment (Zhou and Endreny, 2020). The convex riverbanks are usually gently sloped (Kasvi et al., 2017). The outer bank, or the bend apex, is where scour occurs. Sediment eroded from the outer banks is deposited at the inner banks (Callander, 1978). Deep pools are situated in the bend apex and riverbanks are often steep (Kasvi et al., 2017).

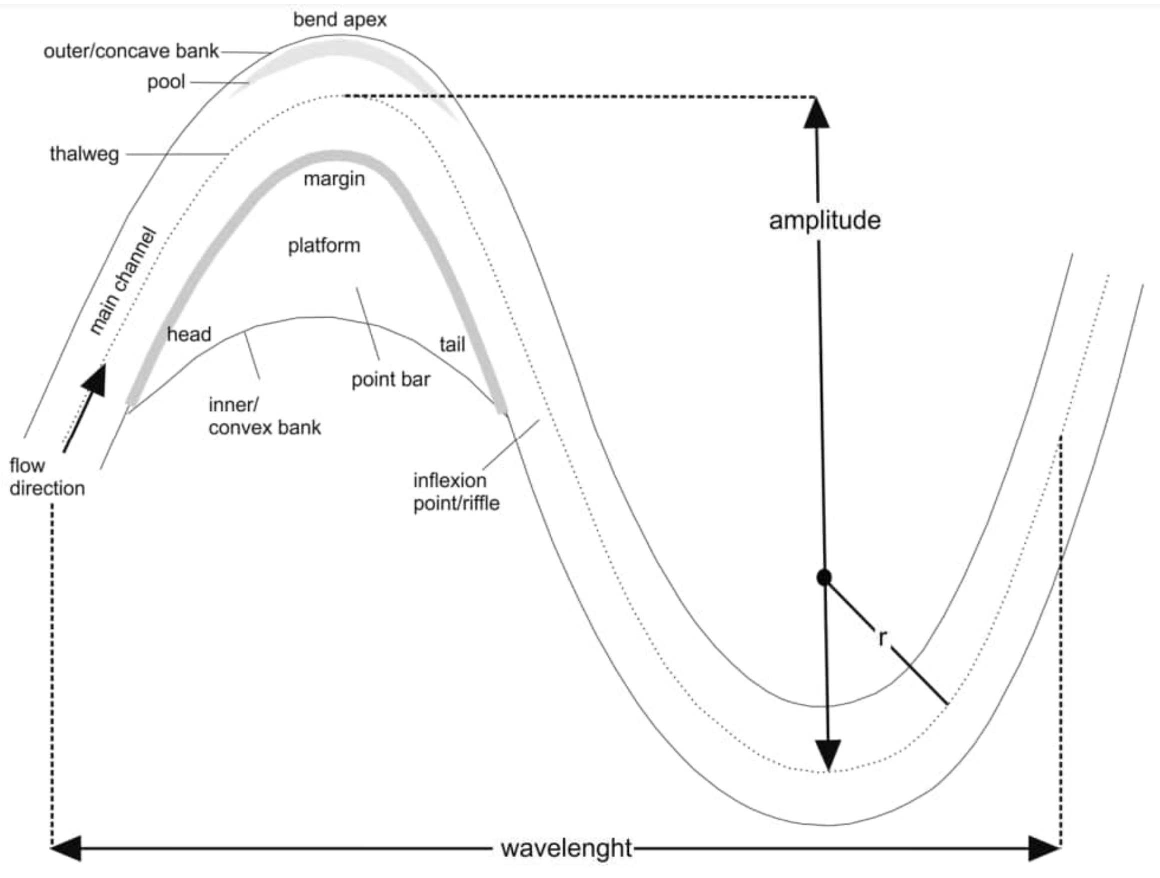


Figure 3.3: Depiction of meander bends in rivers. The inner banks are often gently sloped and subjected to sedimentation. Deep pools occur due to erosion in the bend apex (Kasvi et al., 2017).

The flow velocity is unevenly distributed along the river bend. The high velocity core is generally situated

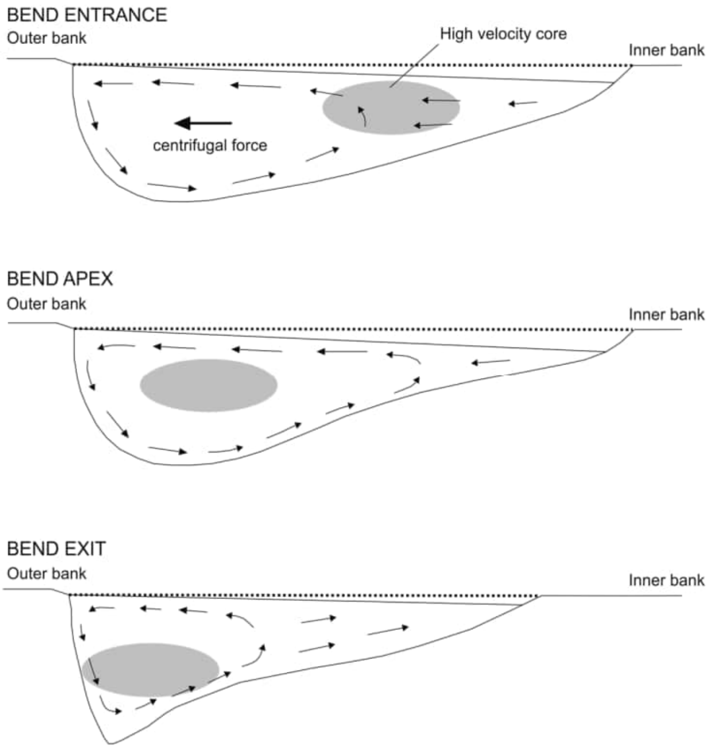


Figure 3.4: Secondary circulation in meander bends. As flow is unevenly distributed in the bends, the water level is slightly elevated in the bend apex. This causes circulation cells (Kasvi et al., 2017).

near the inner bank at the entrance of the meander bend. Naturally, this is very site specific and depends on upstream geomorphology. While progressing through the bend, the high velocity core gradually shifts outwards until situated near the outer bank at the meander exit. This may cause a recirculation zone due to flow separation at the inner bank after the bend apex. Uneven flow distribution causes superelevation at the outer bank, resulting in downward flow which creates circulation cells. Flow is directed inwards near the riverbed and causes upward flow at the inner bank. This phenomenon is called secondary circulation (see figure 3.4). The combination of flow separation and low flow velocities results in deposition of fine sediment (Kasvi et al., 2017).

3.3.2. Groyne fields

As mentioned before, groynes are constructed in order to prevent the riverbank from erosion and deepen the main course by confining the stream flow. Groynes in the Waal are made from solid rocks, causing them to be impermeable. The groynes are emerged during low hydrologic conditions and become partially submerged with mean river discharge. Dimensioning, placing and orientation are important considerations in groyne field design. Figure 3.5 depicts the design variables. The shape of the groynes in the Waal are generally straight and have a width between 50 to 100 meters. A total of approximately 1.600 groynes can be found in the Waal, with a mean spacing of 200 m between each other. Beaches are formed between the groynes. The mean width of these beaches is 25 m, but the variation is large. The beach slope is commonly 1:25. The orientation of the groynes is small compared to the perpendicular of the thalweg. Most groynes are slightly oriented in the upstream direction (Ten Brinke, 2003). This causes the river flow to be deflected away from the bank. Bank protection and sedimentation are increased for perpendicular and upstream directed groynes, as found in the Waal (Yossef, 2002). Depicted dimensions of groyne fields are:

- A: groyne field length
- B: groyne field width
- C: length along water line

- D: beach width
- E: distance betweeen normal line and thalweg
- F: river width between groynes
- G: orientation of a groyne related to the perpendicular with the thalweg
- H: orientation of the groyne field related to the North

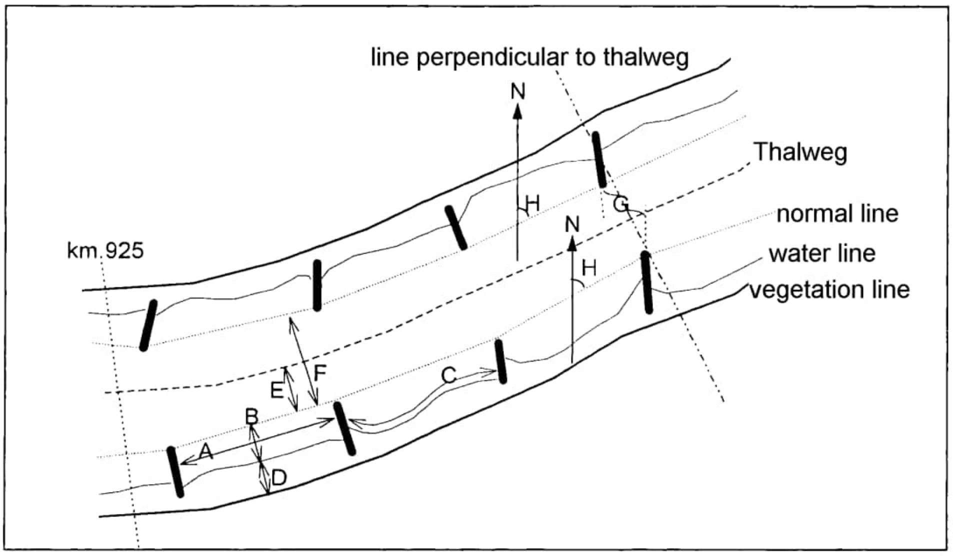


Figure 3.5: Groyne field design dimensions (Yossef, 2002)

Within groyne fields flow is reduced. Exchange of mass and momentum from water inside the groyne fields with the main stream causes circulation and exchange of suspended matter (Czernuszenko and Rowinski, 2005). The flow pattern within groyne fields depends on whether the groynes are submerged or not. Also, the location of a groyne field along the river influences the flow pattern. Generally, flow inside a groyne field consists of a large eddy which causes the flow near the riverbank to be directed upstream (Yossef, 2002). The exact pattern is difficult to predict as the processes of flow separation, mixing and recirculation depend on local geometry and bathymetry (Czernuszenko and Rowinski, 2005). That being said, at least one gyre can be observed in most groyne fields. Smaller counter rotating gyres may occur in the corners of a groyne field (see figure 3.6). This is determined by the length to width ratio of the groyne field. A 1:1 aspect ratio leads to the formation of a single eddy. Larger ratios result in the formation of a secondary eddy (Czernuszenko and Rowinski, 2005).

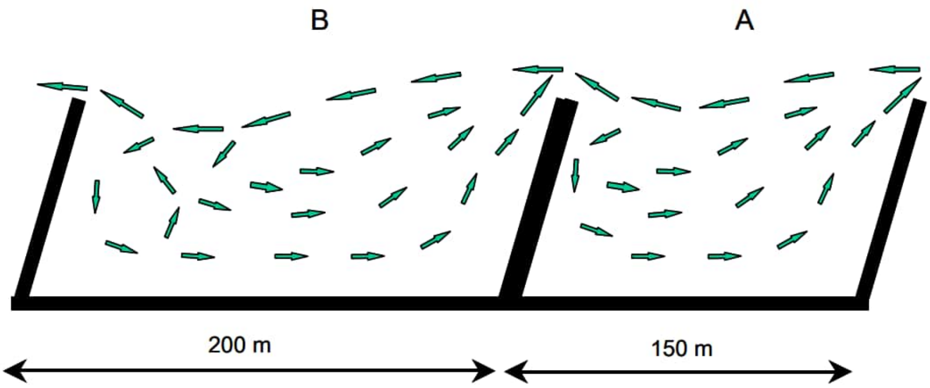


Figure 3.6: Gyres in groyne fields (Ten Brinke, 2003)

A strong current can be observed downstream of the tip of the groynes. If the groynes are emerged, river flow is unable to follow the tip of a groyne, resulting in a vortex which scours the riverbed. This process leads to the formation of so called groyne flames: local sour pools around the groyne tip (see figure 3.7) (Ten Brinke, 2003). In the Waal, the crest of the groynes have been lowered causing the groynes to become partially submerged under normal hydrologic conditions. The groynes become submerged more easily, increasing the discharge potential of the Waal. Flow patterns within the groyne fields alter under these conditions. When the groynes are fully submerged, stationary flow with near parallel stream lines occur over the groynes. Partially submerged groynes cause a dynamic flow field (variations in flow over the groynes at the same location) due to moving eddies in the groyne field (see figure 3.8) (Czernuszenko and Rowinski, 2005).

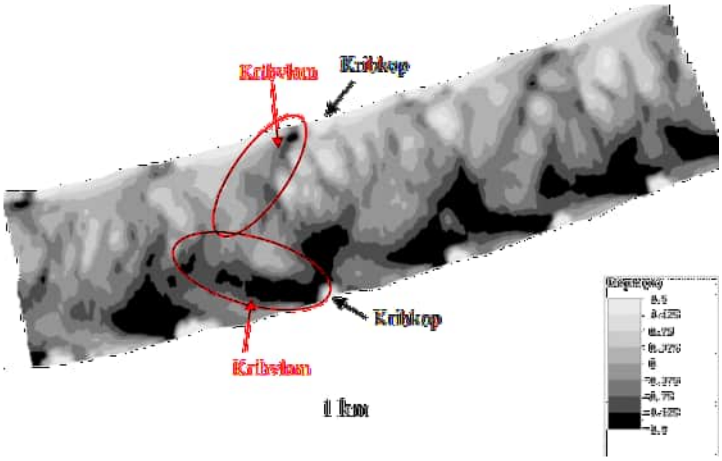


Figure 3.7: Groyne flames are formed by scour at the tip of the groynes. This creates a morphological pattern which bears visual similarities with flames (Ten Brinke, 2003).

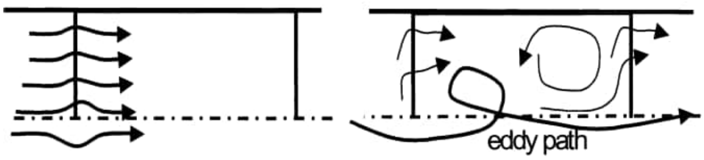


Figure 3.8: Left: Flow pattern over fully submerged groynes. Right: Flow pattern over partially submerged groynes (Czernuszenko and Rowinski, 2005)

3.3.3. Effects of navigation

River traffic mainly consists of commercial shipping. Commonly, loaded ships navigate in the upstream direction while unloaded ships navigate in the downstream direction. Upstream transport often navigates close to the southern riverbank while downstream transport navigates along the north side. Vessels induce waves and currents which influence sediment resuspension (Reeze et al., 2017).

When a ship passes by water is moved. Water is pushed up by the bow, producing the front wave. This is succeeded by a decrease in water level along the hull of the ship and eventually the stern wave. Secondary waves form at the hull. The water displacement at the bow results in a return current along the ship. This current causes suction of water out of the groyne fields, which is followed by rapid refilling. The movement of water amplifies the flow strength of the eddies (Ten Brinke, 2003). The largest flow velocities occur downstream of a groyne, directed perpendicular to the thalweg. The effect of ships decreases when discharge increases. Also, the distance of the vessel to the riverbank is negatively correlated with occurring flow velocities (Verhey and Vermeer, 1987).

Figure 3.10 depicts the influence of a passing vessel in upstream direction on the hydrodynamics in a groyne field. This particular groyne field is situated at the southern banks of the Waal, not far from the study area

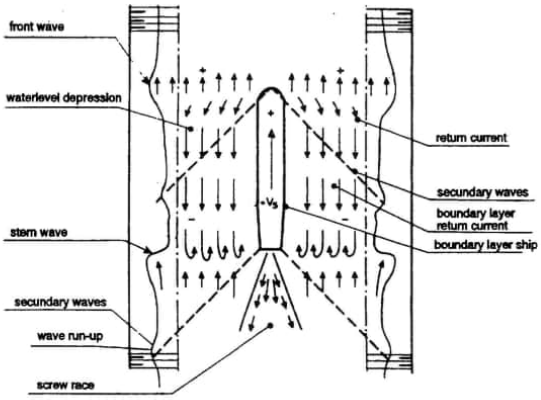


Figure 3.9: Navigation induced water movements on a restricted waterway (Verheij et al., 2008)

(Ten Brinke, 2003). Six phases are distinguished in which water flow accelerates and decelerates. Phase zero describes the situation before ship passage. The river stream causes eddies to emerge in the groyne field, as expected. In phase one, the ship passes the downstream groyne, creating flow acceleration near the tip of the groyne. Water is pushed out of the upstream area of the groyne field. The small eddy disappears and the flow velocity of the main eddy reduces, resulting in deceleration in the upstream corner of the groyne field. This effect is also visible in phase 3. The return current inundated by the vessel counters the flow direction of the eddy within the groyne field. In phase 4 and 5, flow is accelerated again due to the stern wave and following currents. For small vessels, water movement is less profound. (Ten Brinke, 2003).

The intensity of navigation in the Waal has lead to increased sediment transport from the groyne fields to the main channel (Yossef, 2002).

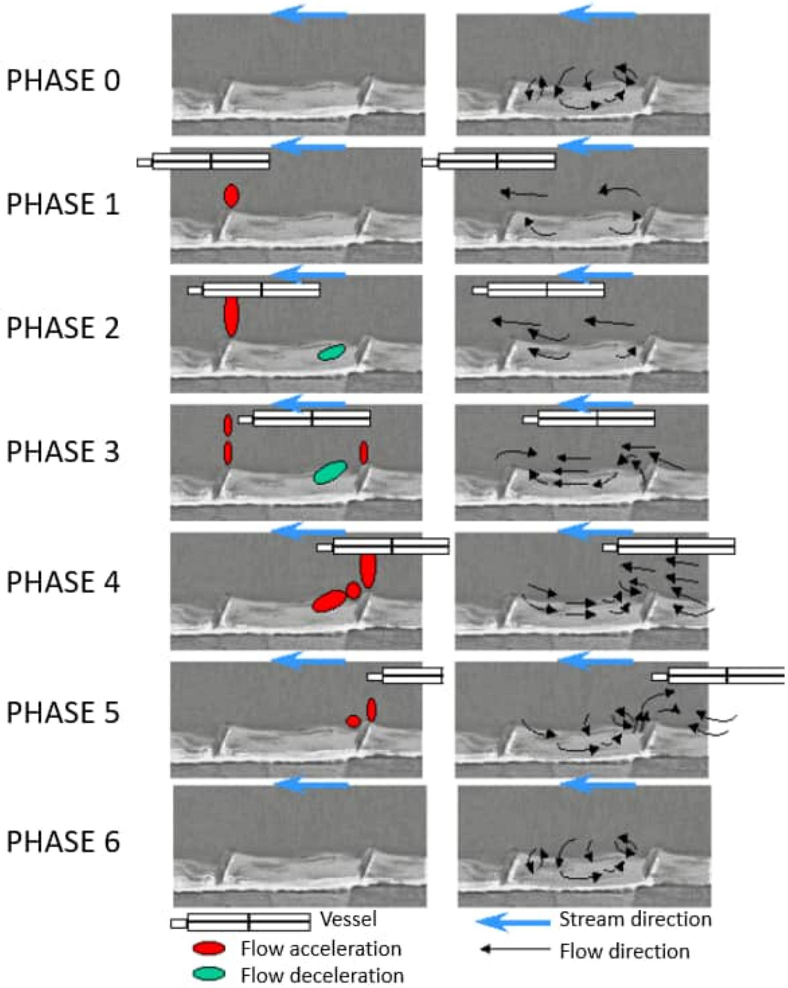


Figure 3.10: Flow acceleration/deceleration and direction due to upstream navigation (Ten Brinke, 2003)

3.4. Study Area

The study area is a groyne field located near the town of Deest (figure 3.11). It is situated at the end of a mild inner bend at the southern riverbank of the Waal. Whether this causes the riverbank to be subject to sedimentation is not clear. Emergent tree roots observed at the riverbank could be an indication of erosion instead of sedimentation.

The nearest upstream urban centre of significance is the city of Nijmegen. This could be a possible source of riverine pollution. Combined sewer overflows are located near the old city centre which flow into the Waal. Many urban riverbanks are also used for recreational purpose, which leads to increased littering. However, this phenomenon is not expected to occur during winter.

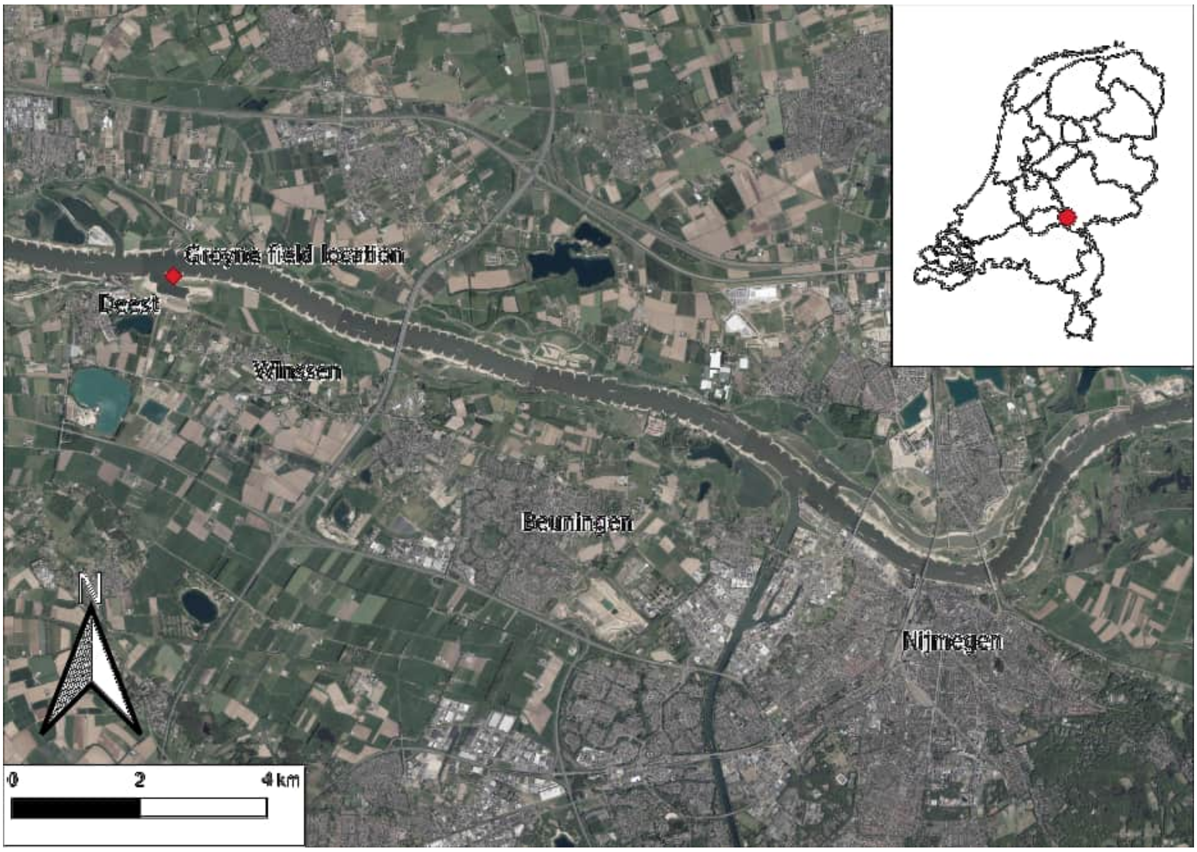


Figure 3.11: The location of the study area

4
Method

An in-situ monitoring campaign was carried out from November 2021 to January 2022. The monitoring location is mentioned in Chapter 3. The goal was to record the locations of riverbank litter throughout time. This allows for assessment of spatial patterns, tracking pathways and observing variations in item quantity. As this is the first study to adopt this a method, a one week trial was conducted. Based on experiences gained during this trial, the method had to be adjusted slightly. There were three important assumptions adopted while using this method: (1) item uptake and deposition only occurs near the water, (2) items located above the flood marks remain immobilised and (3) riverbank morphology does not change during the monitoring period.

4.1. Monitoring approach

During the visits to the study area, the following variables were measured:

- Item location (X, Y, Z)
- Waterline at maximum wave run-up (X, Y, Z)
- Study area morphology (X, Y, Z)
- Items properties (by photographs)
- Substrate (sand, clay, rocks)
- Item position relative to sediment (clean, sandy, buried, tangled in organic material)
- Item size (small: 2.5 cm - 5 cm, medium: 5 cm - 50 cm, large: > 50 cm)

The X,Y and Z variables were measured using a Real Time Kinematic (RTK) positioning system. The RTK was also used to measure riverbank morphology. Items were photographed using a smartphone camera. This allowed for categorization while leaving the items untouched. At the end of the monitoring campaign, the riverbank was cleaned. In order to ensure that items remained undisturbed, a wildlife camera was mounted in a nearby tree. The camera was set to make pictures every 5 minutes. In case of suspected human interference, these images could be checked. No interference occurred during the monitoring period.

4.1.1. Surveying method

The approach was tested during a one week trial period. The initial idea was to conduct weekly measurements of all items present at the riverbank. This was found to be unfeasible, as the amount of items encountered at the riverbank exceeded expectations. Measuring every single item could not be done in one day. Therefore, it was decided to split up the study area in two parts: the area between the flood marks and the waterline and the area above the flood marks. The complete riverbank could be surveyed in two days. Subsequent surveys were only conducted in the area between the flood marks and the waterline.

It was assumed that item mobilisation only occurs due to water level changes and ship induced waves. Items located above the flood marks remained immobilised. This assumption was supported by the observation that wind plays a very limited role in riverbank item mobilisation (see section 5.4).

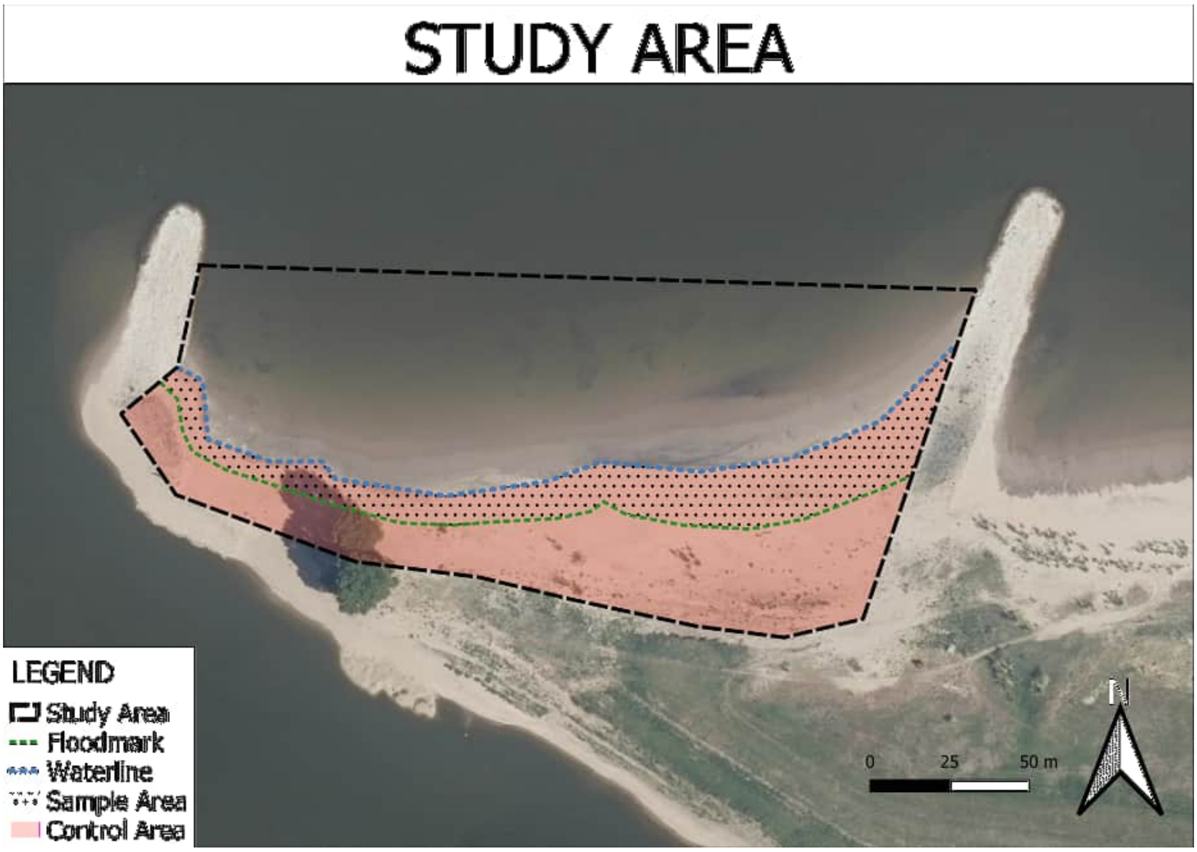


Figure 4.1: The study area is bounded by the groynes (not included) and the vegetated berm. The control area is defined as the area above the waterline and within the bounds of the study area. During the first surveys the entire control area was mapped. Subsequent surveys were carried out between the flood marks and the waterline.

The boundaries of the study area, the sample area and the control area are depicted in figure 4.1. The study area comprised the entire groyne field with exception of the groynes themselves and the part of the riverbank where the grass begins. The control area is the bounded by the study area boundaries and the waterline. Depending on the water level, the control area may change in size. Items situated outside the control area were not considered. The waterline was measured along the maximum wave run up. This was done before the actual survey. Surveying took place in the area between the waterline and the flood marks. Flood marks are visible lines at the riverbank which indicate how far waves have reached in the preceding days. Because the area was visited regularly, new flood marks could be easily distinguished from old flood marks. The sample area, where the survey takes place, changed from day to day. If the water level increased/decreased, the sample area shifted. By measuring the coordinates of points along the flood marks and the waterline, the sample area was defined during surveys. For the area above the flood marks, data points from a prior survey was added.

Distinguishable items were tracked throughout the study area. These items were given a unique name in the database. The goal of tracking these items was to get an understanding of the routes that items travel throughout the study area and to measure the residence time of items at the riverbank. Additionally, fifteen indistinguishable items (wet wipes) were sprayed with yellow, waterproof paint for the purpose of tracking.

4.1.2. Equipment

RTK positioning system

The location of items was measured using the "S100 RTK Receiver" manufactured by Polaris. RTK positioning systems have improved accuracy compared to traditional GPS, providing centimeter level accuracy. A conventional GPS calculates the position of the rover by using the receivers distance relative to three satellites. The distance can be determined by multiplying the travel time of received satellite signals by the speed of light. This method provides meter level accuracy. RTK positioning improves accuracy by using a base station, which should be set up at a location with known coordinates. The base station computes its location using GPS and calculates the measurement error relative to its known position. This information is send to the RTK receiver in order to make corrections, resulting in centimeter level accuracy. The S100 did not require setting up a base station manually. Instead, base correction data was received via the internet from a CORS network (either SmartNet, RTK Direct or TopNETlive).

Smartphone
A Samsung A13 smartphone was used to run the RTK receiver application. On the same device, pictures of items were taken. Every fifth picture was tagged with a number, corresponding to the number of measurements made with the RTK receiver. This minimises the room for error.

Wildlife camera
A wildlife camera (Stealth Cam 2020 DS4K Max) was attached to the tree at the riverbank. It was set to make pictures every 10 minutes with a resolution of 30mp. The images are used to monitor the study area in between surveys. Imagery was analysed for human interference and other unpredictable events.

4.1.3. Temporal planning

The trial survey started at November the 8th, 2021 and lasted a week. During this week, the river discharge was low and stable. Measurements were carried out every day to get a feeling for the temporal variability of riverbank litter. Additionally, the entire area above the flood marks was surveyed in order to get a base case for the subsequent surveys. Based on experiences during this trial, it was decided to perform surveys at least once a week. This was later adjusted to at least twice a week.

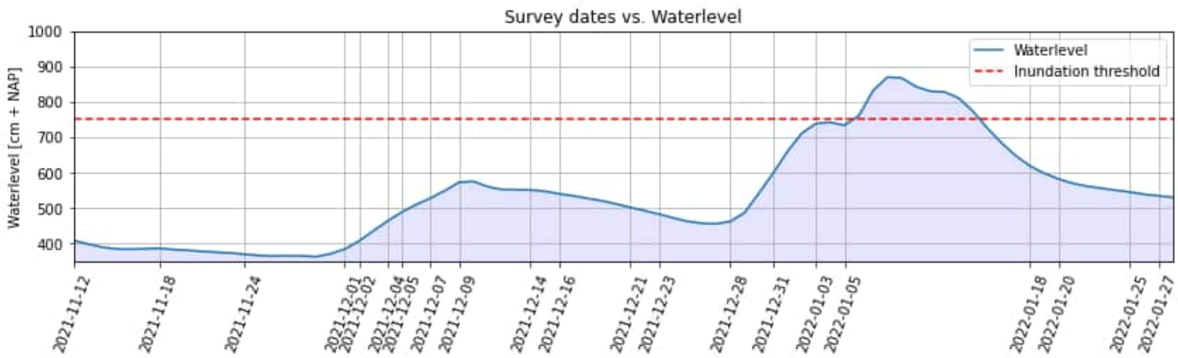


Figure 4.2: The survey frequency is based on water level expectations. Hydrologic peaks should be captured. This figure shows the temporal planning as a result of water level fluctuations. Reliable forecasts were produced five days in advance.

The timing of surveys was decided based on the expected water level. Surveys were carried out at the peaks of the hydrograph. Also, the frequency was increased with rapidly changing hydrologic conditions. During inundation of the study area, no surveys were be carried out. A total of 21 surveys were performed in the period between the 12th of November 2021 and the 27th of January 2022. Figure 4.2 depicts the survey dates with respect to the water level measured at the gauging station in Dodewaard. The study area was flooded when the water level exceeded NAP +7.5 m.

4.2. Post-processing

The raw data obtained from surveys consisted of a list of coordinates (WGS84) and an accompanying set of pictures. The majority of the items are difficult to distinguished from each other. This is especially the situation with pieces of plastic and pieces of cloth. As stated before, special attention was given to the items that have a unique appearance. These items were tracked throughout the monitoring campaign. In addition, fifteen wet wipes were tagged with yellow paint. Item properties based on physical attributes and item locations were deduced from the raw data.

The following variables were considered:

- **Item category** According to the River OSPAR guidelines.
- **Substrate**: Sand, clay, rocks, vegetation.
- **Item size**: Small (2.5 cm - 5 cm) medium (5 cm - 50 cm) and large (> 50 cm).
- **Item position relative to sediment**: Clean, sandy, buried, tangled in organic material.
- **Physical description**: Distinguishable items are given a unique description.
- **Tracking** (yes/no): Indication of whether items are tracked.
- **Location**: Latitude and longitude.
- **Z**: Vertical item position meters above WGS84 reference ellipsoid, derived from the DEM.
- **New/Mobilised** (yes/no): Indicates whether items have moved with respect to the prior survey. Newly deposited items were also included.

A small adjustment was made to the item size indication of the river OSPAR guidelines. The original guidelines define the size of small items with an upper limit of 2.5 cm. As this study only focuses on items larger than 2.5 cm, the upper limit was set to 5 cm. Excluding items smaller than 2.5 cm was done in favour of practical feasibility.

4.3. Estimation of item uptake and deposition

Item uptake and deposition are considered two different processes. It was assumed that these processes occur simultaneously. The amount of items present at the riverbank depends on the magnitude of uptake and deposition:

$$N(t_1) = N(t_0) + dN^+ - dN^- \tag{4.1}$$

In which:

$$\begin{aligned} N &= \text{Amount of items present at the riverbank [items]} \\ t &= \text{Day of survey [days]} \\ dN^+ &= \text{Amount of items deposited on the riverbank between surveys [items]} \\ dN^- &= \text{Amount of items washed away between surveys [items]} \end{aligned}$$

dN^+ and dN^- could not be obtained directly from the data. Uptake and deposition were estimated by counting the amount of items per category and summing the positive and negative differences with respect to the prior survey separately:

$$dN^+ = \sum_i min\{0; N_i(t) - N_i(t-1)\} \tag{4.2}$$

$$dN^- = \sum_i max\{0; N_i(t) - N_i(t-1)\} \tag{4.3}$$

In which:

$$i = \text{Item category}$$

The estimated values of item uptake and deposition may underestimate the true values. This is due to the fact that uptake and deposition within one category is not accounted for. Also, uptake and deposition between measurements may have taken place. It should be noted that dN^- is not an indication of how many items have left the groyne field. Items may still be present in the study area, though under water. Also, it was assumed that the share of items which got completely buried under sediment is negligible.

4.4. Additional data

Riverbank morphology and hydrometeorologic variables were obtained from different sources. For the riverbank morphology, the RTK data was used to derive the DEM. Water level and wind data was retrieved from publicly available databases.

4.4.1. DEM

Under the assumption that the riverbank morphology did not change during monitoring, the DEM was computed from the raw RTK data. Every data point included a measure of altitude. Using SAGA GIS software, the following steps were taken to derive the riverbank morphology:

1. Convert z-dimension from feet to meters.
2. Interpolate altitude values from point cloud data using the "Natural Neighbour" method (Sibson's variant, with the cellsize set at 0.000002) to obtain the *DEM*.
3. Calculate terrain *aspect* and *slope* with the "Slope, Aspect, Curvature" method (Haralick's variant).

The DEM and slope data were used in further analysis.

4.4.2. Water level data

Mean daily water level data was obtained from the gauging station at Dodewaard. The data was made publicly available from Rijkswaterstaat. Differences in water level between the gauging station and the study area was assumed negligible as the distance between the locations is small (3.2 kilometres). The observed water level fluctuations for the period from November 2021 to January 2022 corresponded with discharge fluctuations between 986 m^3/s to 5205 m^3/s. These flow values can be considered normal to slightly increased.

4.4.3. Daily wind data

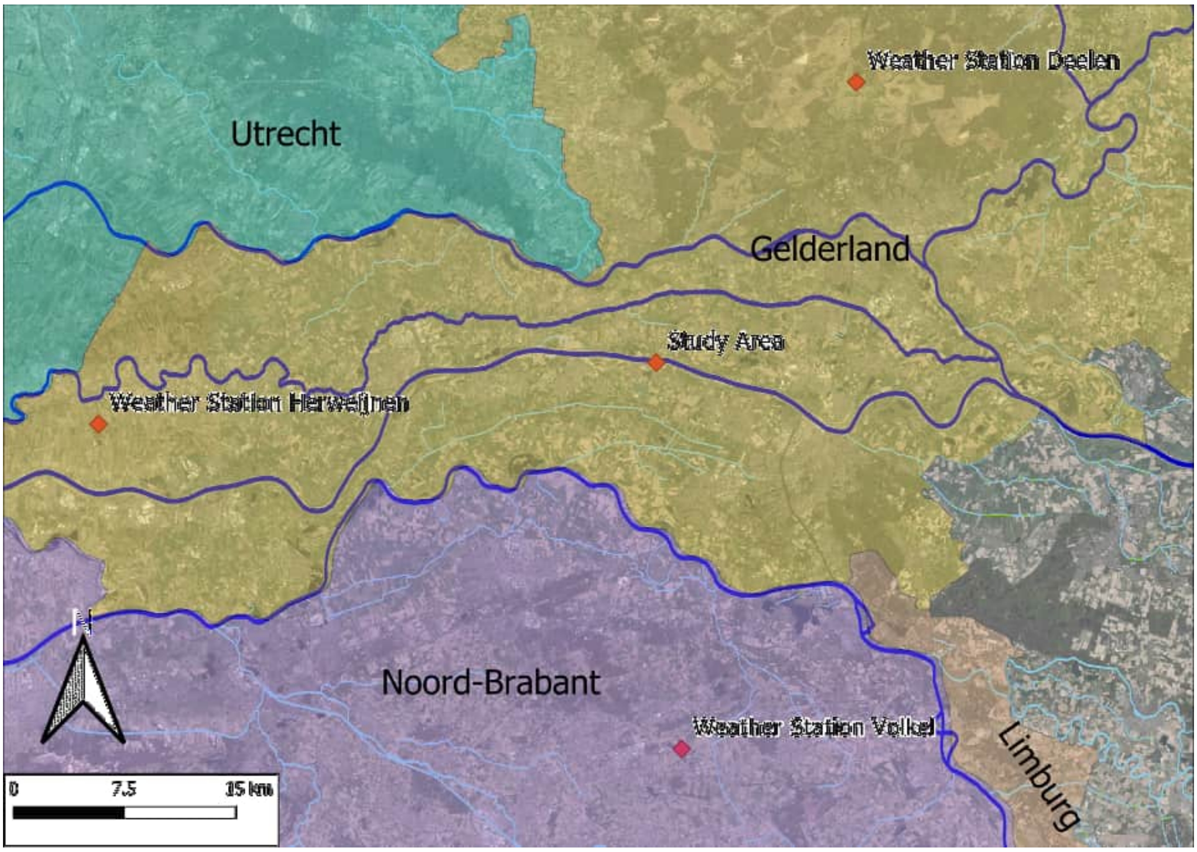


Figure 4.3: Locations of nearest KNMI weather stations

Daily mean wind velocity and direction were monitored at KNMI weather stations. The data is publicly available. The closest weather stations are located in Deelen (23.4 km), Herwijnen (38.1 km) and Volkel (27.0 km). The daily mean wind velocity and direction at the study area was estimated using Inverse Distance Weighting (IDW) interpolation of the wind vector components. IDW is a simple method for spatial interpolation which relies on the principle that the influence of a value at a certain point declines with increasing distance from this point. In reality, wind is affected by terrain roughness and differences in elevation, which leads to researchers often preferring more sophisticated methods Ozelkan et al. (2016). In this case, however, geographic variations are small and measurements from the weather stations only differ slightly. Therefore, IDW interpolation is preferred due to its simplicity.

$$v_{x,j} = \frac{\sum_i \{v_{x,i}/d_{i,j}\}}{\sum_i \{1/d_{i,j}\}} \tag{4.4}$$

$$v_{y,j} = \frac{\sum_i \{v_{y,i}/d_{i,j}\}}{\sum_i \{1/d_{i,j}\}} \tag{4.5}$$

In which:

i = Weather station
j = Study area
v_x = X component of daily mean wind velocity [m/s]
v_y = Y component of daily mean wind velocity [m/s]
$d_{i,j}$ = Distance between station i and location j [km]

4.5. Statistical analysis

An exploratory approach was used to find patterns in the data. For such an approach, no general guidelines exist. The philosophy was to generate hypothesis and observe patterns by visualising the data in many different ways. As underlying data distributions were not known and observations were scarce, non-parametric tests were conducted for testing hypotheses. Possible relationships between variables are assessed using Spearman's Rho. Comparison of distributions is done using the Kolmogorov-Smirnov test, which compares differences between the CDFs of two samples. Where data was insufficient for performing statistical tests, visualisations and descriptions were used to generate hypotheses which can be investigated in future research.

5
Results and Discussion

The footage from the wildlife camera showed no human interference with the items on the riverbank. Therefore it can be assumed that the observed macrolitter behaviour is solely a result of the effect of natural processes. The monitoring results are presented and discussed in seven parts. First, general discriptive statistics and visualisations are presented. Secondly, spatiotemporal variability is discussed by analysing the RTK positioning data. Thirdly, the interaction between items and riverbank morphology is assessed. Thereafter, fieldwork observations and the effect of hydrometeorologic processes are discussed qualitatively. This is primarily based on photographs made during surveys. Then, the acquired data of the tracked items are discussed by reviewing item occurrences and pathways. Next, the vertical positioning of the items relative to the waterline is analyzed. These data may hold information on item behaviour in the swash zone. Finally, item uptake and deposition are estimated and the influence of hydrologic fluctuations and wind is assessed. By analysing the rates of uptake and deposition more insight is gained on which factors control riverbank macrolitter variability.

5.1. Item composition and quantity

Items were categorized using the river OSPAR protocol. The category list is included in the final pages of this report. Figure 5.1 shows the composition of items found at the riverbank. From the 54 distinguished categories, 7 categories made up 89.2% of the items found. Figure 5.4 depicts photographs of items from each of the seven categories. The fact that few categories comprise the majority of the items can be attributed to the fact that many items are fragmented pieces of plastics. Their original product could not be identified. These items are categorised as either soft plastic fragments or hard plastic fragments. Non-fragmented items are relatively scarce.

The vast amount wet wipes found at the riverbank is remarkable. These items can easily be overlooked as they are often sandy, tangled in organic material and have a brownish colour (see figure 5.2). It is unknown to many users that wet wipes contain plastic microfibers. Their use has reportedly increased during the COVID-19 pandemic, most likely for sanitation and disinfection (Shruti et al., 2021). According to surveys carried out by Schone Rivieren (Schone Rivieren, 2020), the mean amount of wet wipes found at the riverbanks of the Waal and the Meuse is 12 items per 100 meter (when present). Although sometimes present in large amounts, their geographical spread seems very localised. Wet wipes are found at 1 out of 5 monitored riverbanks according to Schone Rivieren. In this groyne field, the mean amount of wet wipes was 133 (rounded) items per 100 meter, with a maximum of 226 items per 100 meter. Compared to Schone Rivieren data, this location contains an extraordinarily high amount of wet wipes. Especially considering that the reported mean also includes measurements done while the study area was almost completely inundated.

Fragmented pieces of plastics constituted the second and third largest groups. Distinction is made between soft plastics and hard plastics. The mean amount of fragmented plastics (both hard and soft) is 21 items (rounded) per 100 meter, with a maximum of 42 items per 100 meter. Fragmented plastics are found at many locations along the riverbanks. The monitoring operation conducted by Schone Rivieren in fall 2021 (at the Meuse, the Waal, the Rhine and several smaller rivers) found that hard and soft plastic pieces were present in

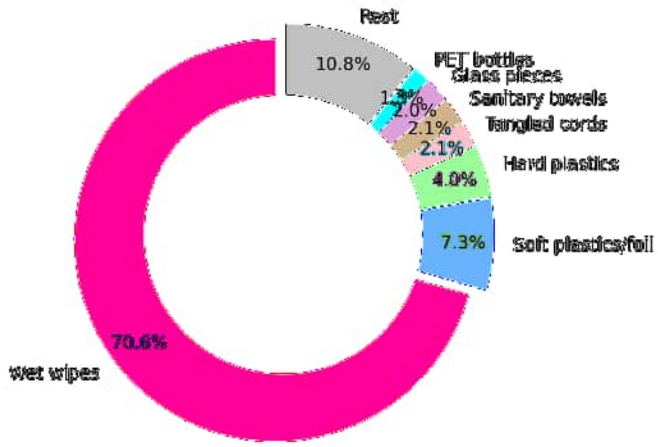


Figure 5.1: 82.9% of the items found in the groyne field can be divided into seven categories. The vast majority consisted of wet wipes, which were present in extraordinarily high numbers when compared to data from Schone Rivieren. Other prominent categories were hard plastic fragments and soft plastic fragments.

76% and 81% of the locations respectively. Together, hard and soft plastic pieces are found with an average of 47 items per 100 meter (Schone Rivieren, 2022). They are either clean or sandy, but rarely tangled in organic material. Table 5.1 depicts the amount of items found per 100 meter for every category compared to the data from Schone Rivieren (2020, 2022).

Category	Mean quantity per 100 m in study area (rounded)	Max. quantity per 100 m in study area (rounded, including date of survey)	Mean quantity per 100 m (according to Schone Rivieren)
Wet wipes	133	226 *at 05-12-2021*	12 (when present)
Soft plastic pieces (<50 cm)	14	27 *at 28-12-2021*	32
Hard plastic pieces (<50 cm)	7	21 *at 18-11-2021*	15
Tangled nets/cords	4	14 *at 02-12-2021*	7
Sanitary towels	4	7 *at 04-12-2021*	9 (when present)
Glass pieces	4	7 *at 28-12-2021*	not mentioned
Plastic Bottles	2	5 *at 01-12-2021*	9

Table 5.1: Item quantity per category compared to Schone Rivieren data.

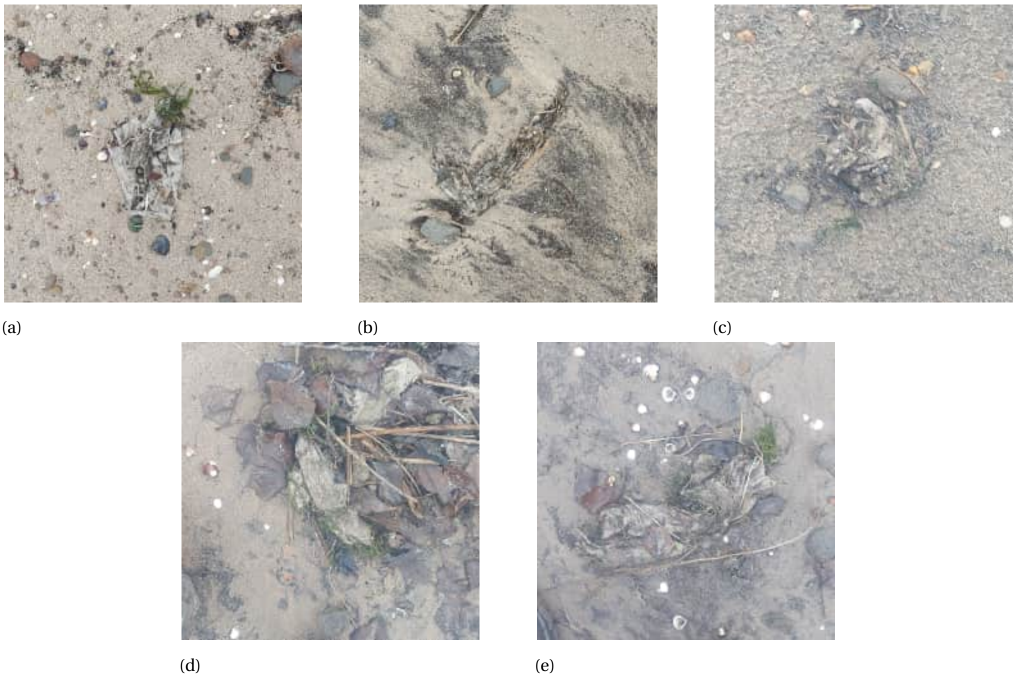


Figure 5.2: Selection of wet wipes found at the riverbank. The pictures show that these items are not clearly visible (b and c). Also, some items are tangled in water plants (a, d and e).

Again, it is evident that the number of wet wipes in this area is high. The quantity of items for other categories is similar to or lower than the reported means. The surveys show that the maximum quantity of items found in the groyne field is often a multitude of the mean quantity. This indicates significant variability within a three months period under normal hydrologic conditions. The dates at which most items are found vary per category. The total amount of items was highest during the period between 18-11-2021 and 28-12-2021. Data shows that when conducting a survey, special attention should be paid to timing as the amount and composition of macrolitter varies significantly.

Figure 5.3 depicts the amount of items found at the riverbank. The total amount of items varied from 6 to 577. A very large part of the total litter variability is explained by the behaviour of wet wipes, as they make up for roughly 70% of the items. The graphs show that, for most categories, increase and decrease occur roughly at the same moment.

There are three periods in which the total item quantity (figure 5.3, bottom right) increases: from 12-11-2021 to 01-12-2021, from 09-12-2021 to 28-12-2021 and from 18-01-2022 to 27-01-2022. These periods coincide with dropping water levels (see figure 4.2). When looking at the item quantity per category, deviating behaviour is noticeable. Hard plastic fragments decreased slightly from 12-11-2021 to 01-12-2021 and generally showed a low rate of increase. Tangled cords where present during the first month of survey but got washed away. Their quantity stayed low afterwards. Soft plastic fragments, on the other hand. increased significantly during these periods.

Item uptake was dominant in the periods from 01-12-2021 to 09-12-2021 and 28-12-2021 to 03-01-2022. These events coincided with rising water levels. While item quantity dropped for most categories, a significant increase can be observed in the amount of wet wipes between 01-12-2021 and 05-12-2021. This was also observed with sanitary towels. Other item categories, like soft plastic fragments and plastic bottles, deviated from the dropping trend during this same period. It shows that the processes of deposition and uptake can occur simultaneously. This is further discussed in section 5.7.

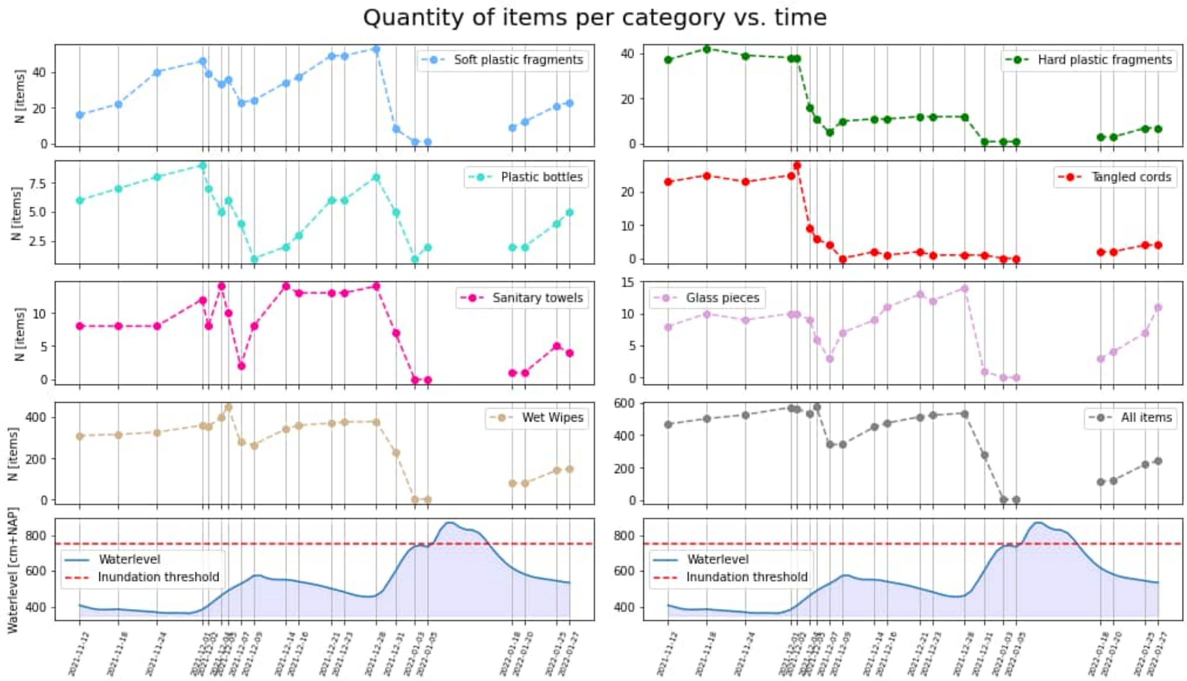


Figure 5.3: Quantity of items in different categories. The period between 05-01-2022 and 18-01-2022 is left out as the study area was inundated. The total item quantity is depicted in the bottom right figure. Wet wipes account for 70.6 % of the items, thus variability is mostly influenced by the dynamics of wet wipes in this groyne field. The figures show that the timing of peaks often coincides for various item categories. However, the rate of increase varies per category.

5.2. Spatio-temporal variability

The spatial distribution of macrolitter is visualised by plotting a top view of the study area, in which the geographic location of the macrolitter items and the waterline are depicted. The figures in appendix A.2 show the spatial item distribution (represented by red dots) for every survey. The waterline, measured along the maximum wave run-up of that particular day, is depicted by a blue line. The plots reveal spatial patterns and movement of macrolitter through the groyne field. This section qualitatively discusses the evolving spatial patterns in chronological order.

Figure 5.5a depicts the spread of macrolitter on the first day of survey (12-11-2021). It is already evident that items tend to accumulate at certain locations. On this day, almost no items were found close to the waterline. Macrolitter is strongly concentrated in the flood marks, at some distance from the waterline. Also, accumulation occurs in the downstream corner of the groyne field. These two patterns are also visible on other days. Item concentration above the flood marks is less dense and quite evenly distributed over the width.

The water level dropped slightly during the subsequent three weeks (figure 5.5b at 18-11-2021, figure 5.5c at 24-11-2021 and figure 5.5d at 01-12-2021). New items are being deposited gradually. At 01-12-2021, a new flood mark is clearly visible. In comparison with 12-11-2021, the amount of items at the riverbank increased with 100.


(a) Hard plastic fragments


(b) Soft plastic fragments


(c) Tangled cords


(d) Pieces of glass


(e) Plastic bottles


(f) Sanitary towels


(g) Wet wipes

Figure 5.4: Examples of items per category

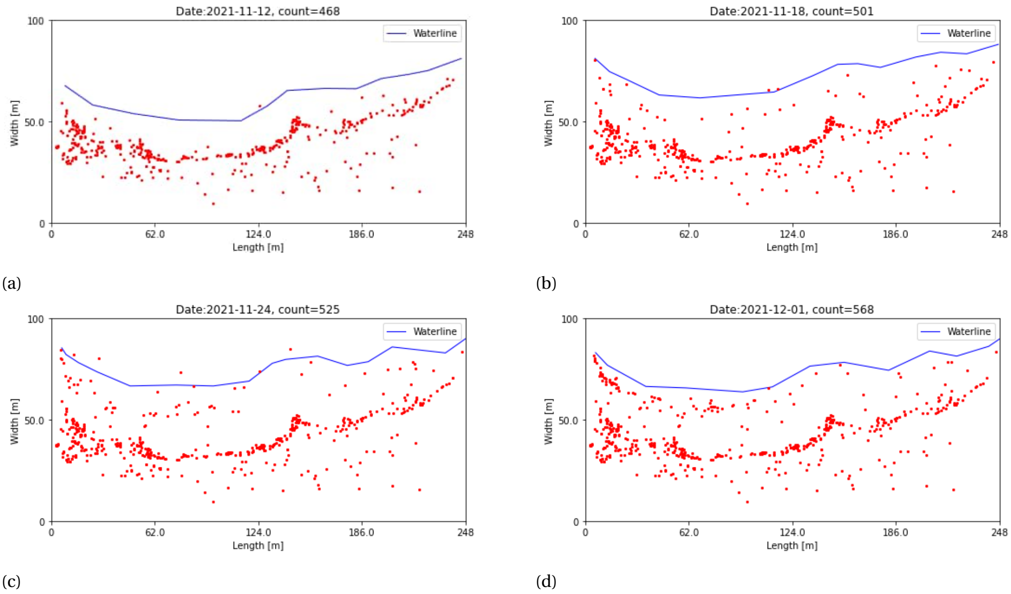


Figure 5.5: Top view of groyne field macrolitter. Litter has accumulated at the flood marks. While the water level drops, new flood marks emerge.

From 02-12-2021 to 09-12-2021, the water level increases roughly 2 meter. Items located in the newly formed flood marks are being pushed upwards and merge with the older flood mark(5.6a and 5.6b). From 04-12-2021 to 05-12-2021, the amount of items suddenly increased. This can also be seen in figure 5.3. A significant amount of wet wipes were deposited that day. During the following survey (07-12-2021, figure 5.6d), the item quantity dropped with 225. This might be the result of rising water levels in combination with increased slope of the terrain at that particular height. Especially in the middle segment of the riverbank (between 62m and 124m), the slope is steeper (see section 5.3).

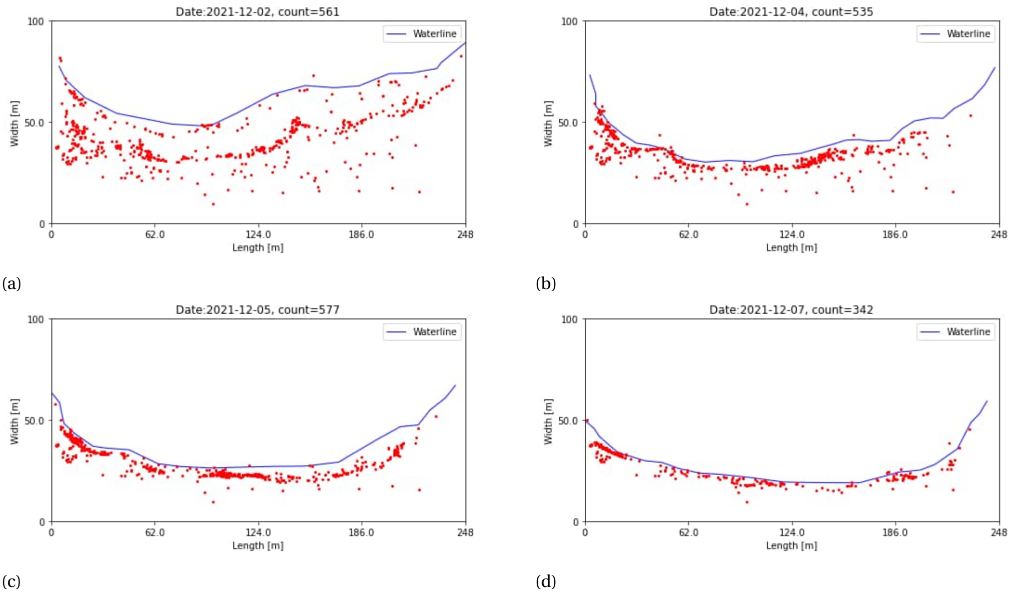


Figure 5.6: Top view of groyne field macrolitter. The water level rises and pushes items higher on the riverbank

On 09-12-2021 (figure 5.7b), many items in the segment between 62m and 124m are washed away while deposition occurs in the upstream corner of the groyne field (around 186m). This movement might be caused by the direction of the currents in the groyne field (see figure 3.6).

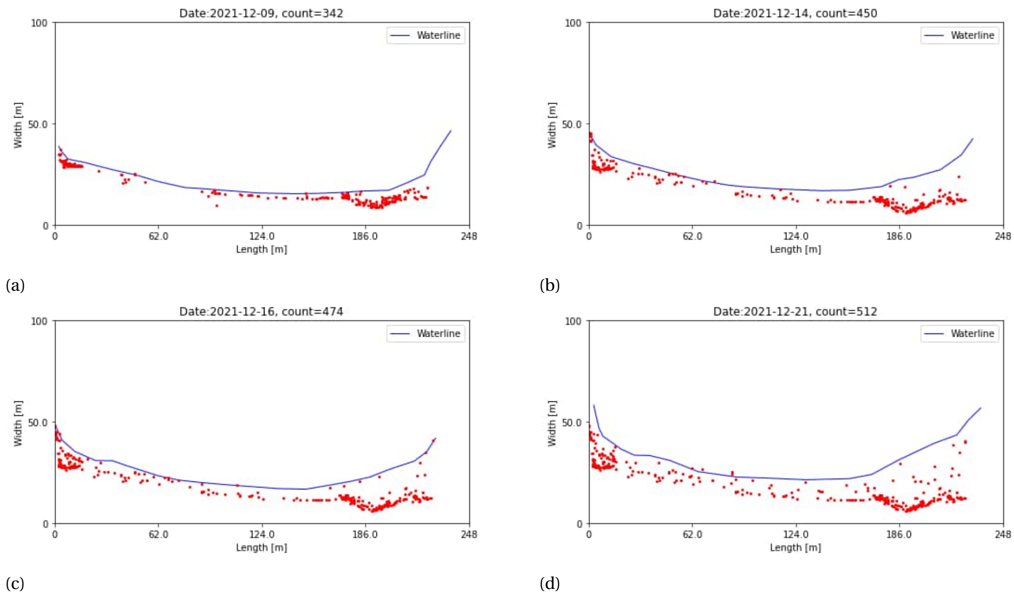


Figure 5.7: Top view of groyne field macrolitter. Item accumulation occurred in the upstream corner while the water level rises, possibly due to riverbank slope and/or groyne field gyres.

From 14-12-2021 to 28-12-2021 (figure 5.7c to 5.8c), the water level dropped again. During this period the item quantity increased with 115. At 31-12-2021 (figure 5.8d), the water level increased significantly and the number of items decreased with 258. On 03-01-2022 (figure 5.9a), almost the entire riverbank is inundated. Only 6 items are present within the bounds of the study area. The water level remains stable for two days (until 05-01-2022, figure 5.9b) and then increases significantly, leaving the entire groyne field inundated and the groynes submerged (see figure 4.2).

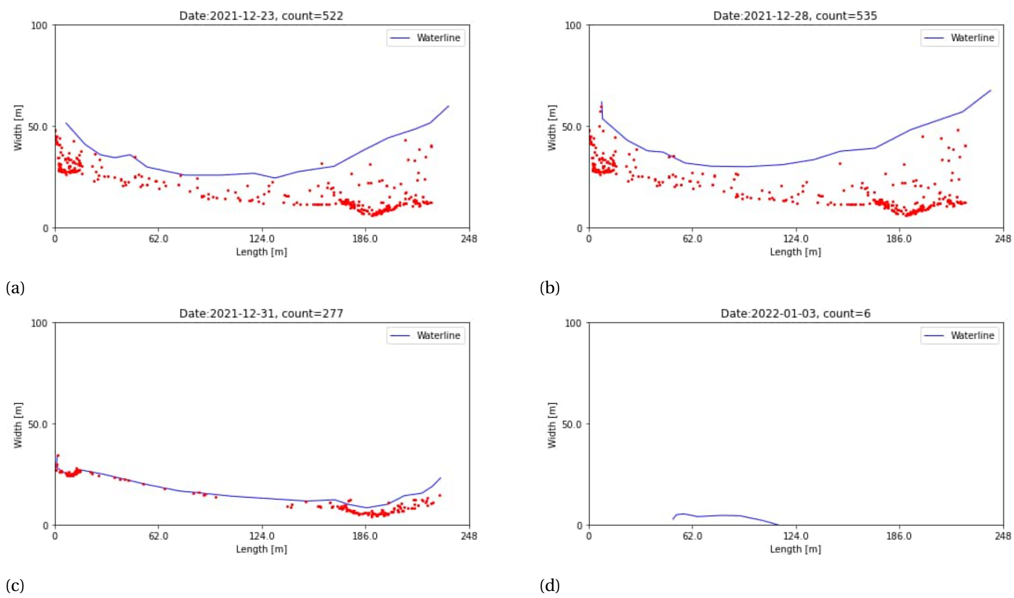


Figure 5.8: Top view of groyne field macrolitter. After a slight decrease in water level, the study area gets flooded.

No measurements were carried out until 18-01-2022 (figure 5.9c). Item accumulation was concentrated at 62m. At this spot, roots from the tree became exposed due to erosion which took place during the flood. Many wet wipes got trapped between the roots (see section 5.3.2). While the water level dropped again, item quantity gradually increased. At 27-01-2022 (figure 5.9e), 242 items were present. Most of the items accumulated between the roots of the tree and the downstream corner of the groyne field.

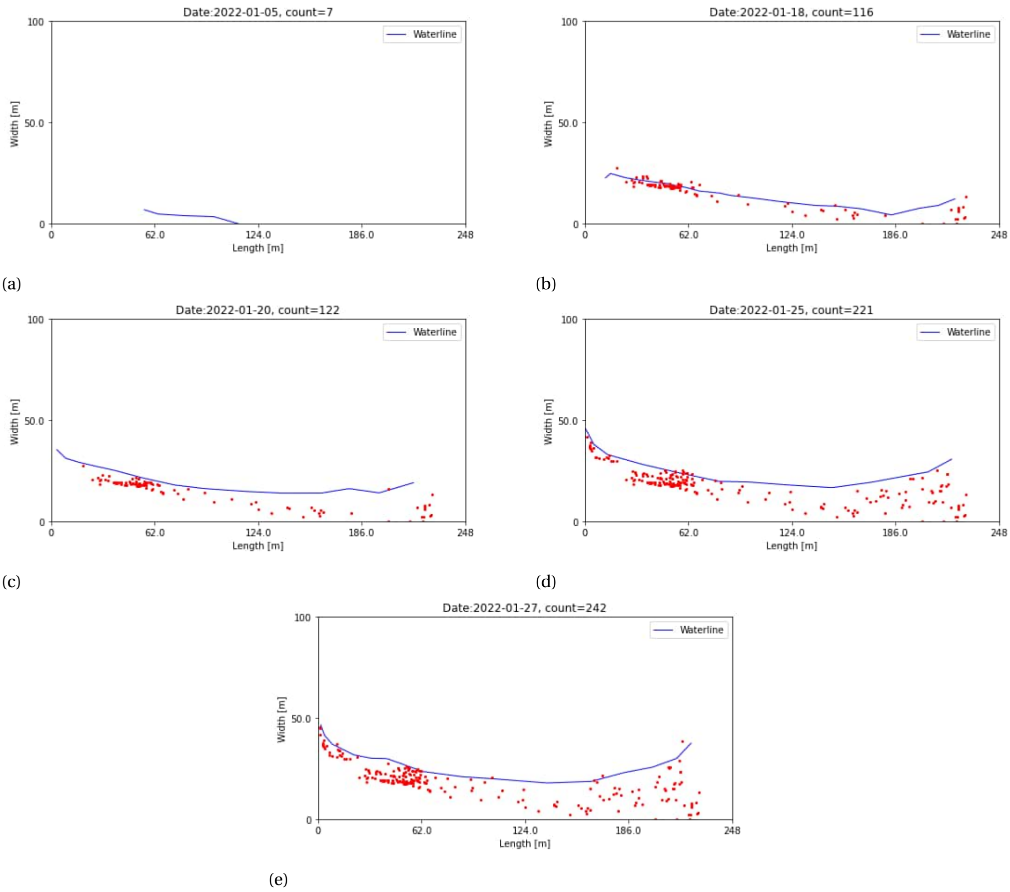


Figure 5.9: Top view of groyne field macrolitter. The water level drops again. Item accumulation occurred in emerged tree roots near the downstream corner of the groyne field.

5.3. Item accumulation and riverbank morphology

Spatiotemporal behaviour of riverbank macrolitter and the likeliness of item accumulation can partly be explained by riverbank morphology and vegetation (Newbould et al., 2021; Tramoy et al., 2020b). This section explores possible relations between these variables. The purpose of this analysis is to generate hypotheses by qualitative assessment of observations and spatial data. No definitive conclusions can be made yet.

5.3.1. Riverbank slope

The morphology of the study area is thought to influence the accumulation of items. Figure 5.11 depicts item accumulation zones on top of a slope map of the terrain. The lower parts of the riverbank are mildly sloped. A steep berm is situated higher on the riverbank. The downstream corner of the groyne field had a moderate slope and is characterised by relatively coarser sediment, while the upstream corner is sandy and mildly sloped. During the flood, the riverbank was subjected to erosion. This was observed when the roots of the tree (situated at y = 27.72 and x = 69) became exposed (figure 5.10). Although morphology changed slightly in reality, the shape of the riverbank is assumed constant in this analysis.

The red dots in figure 5.11 depict the complete set of locations were items have been deposited during the monitoring period. That is, all items in the data set that are attributed with 'NEW/MOBILISED = True' (see section 4.2). This ensures that there are no duplicate data points from prior surveys above the flood marks.

(a) 13-01-2022

(b) 18-01-2022

Figure 5.10: Trees during inundation 5.10a and exposed roots after inundation 5.10b. During the period of inundation the riverbank was subjected to erosion.

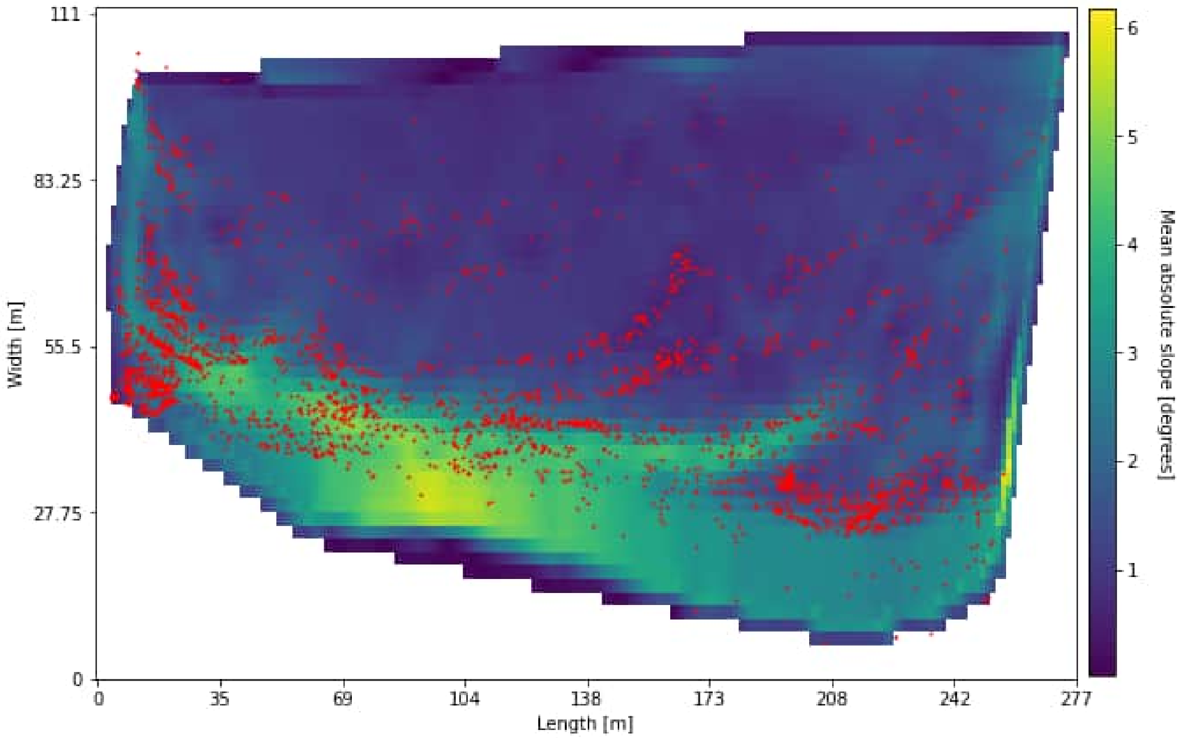


Figure 5.11: Item accumulation zones against the slope of the terrain

Accumulation in flood marks parallel to the waterline is visible. The extent of the swash determines where items are deposited. An increase in slope would hypothetically lead to deposition of items closer to the waterline due to the larger influence of gravity and the decreased reach of the swash. Figure 5.11 shows that item density is lower on steep terrain. Noticeable is the accumulation of items in the upstream corner of the groyne field (x = 208m, y = 27.75m). The slope map depicts a flat area surrounded by ridges with one opening. Flow separation is likely to occur beyond the ridge as waves propagate around the berm and lose energy, promoting item deposition. Accumulation also occurs in the downstream corner, which may be primarily caused by coarse substrate and rocks (discussed in section 5.3.2).

The possible effect of morphology becomes more evident when studying the spatial variation with respect to the terrain slope per time step. The terrain slope, waterline and item locations are plotted for several surveys in figures 5.12 and 5.13. From 12-11-2021 to 04-12-2021 items are situated mainly on mildly sloped terrain at a certain distance of the waterline. At 05-12-2021, while the water level has raised, items are deposited just at the edge of the berm. As the water level increases further, items located on steep sloped terrain are taken up. Simultaneously, deposition occurs in the upstream corner pocket. These processes unfold until 09-12-2021 (figure 5.12). On the following days, the water level drops again and items are being deposited along the full width of the riverbank (16-12-2021 to 28-12-2021). It seems that steep terrain promotes the uptake of items

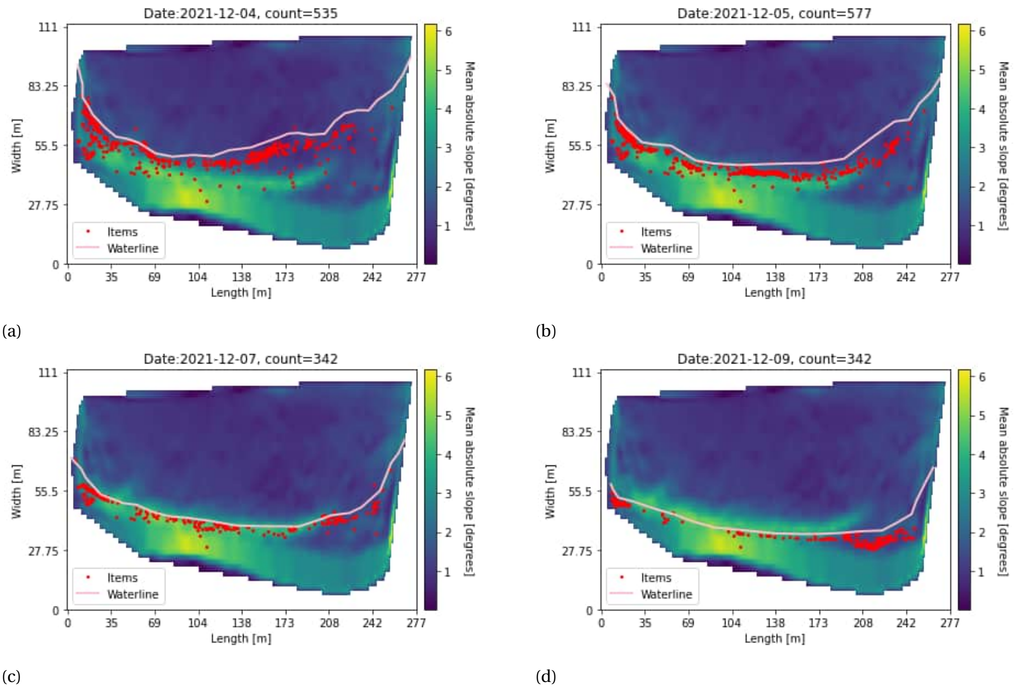


Figure 5.12: Top view of groyne field macrolitter with a depiction of the terrain slope during rising water levels.

during rising water levels but does not affect deposition when the water level drops. This is observed again when the water level increases significantly from 28-12-2021 to 31-12-2021.

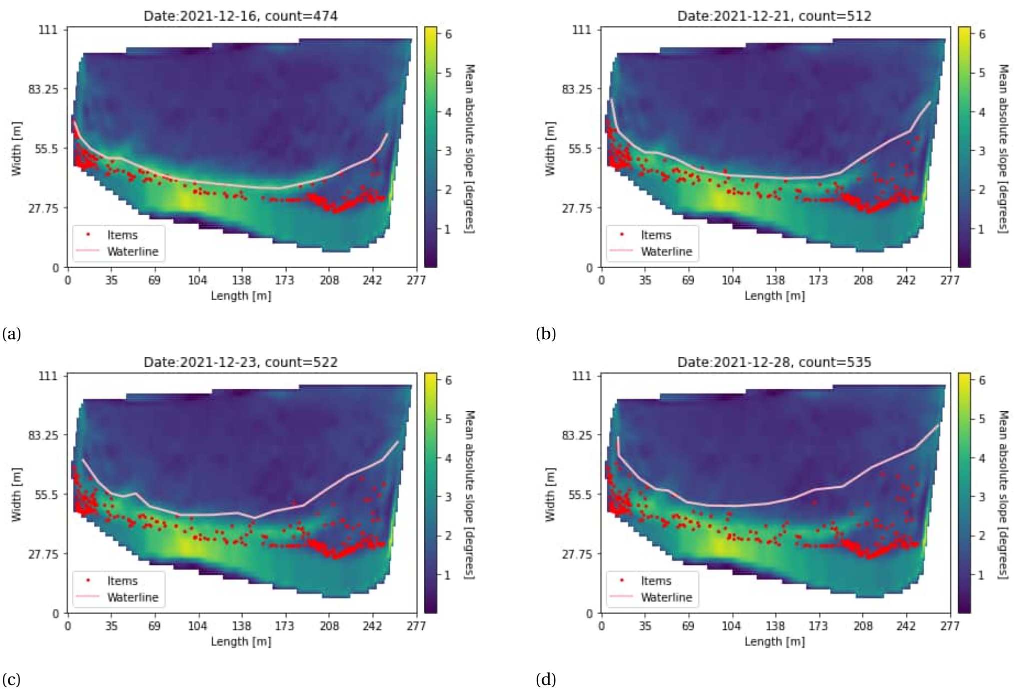
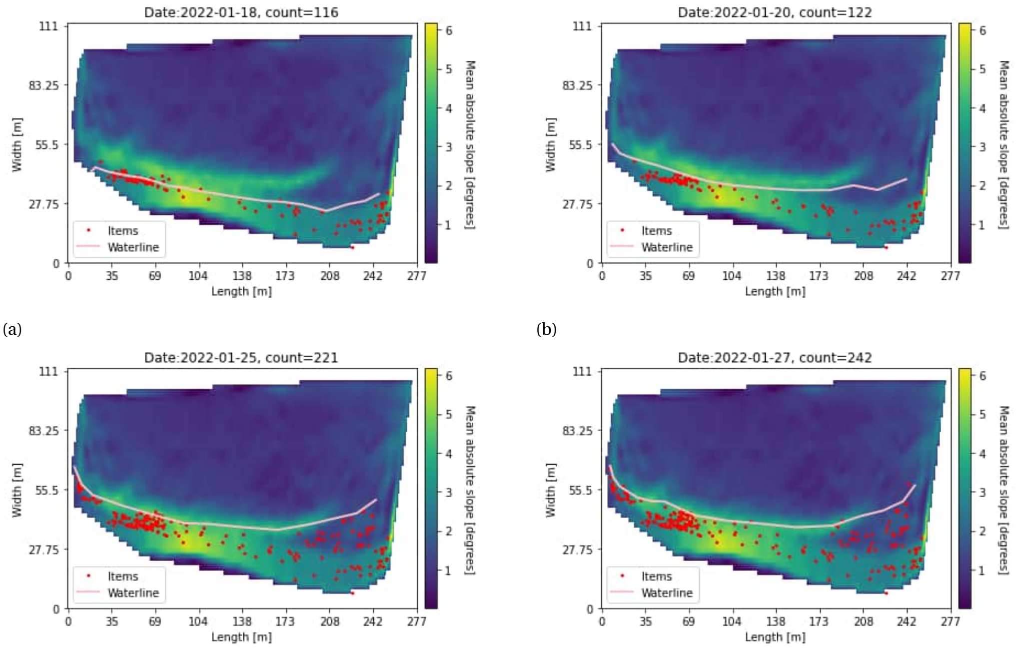


Figure 5.13: Top view of groyne field macrolitter with a depiction of the terrain slope during dropping water levels.

It should be noted that the observed spatial patterns of uptake and deposition may also be the result of variations in flow velocity. Due to the flow patterns in the groyne field, flow velocity is stronger in the middle of the riverbank (see figure 3.6). This may promote item uptake. Flow directed towards the riverbank in the downstream corner may lead to increased deposition. Additionally, deposition concentrated in the upstream corner could be explained by a decrease flow energy from passing ships (see 3.10). The Waal is a heavily navigated river and morphology is defined by the effect of passing vessels.



(a) (b) (c) (d)

Figure 5.14: Top view of groyne field macrolitter with a depiction of the terrain slope after the period of inundation.

After the flooding, from 18-01-2022 to 27-01-2022 (figure 5.14), item deposition is relatively spread as the water level decreases. The exceptions are accumulation in the downstream corner (x = [0m, 35m] and y = 55.5m) and accumulation in the tree roots (x = [35m , 69m]), which became exposed due to erosion. The next section further discusses how substrate and vegetation relate to item accumulation zones.

5.3.2. Substrate and vegetation

Vegetation and substrate seem to affect the mobility of items. Accumulation has been observed between rocks, on course sediment and in vegetation. For every item, the substrate at which it was found was noted. Four types of substrate are considered: sand, stones, clay and vegetation. Examples of cases for every substrate are shown in figure 5.15. The position of items towards sediment is also noted. Five categories are distinguished: 'clean', 'sandy', 'buried', 'filled with sediment' and 'tangled in organic material'.

(a) Clay (b) Sand (c) Stones (d) Vegetation

Figure 5.15: Examples of substrates

The items depicted in figure 5.15d and 5.16d are both categorised as 'tangled in vegetation'. However, in the case of 5.16d the substrate at which the item is found is noted as 'sand'. Some items are more likely to get trapped in vegetation than others. Table 5.2 depicts how many times items were deposited on various substrates. The majority of the items are found on sand, which is to be expected as sand makes up almost the entire riverbank. One tenth of the items were deposited on stones. Item deposition on clay and in vegetation was observed rarely as the majority of the study area consisted of sand. Notable is that pieces of glass and wet wipes are more commonly found on stones than other item categories.

(a) Clean

(b) Sandy

(c) Filled with sediment

(d) Tangled in organic material

(e) Buried

Figure 5.16: Examples of item positions towards sediment

The position towards sediment is very dependant on item shape, material, and texture. Only bottles, food containers, plastic bags and similar items can be filled with sediment. Smooth textured items made from plastic and glass were often clean. Weathered plastic items or items affected by bio-fouling were more likely to be covered with sand (see figure 5.16b). Wet wipes were rarely found clean due to their rough texture. Cords and wet wipes were also more likely to be tangled in branches, leaves or tree roots.

	Substrate				Position towards sediment				
Category	Sand [%]	Clay [%]	Stones [%]	Vegetation [%]	Clean [%]	Sandy [%]	Filled with sediment [%]	Buried [%]	Tangled in organic material [%]
Wet wipes	83.0	0.0	15.6	1.4	0.2	43.5	0.0	2.8	53.5
Soft plastic fragments	94.9	0.9	2.5	1.7	23.4	66.0	0.4	5.1	5.1
Hard plastic fragments	94.6	0.0	4.1	1.3	54.1	43.2	0.0	1.4	1.4
Tangled cords	93.5	0.0	3.2	3.2	9.7	6.4	0.0	0.0	83.9
Sanitary towels	95.1	0.0	4.9	0.0	18.0	72.1	0.0	4.9	5.0
Glass	84.0	0.0	16.0	0.0	88.0	12.0	0.0	0.0	0.0
Plastic bottles	100	0.0	0.0	0.0	20.6	55.9	14.6	5.9	0.0
All items	85.7	0.2	12.8	1.3	9.5	45.7	0.5	3.1	41.2

Table 5.2: Substrate and position towards sediment for deposited items per category

Appendix A.4 and A.5 show the substrate on which items were found and their position towards sediment respectively per time step. In appendix A.4, it can be seen clearly that items accumulate on coarse substrate (stones) in the downstream corner of the groyne field. Figure A.4r and A.5r show which items were trapped in vegetation and tree roots. It seems that, due to their immobility, some items remain stationary in the swash zone and do not accumulate in the flood marks.

5.4. Observed effects of hydrometeorology on item state and condition

A large amount of photographs were collected during the surveys. These include both pictures taken with the smartphone camera as pictures taken with the wildlife camera (unfortunately, pictures from the wildlife camera rarely captured items). In some cases, the photographs show changes in the state of items and their position relative to sediment. These changes are a result of hydrometeorologic processes. This section discusses the observed effects of these processes qualitatively.

5.4.1. Weather

Changing weather conditions may affect the state of riverbank macrolitter. Wind, humidity and temperature had a visible effect on the state of items. However, direct item mobilisation due to rain or wind was rarely observed. Merely three instances of item mobilisation by wind were observed. Once with a piece of sandpaper and twice with clean beer cans. This is contrary to what one might expect. An explanation for the lack of wind induced mobilisations might be that items are mostly wet, sandy and slightly dug into the sediment. The most profound observed consequence of wind was that items got further covered with sand. Whether this has leads to significantly reduced mobility is unsure. A comparison of photographs taken on 24-11-2021 and 01-12-2021 provide a good example of how wind can cover items with sand while items remain stationary (see figure 5.17).

(a) 24-11-2021 (b) 01-12-2021 (c) 24-11-2021 (d) 01-12-2021

Figure 5.17: Effect of wind on items. Contrary to what one might expect, items were rarely mobilised by wind. In some cases, wind caused items to become covered with sand. Whether this as any significant influence on mobility and probability of uptake by water remains unclear.

Rainfall causing overland flow was observed on 01-12-2021. During the survey, the overland flow did not initiate mobilisation. Supporting imagery, captured by the wildlife camera, is provided in appendix B.1. As overland flow was only observed once, no solid statements can be made on whether this process may lead to item mobilisation.

5.4.2. Waves

Ship induced waves can capture, mobilise and deposit items (see section 2.3.5). Although it is assumed that waves are important controls on riverbank macrolitter, it was not the intention of this study to analyse this process in detail. Instead, item mobilisation, uptake and deposition are assessed on a timescale of days/weeks (further discussed in section 5.5 and section 5.7) while waves act on a timescale of seconds/minutes. However, the constant presence of waves also leads to processes which act on a longer timescale. Berm formation was observed by low energy waves along the waterline (Kater et al., 2012). When items were situated in the swash zone and did not get pushed further on the riverbank, wave action caused litter to get buried and be stored in sediment. This reduces item mobility significantly and may lead to macrolitter storage for long periods of time. Figure 5.18 depicts examples of items which underwent this process.

(a) 18-11-2021 (b) 18-11-2021 (c) 09-12-2021

(d) 24-12-2021 (e) 24-12-2021 (f) 14-12-2021

Figure 5.18: Items which got buried under sediment due to berm formation as a result of vessel induced waves. When buried in sediment, macrolitter may remain stored for long time periods.

5.5. Macrolitter movement

A total of 86 distinguishable items were tracked during the monitoring period. Additionally, 16 (indistinguishable) wet wipes located in different areas of the groyne field were tagged with yellow spray paint. By tracking occurrences and locations of these items, a better understanding of item pathways and retention is developed. First, item pathways of tracked items with various properties is discussed. Then, observed behaviour of tagged wet wipes is discussed. The content of this section is based on observations supported with tables and graphical representations.

5.5.1. Tracked items

For the 85 tracked items, eight groups are distinguished. These are made up based on item material and distinguishable properties. For example, plastic bottles are considered a separate group from other plastics as they have a unique shape and the property of trapping air or sediment. The following groups are considered:

- Hard plastic items: 21 items
- Plastic bottles and tubes: 15 items
- Soft plastic items: 12 items
- Textile and clothing: 14 items
- Carton and paper: 2 items
- Sponges: 6 items
- Metal: 8 items
- Glass: 4 items
- Wood: 1 item

Pictures of each item can be found in A.6. The items were observed on different days. Some of them remained on the riverbank for quite a long time while other items were observed only once. Note that the periods between surveys was not always the same. Per item group, instances of occurrence are depicted in figure 5.19. Note that discharge had peaked on 09-12-2021 and the study area was inundated from 05-01-2021 to 18-01-2021.

The movement patterns of the tracked items (appendix A.7) are chaotic. Sometimes, large distances are traversed in latitudinal (upstream/downstream) direction. However, whether items move upstream of downstream seems random and is probably a consequence of the direction of incoming waves. One thing that stands out is that item deposition as a consequence of backwash transport does not occur. Items either remain stationary, are pushed higher on the riverbank (by swash) or are taken up by the water. After uptake, items sometimes reappear again. This phenomenon is discussed below with support of figure 5.19.

Hard plastic items: This group of items is very diverse in shape and size. It includes food packages, fragments of larger objects, cutlery, cups and pieces various tools or devices. Most items that were present at 12-11-2021 did not reoccur after the first hydrograph peak. The exceptions are 'Yoghurt package (large)' (figure A.635), 'Yoghurt package (small)'(figure A.660) and 'Blue fork'(A.65). Some new items where deposited while the water level was rising from 01-12-2021 to 09-12-2021. None of the items remained in the study area after inundation of the groyne field. Due to large variability of these items, it is difficult to explain retention time by physical item properties, especially since the location of items within the groyne field may also influence uptake (i.e. substrate and/or slope). Most of the items, however, did not reappear after being flushed away, indicating high mobility in water.

Plastic bottles and tubes: Although plastic bottles did not differ much in shape, they appeared in varying conditions. During the first hydrograph peak most items remained at the riverbank. This indicates that bottles are easily pushed higher on by rising water. When submerged, however, mobility may decrease due to filling with water or sediment. This might explain why bottles seem to reappear at the riverbank after having been submerged. Another possible explanation is deposition by wind directed towards the riverbank. This would likely affect buoyant items (further discussed in section 5.7).

Soft plastic items: These items are generally foil-like but differ in shape and size. Opposed to what one might suspect, wind rarely mobilises these items (no instance was observed). This might be due to items being wet or covered/filled with sediment. In water, foils are influenced by flow and turbulence (see section 2.3.3).

Textile and clothing: This group also has a lot of variance in item properties. A few items remained in the study area for a long time. The two face masks, the two gloves (while in different states) and the small shoe were retained for a long time.

Carton and paper: The milk carton was one of the few items that remained in the groyne field during the whole monitoring period. This item was often found wet and partly covered in sediment. Its location started near the downstream corner and slowly moved upstream.

Sponges and foam: These items absorb water. It is not known how these items move in water. However, re-occurrences after uptake were not observed, indicating high mobility in water.

Metal: Based on this data it is difficult to relate physical characteristics to retention time. Very different behaviour is observed in both movement patterns and retention time.

Glass: Glass items are quickly washed away from the riverbank and rarely get pushed on higher. This can be seen in both item movements and occurrences.

Wood: Only one, very large, wooden item was studied. It was only observed once and got washed away. This items was possibly buoyant.

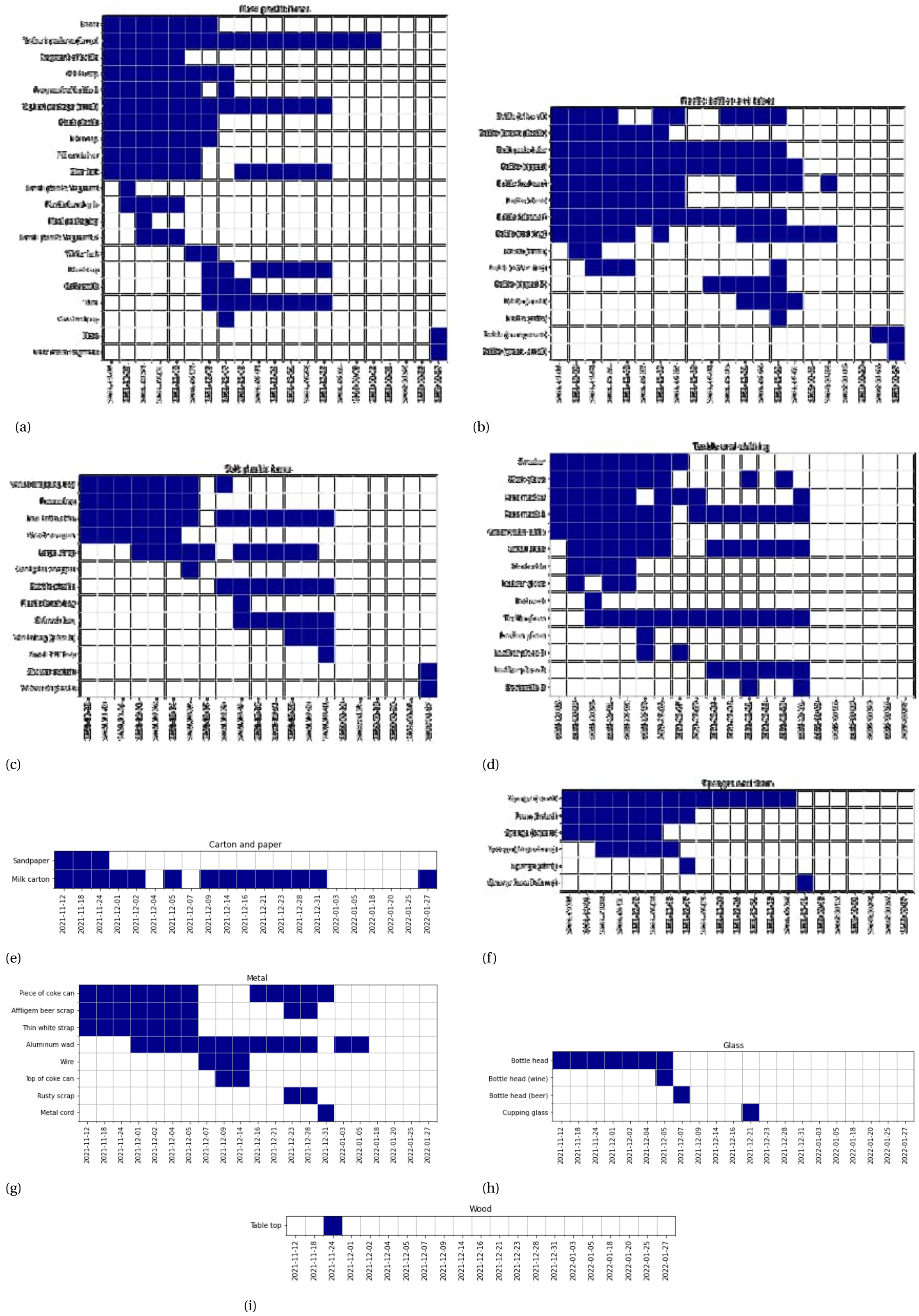


Figure 5.19: Occurrences of tracked items

5.5.2. Tagged wet wipes

Figure 5.21a depicts the initial location of all tagged items. The items were already present at the riverbank before tagging. Their location was chosen such that items situated at different parts of the riverbank could be followed.

Figure 5.20: Example of submerged wet wipes

The behaviour of wet wipes was found to be quite characteristic when compared to other litter items. During surveys it was observed that submerged wet wipes were located on the riverbed (see figure 5.20). As these observations were only made in shallow parts, no statement could be made on the vertical positioning of wet wipes in deeper waters. It could be that, due to their shape and structure, submerged wet wipes positioning is influenced by turbulent flow. Another possibility is that wet wipes are transported by saltation as they become heavy due to entanglement with sand and organic material. When looking at the spatiotemporal variations of the tagged items during the first discharge peak, a strong pattern of movement towards the upstream corner of the groyne field is observed. This leads to believe that wet wipes are being transported by the typical groyne field eddies.

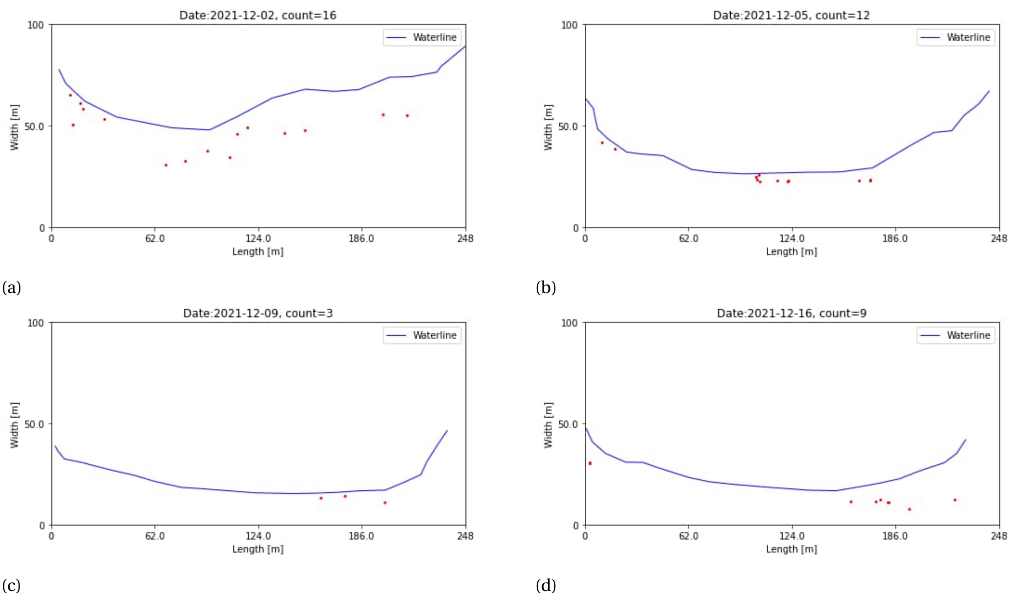


Figure 5.21: Tagged item locations during and after the first discharge peak. Almost every item moved towards the upstream corner. This could be a result of the gyres which typically occur in groyne fields.

The data also suggests that wet wipes slowly propagate through the fluvial system. Figure 5.22 depicts the amount of tagged items found every day. When the water level drops, tagged items often reappear. This suggests that wet wipes remain submerged within the groyne field during discharge peaks. After inundation of the groyne field, one of the tagged items was still found at the riverbank.

The curve as shown in figure 5.22 is in some ways similar to 'wet wipes' curve shown in figure 5.3. Comparison indicates that while the total amount of wet wipes increases due to the addition of new items, a share of the

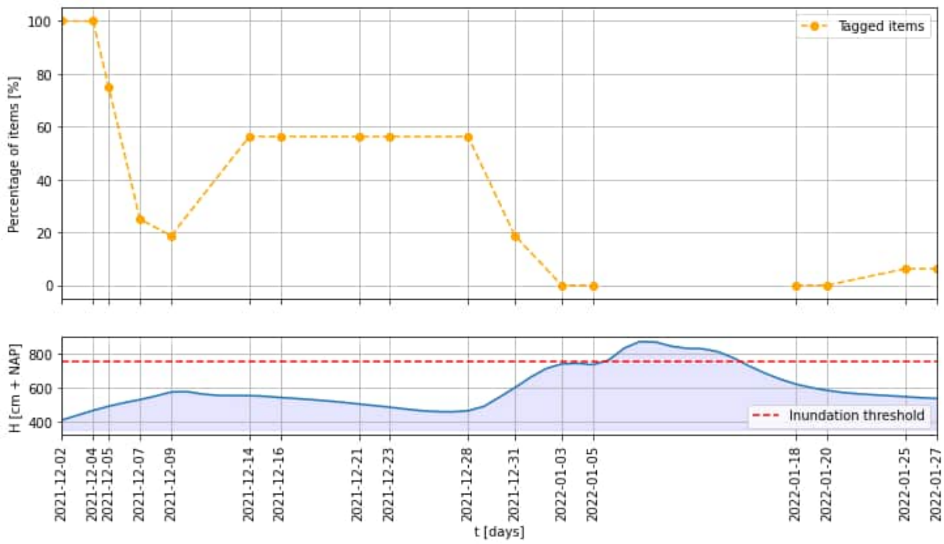


Figure 5.22: Amount of tagged items observed during surveys

deposited items may have been present in the groyne field for a longer period of time. The groyne field acts as a trap for wet wipes.

5.5.3. Interpretation

Of all tracked items present on the first day of survey, only two items remained after the second discharge peak. Assuming that items do not accumulate under water, the data indicate that item retention within groyne fields under normal hydrological conditions is defined by the magnitude and timing of moderate water level fluctuations.

5.5.4. Remarks

The way in which item movement is influenced by item properties remains uncertain. The data shows much variation in both items and movement patterns. However, the way in which some items (mainly wet wipes but also the milk carton) move into the upstream corner stands out as these were also the items characterised by long retention in the groyne field. Although the movement of submerged items could not be monitored in this study, long retention time of items in the groyne field is hypothetically related to item immobility in water.

5.6. Vertical macrolitter distribution

As seen in the previous sections, items accumulate in flood marks and can be pushed higher when the water level rises. In order to get a better understanding of how far items are being deposited from the waterline, the *vertical* distance between the measured water line and every single item is calculated. The reason for focusing only on the vertical distance is that the riverbank morphology is not constant everywhere. When also considering horizontal distance, variation in riverbank slope would affect the analysis. The following procedure is followed for determining macrolitter distance with respect to the waterline:

1. For every litter item, its closest point on the waterline is determined. The locations of all items are projected on the waterline using the *linear referencing* from the Shapely package in Python
2. The vertical distance between every item and its projected location along the waterline is obtained from the DEM map

This section explores vertical item distribution and whether significantly different behaviour can be observed in location of deposition for different categories. In this analysis, a distinction is made between mobilised/deposited items and old items. Figure 5.23 depicts a histogram of the vertical macrolitter distribution with respect to the waterline. Similar plots for other surveys can be found in appendix **??**. Note that the figures are plotted horizontally for the purpose of readability. The first thing to note from the figures is that

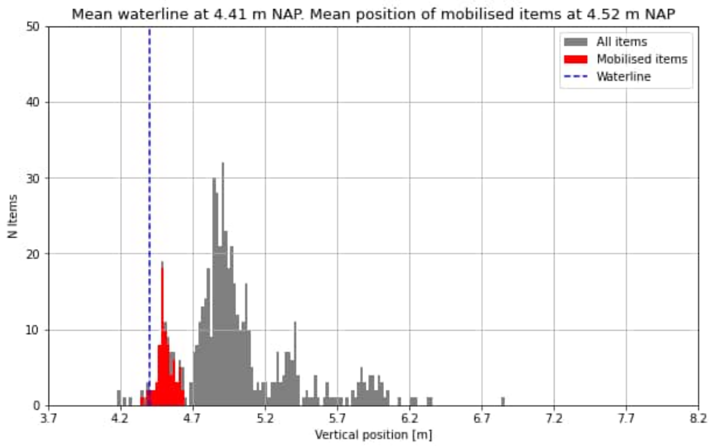


Figure 5.23: Vertical distribution of macrolitter depicted together with the altitude of the measured waterline during surveys. Items which were deposited/mobilised with respect to the previous survey are depicted in red.

items are mostly deposited in a bell shaped distribution (sometimes skewed). The peak would coincide with the location of the flood marks. The second observation is that the shape of the item distribution seems to differ for rising water levels and dropping water levels. When the water level drops, items are more spread out.

5.6.1. Distance of deposition during rising/dropping water levels

Difference in distributions could indicate that processes resulting in item mobilisation/deposition are not the same under varying circumstances. A suitable test for comparing two distribution which each other is the Kolmogorov-Smirnov test (Berger and Zhou, 2014). This is a non-parametric test which compares the distance between the cumulative distribution functions (CDF) of two samples. It can also be used to test whether a single sample is drawn from a certain hypothetical distribution. As the test is non-parametric, it can be used without assuming normality of the data. It is therefore suitable to use in this case. The test is performed using the *scipy.stats* module in Python.

For comparing item deposition under rising and dropping water levels, a two-sided Kolmogorov-Smirnov test is used. Two samples are compared. The first sample consists of the vertical distance to the waterline of all mobilised/deposited items recorded during rising water levels. Similarly, the second sample is the complete set of observations recorded during dropping water levels. Observation made between 18-11-2021 and 27-01-2022 are used. The survey from 14-12-2021 (figure A.89) is left out as both rising and dropping water levels occurred. The following hypotheses are considered for the two-sided Kolmogorov-Smirnov test:

$$H_0 : F(x) = G(x), \text{ the distributions are identical}$$
$$H_1 : F(x) \neq G(x), \text{ the distributions are not identical}$$

The test returns the D-statistic and the p-value. The D-statistic is the maximum difference between the two CDFs. The p-value is the probability of obtaining a D-statistic at least as extreme as the one observed, were the null hypothesis true. If the distributions are identical, the p-value would be high. The null-hypothesis is rejected when $p < 0.05$.

Figure 5.24 depicts the CDFs of the two samples. The CDFs show that the vertical item distribution is more dense when the water level rises. The means for both samples are 0.16 m with rising water and 0.23 m with dropping water. The test results show a p-value of 2.44e-15, thus rejecting the null hypothesis. This indicates that there is a difference between how macrolitter items are distributed vertically on the riverbank during rising and falling limb conditions respectively.

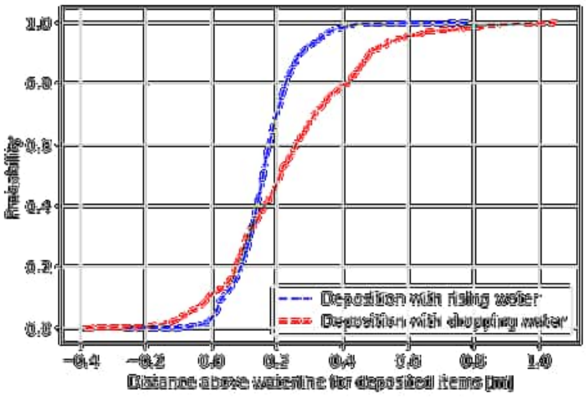


Figure 5.24: CDFs of item distance to waterline under different hydrologic conditions

5.6.2. Distance of deposition for different item categories

The transport mode of items in the swash and surf zone probably influences uptake and deposition. It is expected that variation in item distance to waterline is an indication of how items are transported by waves. Hypothetically, items would experience resistance from gravity and friction during deposition, reducing the travelled distance. Non-floating items and heavy items would experience more resistance than lightweight, buoyant items. Therefore, they are likely to be deposited further from the waterline. Texture and shape may also play a role. Differences would be visible between buoyant items and items that move by saltation. Whether this is indeed the case is analysed below.

Unfortunately, item properties have not been measured in this study. Assumption have to be made on how items from a certain category would behave. Based on river-OSPAR categorisation, the following categories are assumed likely to be **buoyant and/or lightweight**:

- (Cleaner) bottles
- Drinking cans
- Food packaging/containers (yoghurt, meals etc.)
- Packaging of medical products (plastic)
- Hard plastic fragments (small/large)

Items which are thought to experience the **most resistance** are:

- Wet wipes

Wet wipes are often mixed with sediment or other materials and are often stuck between stones and vegetation.

In order to see whether some items are significantly located further above the waterline than others, a one-tailed Kolmogorov-Smirnov test is performed. The test is similar to the two-tailed test, but the hypotheses are formulated as:

$H_0 : F(x) \geq G(x)$, the CDF of sample 1 is equal or greater than the CDF of sample 2 for all z [m]

$H_1 : F(x) < G(x)$, the CDF of sample 1 is smaller than the CDF of sample 2 for all z [m]

If the alternative hypothesis is true, than the items of sample 1 are being deposited at greater vertical distance. The analysis is performed for **buoyant and/or lightweight** items vs. **wet wipes**. Buoyant/lightweight items were hypothesized to be deposited at greater (vertical) distance.

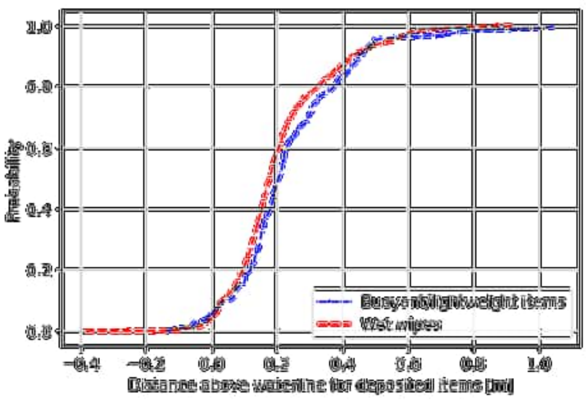


Figure 5.25: CDFs of item distance to waterline for buoyant/lightweight items and wet wipes

The CDFs in figure 5.25 show that lightweight/buoyant items are indeed deposited at greater distance, though the difference is very small. The Kolmogorov-Smirnov test gives a p-value of 0.025. While the null-hypothesis is rejected, it was expected that the CDFs would lie further apart. Judging by the graph, the difference between the distributions would be in the order of centimeters. This means that, although the effect is statistically significant, its magnitude is limited.

5.7. Macrolitter uptake and deposition

The amount of items present at the riverbank is a result of the balance between item uptake and deposition (see equation 4.1). Quantifying uptake and deposition and studying their variation over time may improve understanding of how many items travel through the fluvial system and how variability in riverbank macrolitter can be explained.

5.7.1. Quantifying uptake and deposition

Uptake and deposition are estimated with equation 4.3 and 4.2. In doing so, it is assumed that item movement in and out of subsurface storage occurs rarely and is negligible. Figure 5.26 shows the cumulative distribution of item uptake and deposition. For the period of inundation no data is plotted. The number of items at the riverbank can be determined by subtracting dN^{-} from dN^{+}. The bottom plot depicts the water level as observed at Doodewaard.

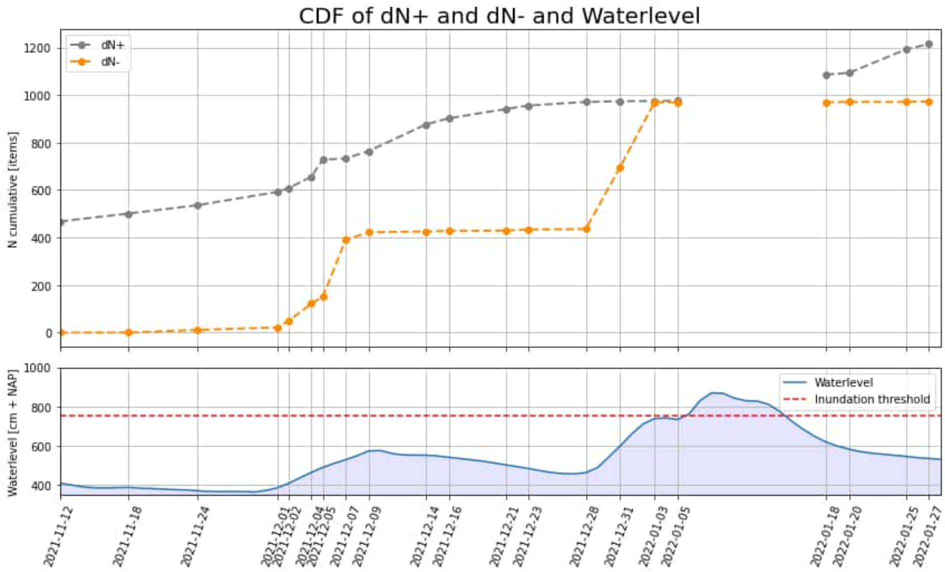


Figure 5.26: dN- and dN+ represent item uptake and deposition respectively. The graph depicts the cumulative distribution of uptake and deposition. The amount of items at the riverbank is determined by the space between the curves. The bottom graph shows the water level measured at Doodewaard. Between 05-01-2022 and 18-01-2022 the groyne field was entirely inundated. No surveys could be carried and therefore no uptake and deposition is depicted in the figure for this period.

The graph shows that the course of uptake is significantly different from that of deposition. Item uptake shows large variations. During stable or dropping water levels, it is (almost) zero. However, when the water level increases, item uptake intensifies heavily. From the cumulative distribution curve a relationship between uptake and hydrology seems evident.

Deposition, on the other hand, seems to occur at a relatively constant rate during the period of observation. This process seems to be continuously present. Compared to item uptake, variation is small. At first sight, figure 5.26 does not clearly suggest that variations in deposition are related to water level fluctuations. Possible relationships with hydrology is discussed in the next section.

5.7.2. Influence of hydrology

In studying the influence of hydrology on riverbank macrolitter, water level and variations in water level are considered as explanatory variables. As data on river discharge was not available, water level is treated as a proxy variable for discharge.

Based on previous studies, it is expected that macrolitter transport is positively correlated with river discharge. Hypothetically, a larger macrolitter concentration in the water would translate into an increase in item deposition. Figure 5.27 depicts the observed uptake and deposition against the measured water level at

Doodewaard. Based on these plots, correlation between item deposition and water level is not evident. This is similar for item uptake and river discharge.

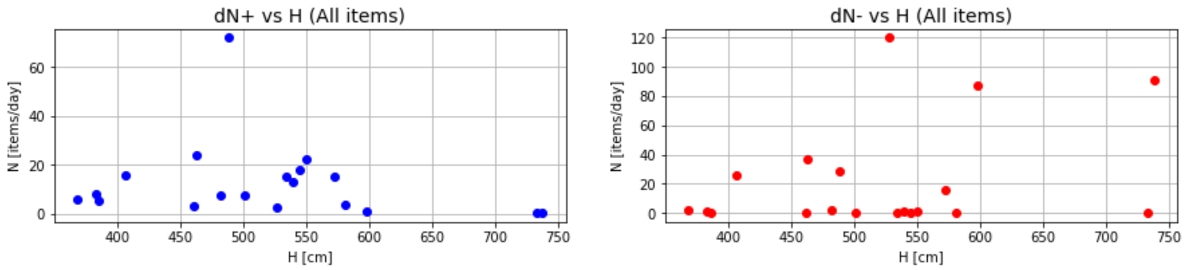


Figure 5.27: Uptake and deposition for all item categories are plotted against the water level measured at Doodewaard. The water level is considered a proxy for river discharge. It is expected that macrolitter transport increases during high discharge. If the concentration/amount of litter in the river is correlated to deposition at the riverbank, this correlation might also be seen when treating water level as an explanatory variable. By judging from the figure however, correlation is not evident.

A more interesting relationship to explore is that of uptake an deposition versus changes in water level, depicted in figure 5.28. In the previous section it is briefly mentioned that item uptake coincides with rising limbs in the hydrograph. This can be seen very clearly in figure 5.28. When dH < 0, item uptake is almost zero. For dH > 0, item uptake seems positively correlated with dH when considering all item categories. Uptake seems to be initiated when the water level increases. A relationship between deposition and dH seems absent. Two outliers can be identified in both uptake and deposition. The outlier in deposition occurred between 04-12-2021 and 05-12-2021 and the outlier in uptake occurred the following days, from 05-12-2021 to 07-12-2021. No explanation is found for these outliers.

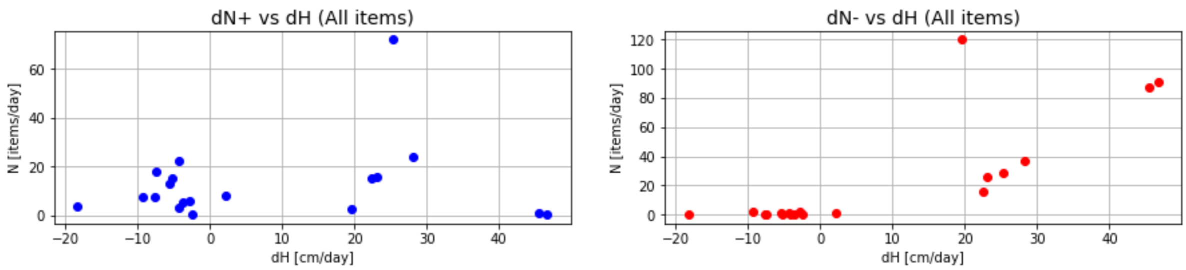
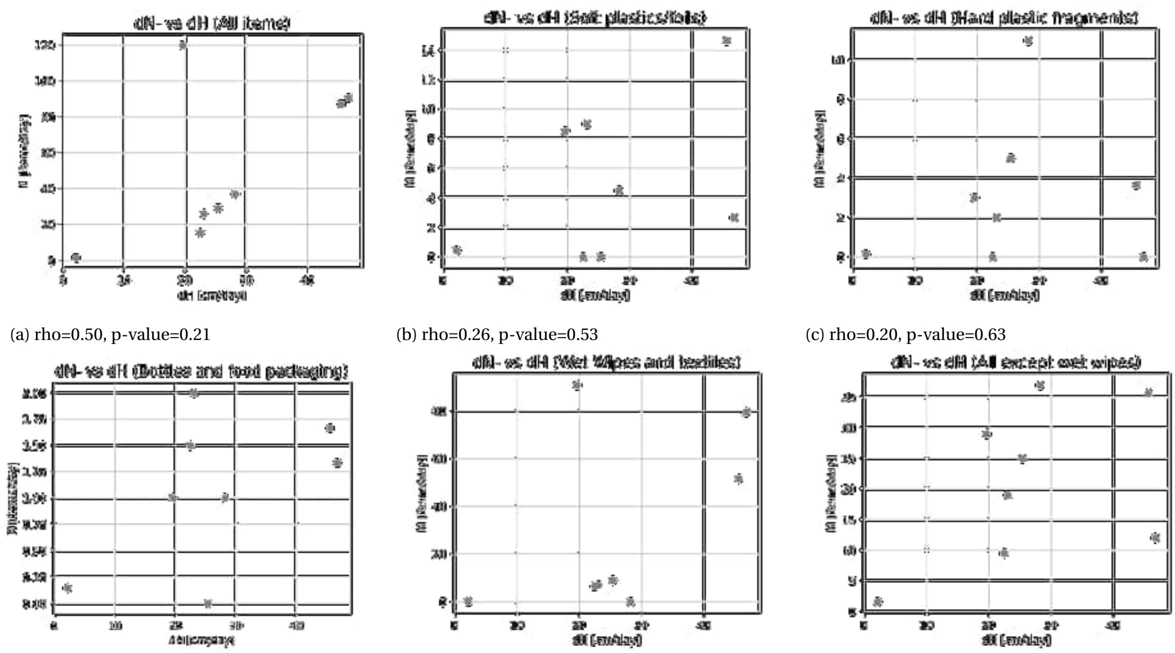


Figure 5.28: Uptake and deposition for all item categories are plotted against changes water level measured at Doodewaard. Item uptake is initiated when the water level increases. Uptake increases with an increase in dH. Item deposition seems independent of dH.

Correlation between uptake and dH for dH > 0 is assessed using Spearman's rho. This has the advantage of testing correlation without assuming normality of the underlying distribution, nor linearity of the relationship. The analysis is performed for the complete set of items and 5 subsets, chosen based on similar physical/materialistic characteristics:

- All item categories
- Soft plastics/foils (OSPAR: 46.2, 117.2, 3)
- Hard plastic fragments (OSPAR: 46.1, 117.1)
- Bottles and food packaging (OSPAR: 4, 6, 5)
- Wet wipes and textiles (OSPAR: 102.2, 99, 59, 54)
- All categories except wet wipes

Scatterplots for these sets are depicted in figure 5.29. In every case, positive correlation was found. However, the corrolations are not statistically significant (p-value > 0.05). For more narrow item subsets the p-value is higher. This could be attributed to reduced accuracy in determining uptake and deposition when less categories are included. Uptake and deposition within categories could not be accounted for. Although correlation is not significant, the influence of changing water levels on litter uptake is evident. It is very clear that uptake is initiated when dH > 0. The high p-values indicate that there are more factors determining the magnitude of uptake. Presumably, these are riverbank morphology, substrate and vegetation.



(a) rho=0.50, p-value=0.21 (b) rho=0.26, p-value=0.53 (c) rho=0.20, p-value=0.63

(d) rho=0.29, p-value=0.49 (e) rho=0.24, pvalue=0.57 (f) rho=0.45, p-value=0.26

Figure 5.29: Scatterplots of item uptake vs. dH for dH > 0. Correlation is tested for various groups of items with Spearman's rho. In all cases, correlation is positive. However, in none of the cases the correlation is statstically significant (p-value > 0.05). This leads to believe that there are more variables explaining item uptake. Suggestions made earlier state that riverbank morphology, substrate and vegetation also play an important role.

5.7.3. Influence of wind

Next to hydrology, wind is also thought to influence the dynamics of macrolitter. As mentioned in section 5.4.1, riverbank macrolitter was seldom mobilised by wind. The influence of wind on floating items, on the other hand, might affect the rate of deposition. The effect of wind on macrolitter deposition is studied using mean daily wind velocity data (see section 4.4.3). Only the North/South components of wind is considered as the riverbank is oriented parallel to the Earth's latitude. The hypothesis is that, when wind is originating from the North, floating items have a higher chance of deviating from the river's thalweg and entering the groyne field. In this analyses, only buoyant items are considered. It should be noted that it is not entirely certain that all considered items were buoyant as this is not tested experimentally. Item categories included in this analysis are:

- (Cleaner) bottles
- Tin cans
- Food packaging
- Medical packaging
- Large wooden pieces (>50 cm)

For this subset of items, the cumulative uptake and deposition curves are depicted in figure 5.30. Instances of Northern wind are, unfortunately, very rare. The effect it has on item deposition can therefore only be

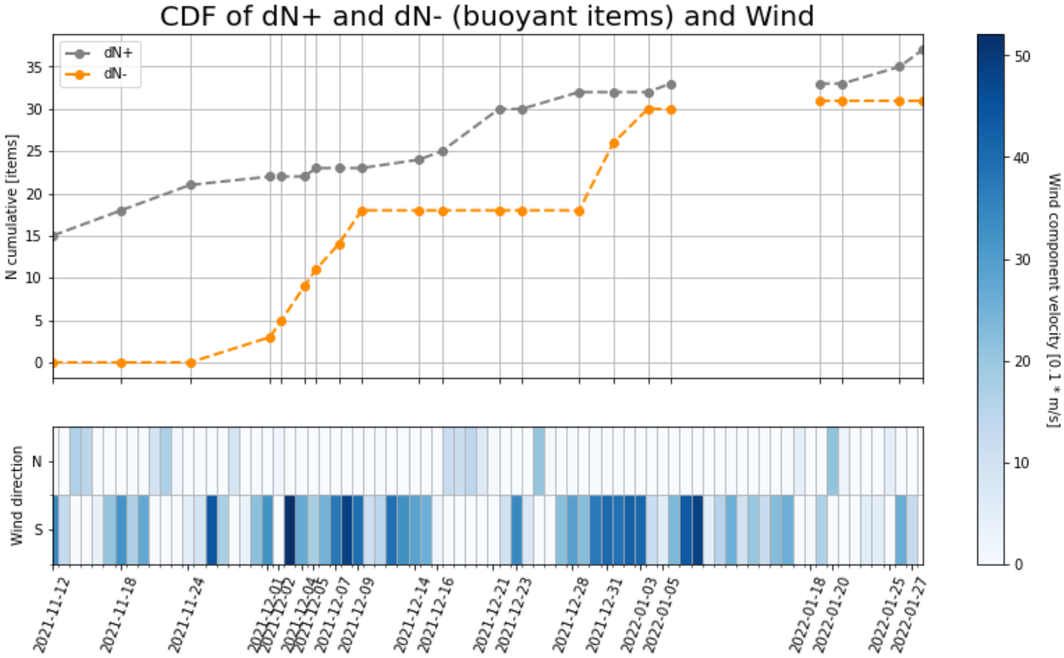


Figure 5.30: Uptake and deposition for buoyant items are plotted against the velocity of the North/South component of the wind. Wind originating from the North would hypothetically promote buoyant item deposition. The bottom plot depicts the direction from which wind predominantly originated per day. The colour intensity depicts wind velocity (projected along the longitudinal axis). Wind velocity values are depicted in the bar chart. Northern wind is rarely observed. Also, at first glance, a strong increase in item deposition during Northern wind is not evident.

assessed for a few time periods. From the figure, a few moments at which increased deposition coincides with Northern wind can be identified. These are the period between 12-11-2021 and 18-11-2021 and the period between 16-12-2021 and 21-12-2021. The possible relationship between the amount of items deposited between surveys and the dominant wind direction for that period is assessed by taking the mean daily wind velocity in North/South direction as predictor. Thus for an arbitrary period of several days, the mean wind velocity per day is calculated and compared to item deposition within that same period. Item deposition against wind velocity is depicted in figure 5.31.

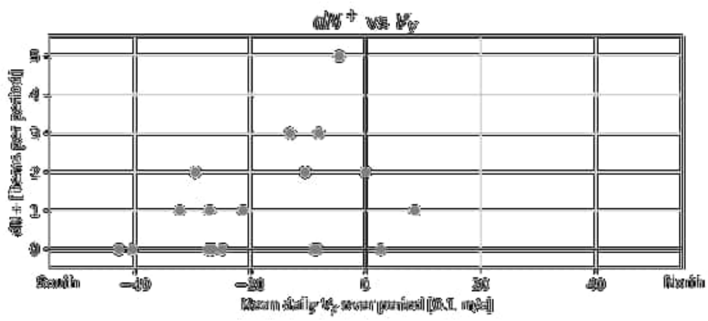


Figure 5.31: Item deposition of buoyant items (dN^{-}) is plotted against the mean wind velocity per day in North/South direction. Negative velocity originates from the South while positive velocity originates from the North. A slight preference of item deposition during periods with less dominant Southern wind can be detected. However, correlation is not statistically significant (rho = 0.33 and p-value = 0.17).

The Spearman's rho correlation test indicates that there is positive but insignificant correlation (rho = 0.33, p-value = 0.17). As Northern wind was rarely observed, the timing between surveys is inconsistent and the buoyancy of items is uncertain, the effect of wind on item deposition is difficult to assess. Furthermore, this method can not account for the effect of wind gusts, nor can the exact timing of deposition and the possibility of time lag playing a factor be assessed. All that can be said is that no significant effect of wind on item deposition/uptake can be observed using this data.

5.7.4. Other possible controls on deposition

Variability in deposition rates could not be explained by either discharge, change in water levels and wind. It could very well be possible that deposition is determined by factors outside of the scope of this study. Another possibility is that variation occurs on a timescale larger than three months or smaller than one day (hourly, for example). In literature, proximity to a macrolitter source is often identified as an important explanatory variable (Kiessling et al., 2021; LI et al., 2016). Another suggestion is that local river hydrodynamics play an important role. Processes influencing erosion and sedimentation may also influence macrolitter transport pathways, as suggested by Tramoy et al. (2020b) and Newbould et al. (2021). A combination of these factors may result in a constant or seasonally variable rate of deposition which is characteristic to a specific area. Alternatively, deposition could be influenced by hourly wind variations or wind gusts. Such variations could not be analysed with the available data in this study. For the groyne field considered in this study (and during winter), item deposition rates are characterised by the distribution depicted in figure 5.32.

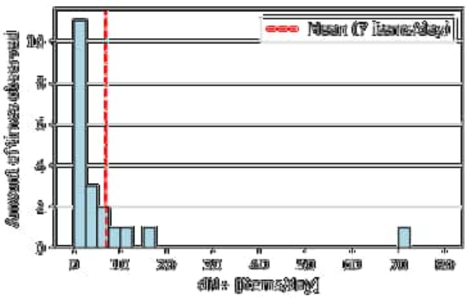


Figure 5.32: Histogram of observed item deposition for all item categories (daily values). The mean deposition rate is 7 items per day (rounded). The sample has a size of 20 observations and includes the survey done after inundation.

6

Reflection and Reccomendations

This chapter provides a review of observations made during surveys and a reflection of the used method. The reflection is intended to serve as support for feature research/monitoring design. It is primarily based on experiences gained during fieldwork. First, a conceptual model of macrolitter dynamics on riverbanks is presented. This may serve as a framework for studying/modelling the behaviour of riverbank macrolitter. Secondly, practical aspects regarding efficient monitoring of riverbank macrolitter are discussed. These are based on the applied method using RTK positioning, the obtained results and the imagery captured by the wildlife camera.

6.1. Conceptual model of riverbank macrolitter

As described in chapter 5, macrolitter dynamics can be the result of many different factors, processes and mechanisms. In order to maintain a clear overview of relevant elements and interactions, a conceptual model is proposed (figure 6.1). The intention of the model is to provide a framework which can be used to explain the behaviour of riverbank macrolitter as a result of natural processes. It can be seen as an extension of the conceptual model proposed by Liro et al. (2020), but at a smaller spatial and temporal scale. The spatial extend of the model is limited to riverbanks only and does not include transport through the river. Anthropogenic inputs on the riverbank are also outside of the scope of this model.

The model aims to describe macrolitter dynamics through a causal chain of measurable variables, which are selected based on literature and observations made during surveys. The variables are divided between 4 levels of decreasing detail (i.e. bottom up approach). The magnitude and/or value of variables within one level act as a control on variables within the subsequent level.

Level 1: Item

Every macrolitter item is defined by internal properties, such as shape, size and material. External attributes are the location and the condition of the item. The condition can be affected by, for example, bio-fouling. Combined, these variables define the susceptibility of each individual item to the processes described in level 2. For example, a heavy item buried in sediment is not very likely to affected by wind.

Level 2: Environment

Both hydrometeorologic and morphologic variables are included in level 2. Hydrometeorologic processes are considered forcing as they initiate movement, whereas morphology and vegetation obstructs movement. The occurrence and magnitude environmental forcing/resistance, as well as the item attributes defined in level 1, determine which exchange processes are activated.

Level 3: Exchange processes

Movement of items occurs in four directions: uptake (into the water), deposition (out of the water), storage (in to the sediment) and mobilisation (out of the sediment). The magnitude of item exchange regulates the amount of items situated in the three domains identified in level 4. As discussed in chapter 5, environmental processes like wind or waves may promote storage of items (by burying them in sand). However, waves

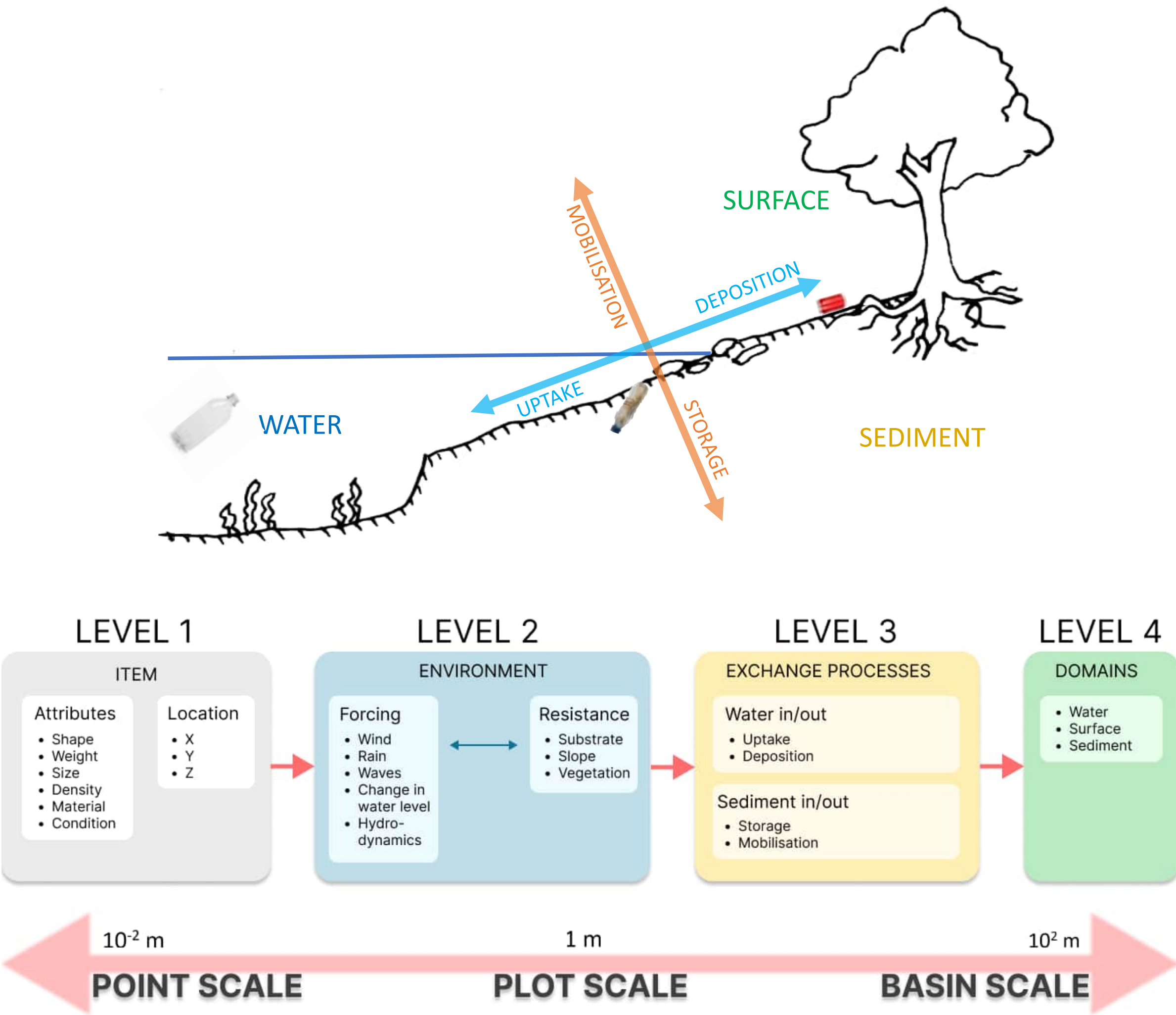


Figure 6.1: The conceptual model of riverbank macrolitter depicts four levels of variables which act on increasing spatial scale. Every variable within a level influences variables of the subsequent level. For instance, item attributes and location determine item susceptibility to environmental forcing and resistance. The magnitude of environmental forcing and resistance, together with the variables determined in level 1, determine the magnitude of exchange processes. Likewise, the magnitude of the exchange processes determines the magnitude of items situated within each of the three domains.

and/or rapidly changing water levels can also mobilise items which were partly covered in sediment. After mobilisation, items can be situated on the riverbank surface or in the water. Exchange between water and riverbank surface occurs by uptake and deposition. Uptake and deposition are each controlled by active/passive environmental processes.

Level 4: Domains
The highest level of variables are the three domains in which items can be situated. Each domain is expressed in the amount of items it holds. Naturally, the amount of items within each domain is a consequence of the magnitude of the exchange processes defined in level 3, which in their case are defined by the variables in level 2 and level 1. The domain in which a particular item is situated partly determines the "location" variable defined in level 1.

Propagation from level 1 to level 4 should be seen as an iterative process which repeated per time step. When macrolitter flow in the river is assumed constant for a particular area during a particular season, the outcome of every iteration determines the starting conditions for the next one.

6.1.1. Suggestions for research design

This study was carried out in a natural environment. Consequently, the number of variables which may affect the subject of the study is very large, which may lead to difficulties in data analysis. For example, in this study it was difficult to analyse the interaction between riverbank morphology and item attributes quantitatively as many other variables could have had an influence. Also, the temporal extent and/or the survey frequency were not large enough for performing regression analysis. Another problematic factor is that interaction between variables occur at varying spatiotemporal scale. The survey frequency and timing in this study was based on expected water level variations. This decision made the data less suitable for analysing the influence of wind, as variability in wind strength and direction occurs at a higher temporal frequency.

In order to overcome these difficulties in future research design, the conceptual model presented in section 6.1 can be used as guidance for deciding which variables to focus on and at what level of detail the study should be carried out. The first step in research design is to decide at which level the variables of interest take place. Interaction between level 1 and level 2 variables take place on small spatial scale and require a controlled, experimental environment. The temporal scale of the study should be based on the temporal variability of the environmental processes of interest. Such studies should focus on measuring the behaviour of single items with regards to the environmental processes of interest.

Interaction between level 2 and level 3 variables can be studied in either natural or experimental environments. The subject of interest would be the effect of environmental processes on the magnitude of the exchange mechanisms.

Finally, studies carried out on level 4 variables should be carried out in a natural environment. The subject of interest is the quantity of macrolitter items within the domains, which is considered a result of the magnitude of exchange mechanisms. Level 4 studies can focus on both spatial and temporal variability. Observations say something about the long term balance of exchange mechanisms, which is controlled by environmental processes. The spatiotemporal resolution of the study should therefore be based on the expected variability of the environmental processes of interest. For example, the influence of vegetation can be studied by seasonal surveys of the same location while the influence of river hydrodynamics can be studied by surveying a large extend of the riverbanks at a single moment in time. It is very important to keep in mind that anthropogenic factors (which are not included in this model) may also influence macrolitter abundance.

6.2. Reflection on survey methodology

The survey methodology used in this study produces a unique data set on riverbank macrolitter. It allows for counting, localising and tracking of individual items. Before commencing with monitoring, it was not entirely certain what to expect. To this date, no study has focused on short term macrolitter variability on riverbanks. As mentioned in chapter 4, a trial was conducted in order to test the feasibility of the method and make necessary adjustments to the initial survey design. Experiences gained during surveys are discussed in this section.

6.2.1. Monitoring with RTK positioning

Item localisation with RTK positioning was done in combination with photographing individual items. **Advantages** of the survey methodology are:

- The method can be used in all weather conditions. For safety it is advised to wear waterproof clothing and a life vest. Electronic devices like smartphones can be protected with additional casings. Weather conditions do not influence measurements.
- The method is simple to understand and does not require expert knowledge. Operating the RTK rover is straightforward when a base station is provided.
- Surveys can be performed with high detail and accuracy, although boundary conditions need to be specified clearly beforehand. For example, a lower limit of item size included in surveys should be set.
- Many different item attributes can be recorded based on photographs.

Disadvantages of the survey method are:

- Surveys can be very time consuming, depending on the amount of litter present at the riverbank. This study was carried out by one researcher. Covering the area between the waterline and the flood marks can take up to 5 hours of continuous surveying. Time can be reduced by increasing personnel.
- Only the dry area of the riverbank can be monitored.
- The study area needs to be accessible. Flooding could reduce accessibility.
- Due to the large amount of items, uptake and deposition could only be estimated by comparing the quantity in item categories. True uptake and deposition rates may be higher as intercategorical item exchange was not accounted for. Also, the fate of disappearing items is not 100% certain. Although assumed to occur very rarely, items may also get buried entirely by sediment. This is difficult to determine using this method.

6.2.2. Monitoring with wildlife camera

The wildlife camera provided 30mp imagery of the riverbank (see figure 6.2). The ground sampling distance was 1 cm/pixel over a distance of 110 meters. The images were analysed for usability in macrolitter detection. While some items could be identified well (for example: bottles and coloured drinking cans) it was not possible to distinguish smaller items. Especially when leaves, clay or rocks are present on the riverbank, items become indistinguishable from their environment. It is expected that visibility would increase when the camera is directed perpendicular to the surface instead of with an angle.

Figure 6.2: Image captured with the wildlife camera. Some items can be identified well (the green sweater and the plastic bottle). However, clay and leaves make item identification more difficult. At increasing distance it is not possible to distinguish between macrolitter and environment.

6.2.3. Item tracking

In this study items were tracked by physical appearance or paint spray. It was found that the vast majority of items are hard to distinguish from each other. Item tagging with paint spray does not solve this issue. Another limit is that items can only be tracked when they appear on the dry surface of the riverbank. Item pathways/locations when situated in the water remain unknown. A possibility is to tag items with advanced tracer techniques like silica encapsulated DNA microparticles (Tang et al., 2021).

6.3. Recommendations

There are still many knowledge gaps on the behaviour of macrolitter in fluvial systems. The following recommendations for future research are suggested:

1. This study explored dynamics of riverbank macrolitter in groyne fields. As depicted in figure 6.1, there are a lot of variables that can influence the behaviour macrolitter. Quantifying effect of these variables on item uptake, deposition, storage and mobilisation would help in identifying the most important contributing factors. It is suggested that the influence of item attributes are studied in a controlled environment. This allows for selective focus on several variables while others remain constant. For example, macrolitter behaviour under varying hydrological conditions can be studied while keeping item attributes and morphology constant.

2. The magnitude of macrolitter deposition could not be explained. As suggested in section 5.7.4, local river hydrodynamics and seasonality could influence the deposition rates for individual groyne field. More research is needed into which factors contribute to deposition and whether the macrolitter concentration differs along the length of a river.

3. Establishing and quantifying relationships between riverbank morphology and item uptake would allow for identification of possible macrolitter hotspots based on terrain elevation data and satellite imagery. This could be studied in controlled environments.

4. In order to better understand macrolitter pathways, more knowledge is needed on transport modes of various item categories. This will shed light on item mobility in rivers, which can help in the detection of pollution sources by riverbank sampling. Additionally, macrolitter transport in waves can be studied in order to gain more knowledge on the mechanisms behind uptake and deposition. This also affects litter mobility in fluvial systems.

Furthermore, the data shows that the quantity of riverbank macrolitter can vary greatly within a three month period. Based on monitoring results, it is suggested that special attention is given on the timing of riverbank cleanup efforts. During/after discharge peaks, items are more likely be deposited in the floodplains (not included in the study area of this research). Peaks in item quantity at riverbanks are expected to occur after a period of stable or lowering water levels and before rising water levels.

7 Conclusion

Riverbank macrolitter was monitored intensively at a single groyne field for over a period of three months. The goal of the research was to study riverbank macrolitter dynamics as a result of natural processes. Items were localised with RTK positioning and photographed using a smartphone camera. From November 2021 to January 2022, a total of 21 surveys were carried out in which the location and attributes of riverbank macrolitter was recorded. This resulted in a unique data set allowing for spatiotemporal analysis with high level of detail. By comparing the quantity of items per category between two subsequent measurements, macrolitter uptake and deposition was estimated. The influence of hydrometeorologic variables on the riverbank macrolitter was investigated both qualitatively and quantitatively. Based on experiences gained during the monitoring campaign, a conceptual model on the dynamics of riverbank macrolitter is proposed. Answers to the research questions stated in section 1.3 are provided in this chapter.

1. What are the dynamics of macrolitter in groyne fields and which controlling processes can be identified using the newly developed approach?

During surveys it was found that riverbank macrolitter is mostly concentrated in the flood marks. Throughout time, movement of items was observed as a consequent of hydrometeorologic processes. Item susceptibility for mobilisation is determined by many interacting variables. These include item intrinsic properties, morphological characteristics and the position of an item within sediment. Item exchange does not only take place between water and riverbank but also occurs between riverbank surface and subsurface. Wind was found to have a limited effect on item mobilisation, possibly due to the fact that many items are wet or partly covered with sand. Mobilisation almost always occurred due to waves and water level variations. A few occasions were observed in which berm formation due to waves caused items to become buried in sediment. During rising water levels, items can either be pushed higher on the riverbank or taken up by the water. The extent at which controlling variables and item attributes interact with each other could not be determined, more research is needed.

2. What is the magnitude of macrolitter exchange between river and riverbank and can this be explained by hydrometeorologic variables?

Uptake and deposition are processes that occur simultaneously. The balance between the rate of uptake and deposition determine the amount of macrolitter present at a riverbank. Uptake and deposition are indications of the amount of items transported through the river, assuming that no macrolitter accumulation occurs under water within the groyne field. The data depicted that, for this groyne field, deposition showed only minor variations (with one outlier) and occurred continuously. It is suggested that variability in deposition occurs on a larger temporal scale. Item uptake was highly variable and was initiated by rising water levels. It is evident that hydrologic fluctuations are a major control on macrolitter uptake. However, positive correlation between the magnitude of item uptake and change in water level for $dH > 0$ was not statistically significant. It is hypothesized that the magnitude of item uptake also depends on item attributes and riverbank morphology.
After three months of survey, all except two of the tracked items observed at day one had left the study area. This shows that under normal hydrologic conditions (assuming no accumulation under water), retention of

items within groyne fields is limited and defined by timing and magnitude of water level fluctuations.

3. If the influence of hydrometeorologic processes could not be assessed, how should future research be conducted?

Three domains in which macrolitter can be situated are identified: water, surface and sediment. Item exchange between these domains is a result of many interacting processes and variables which act at different spatiotemporal scales. Future research aimed at studying the interaction between environmental processes and macrolitter dynamics should attempt to design its experimental setup in accordance with the scale of the expected spatiotemporal variability of the process of interest. Interaction with small scale processes (waves, wind gusts etc.) should be assessed with high temporal resolution and require a (semi-)controlled environment. Large scale studies should be focusing on explaining macrolitter dynamics as a result of processes with large scale variability and can be carried out in natural environments. For example, studying the effect of hydrodynamic variables requires a spatial extent of the study area that covers the spatial variation of the variable of interest. Large deviations in scale between observations and processes of interest may lead to difficulties in analysis. In this study, assessing the effect of wind on item deposition was problematic because the temporal frequency of surveys were not in accordance with the temporal variability of the wind.

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A
Appendix

A.1. Study area

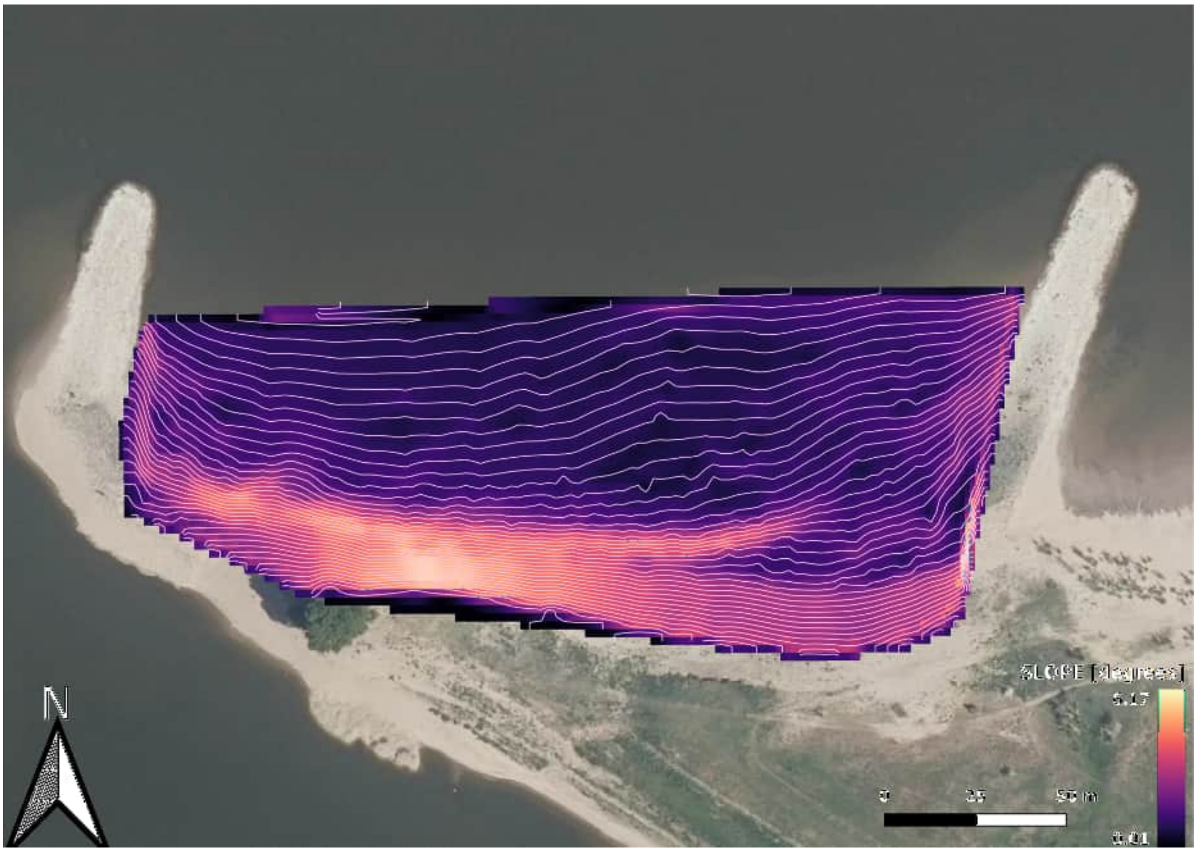
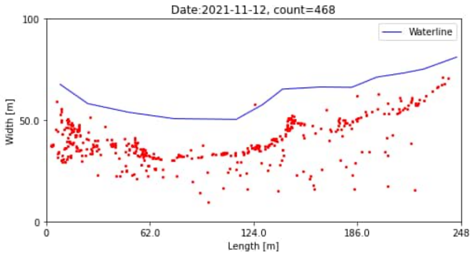


Figure A.1: Study area with depiction of terrain slope and contour lines.

A.2. Daily surveys: item locations and quantity



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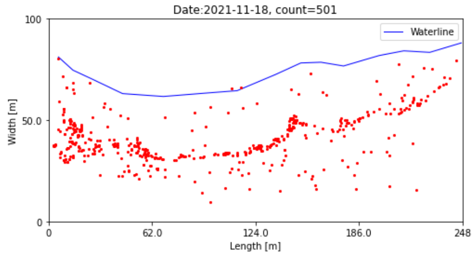

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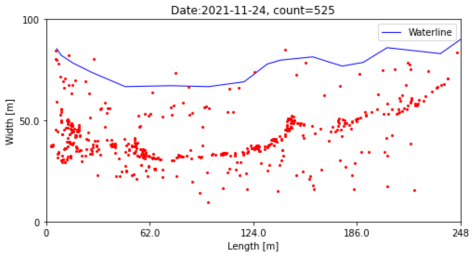

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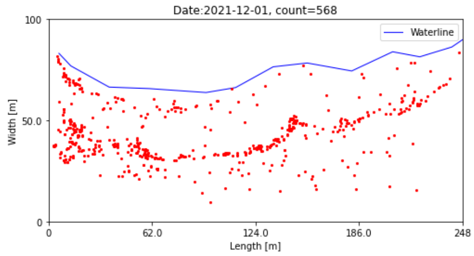

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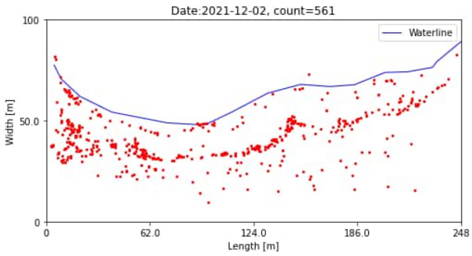

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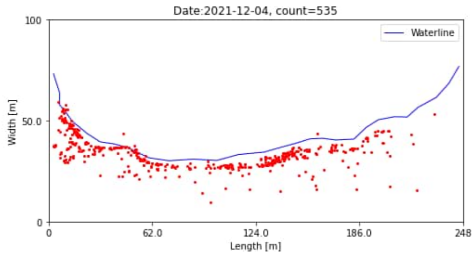

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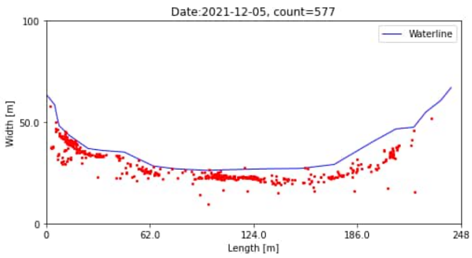

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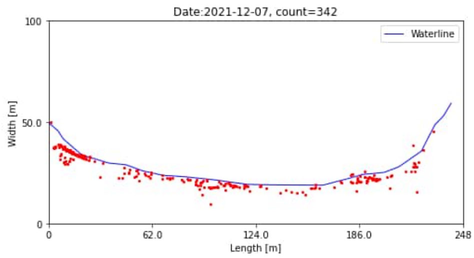

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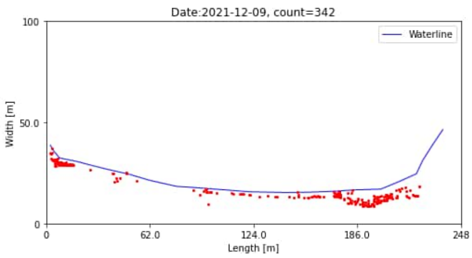

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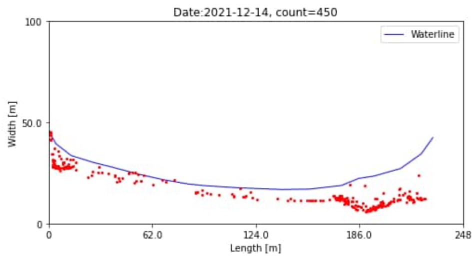

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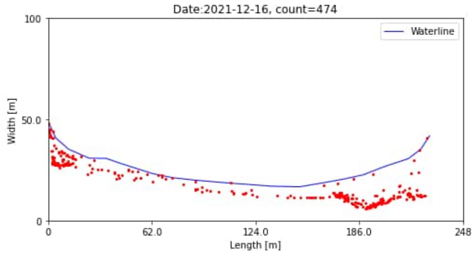

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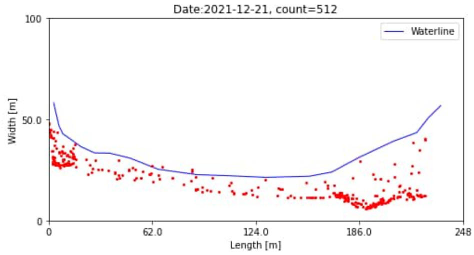

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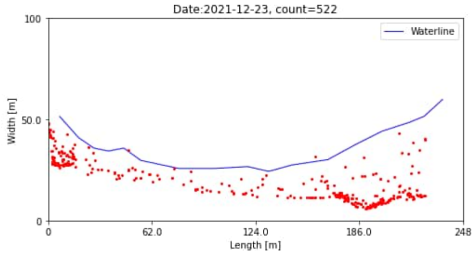

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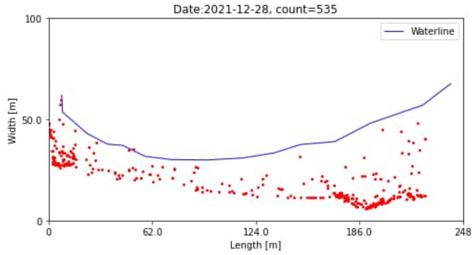

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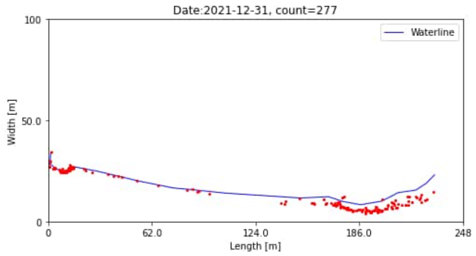

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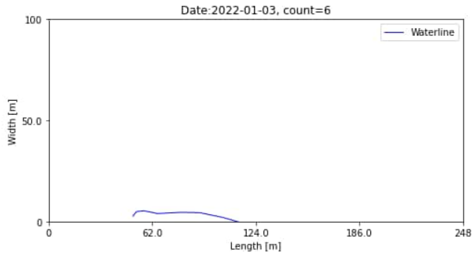

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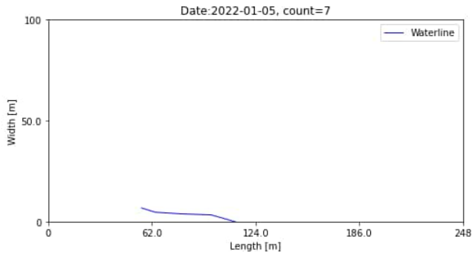

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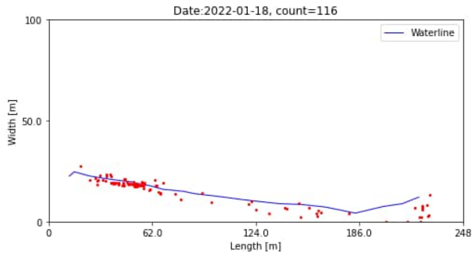

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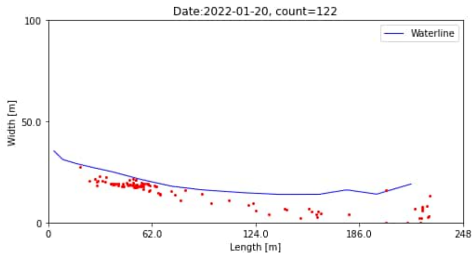

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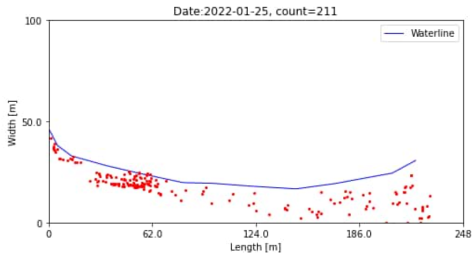

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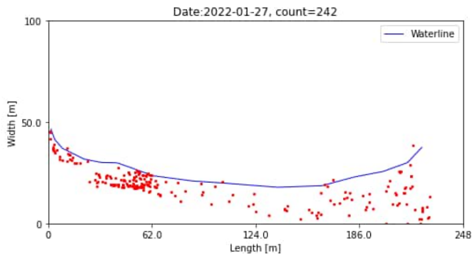
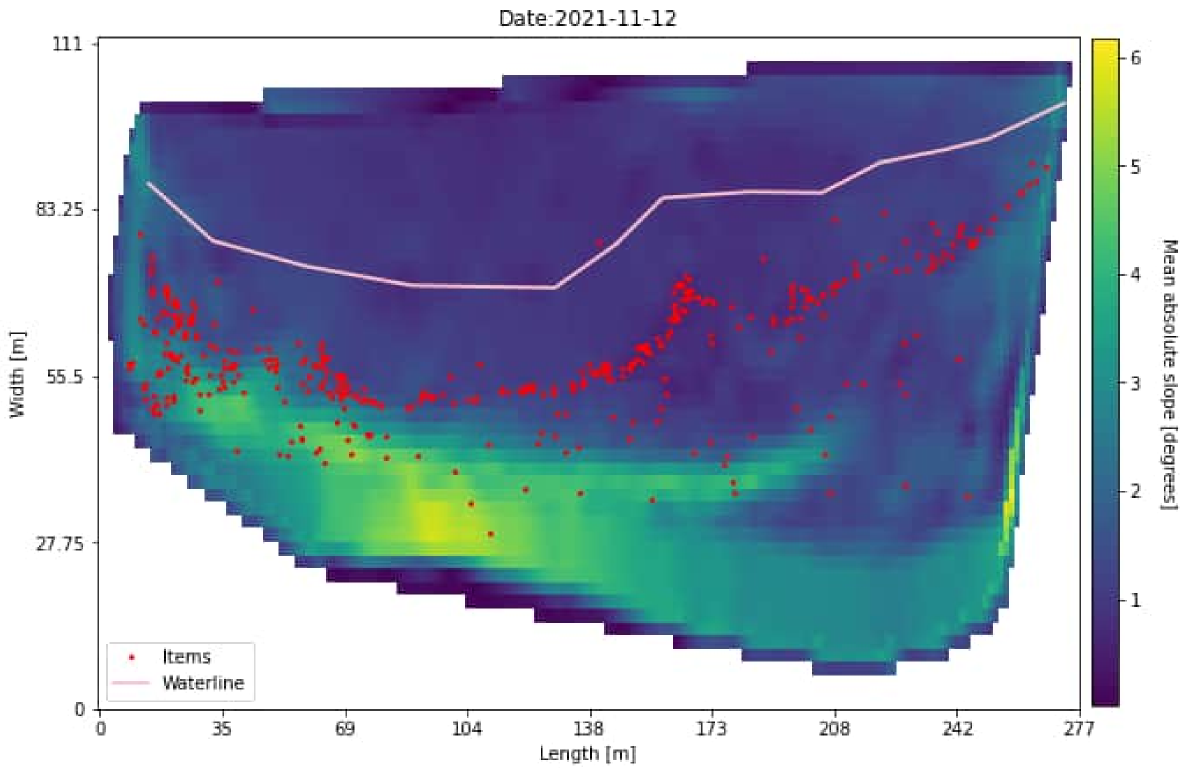


(u)

A.3. Daily surveys: item locations with terrain slope



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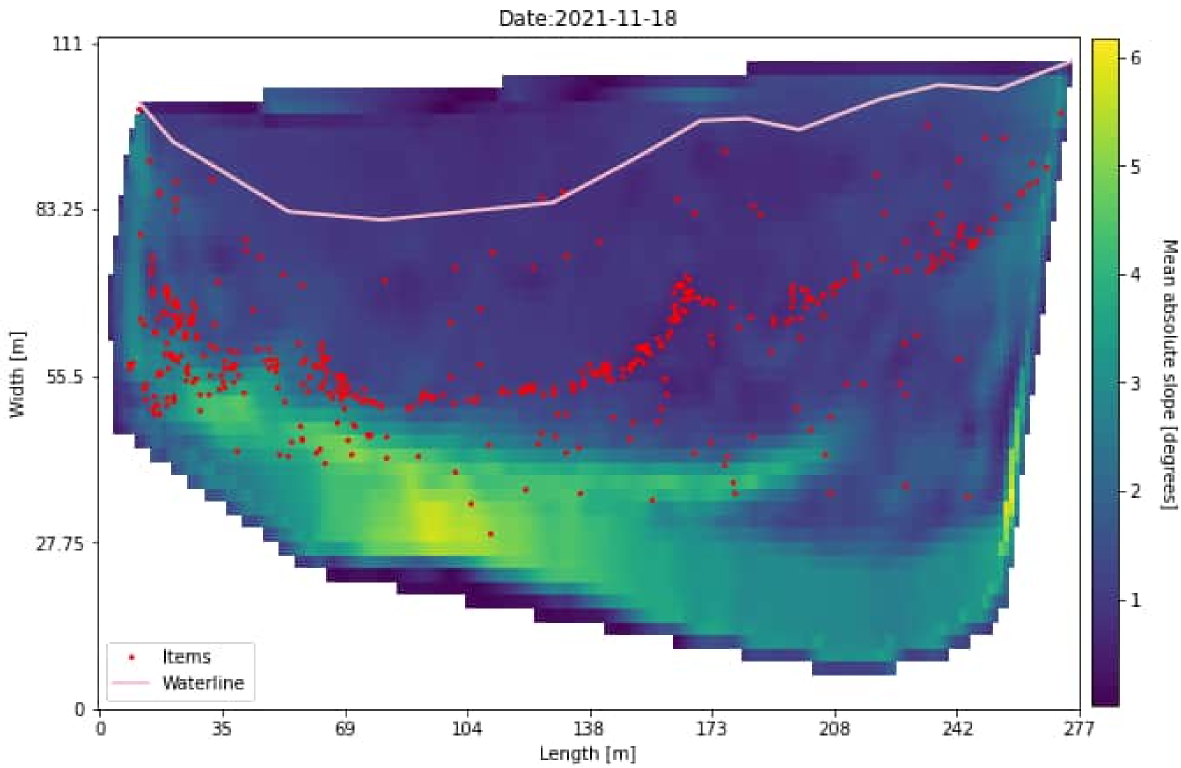

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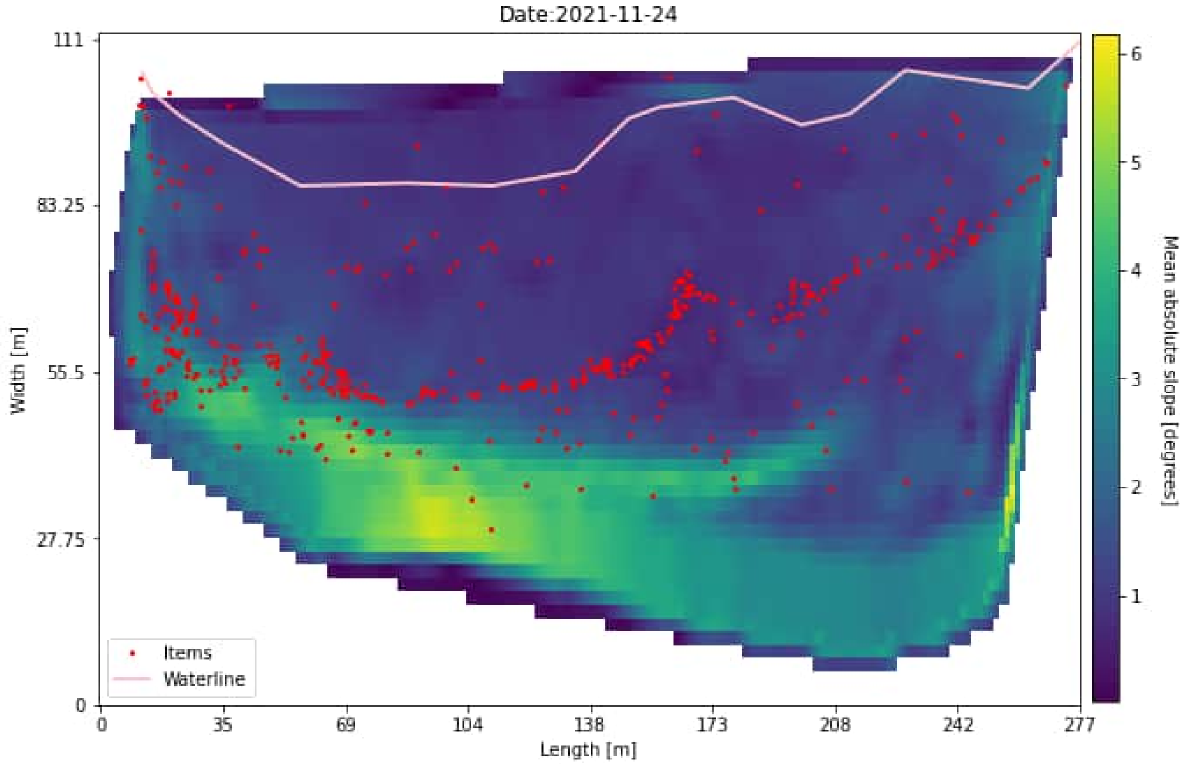
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173
208
242
277
Length [m]
Items
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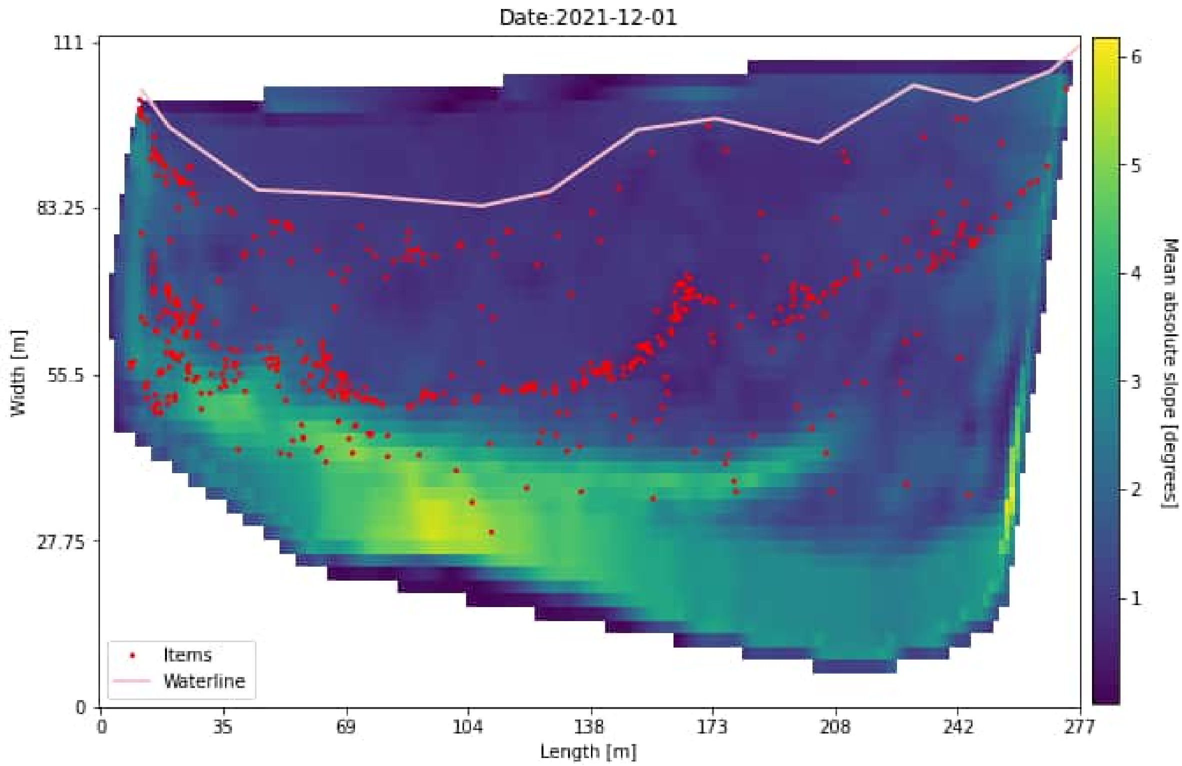
5
4
3
2
1
Mean absolute slope [degrees]

(c)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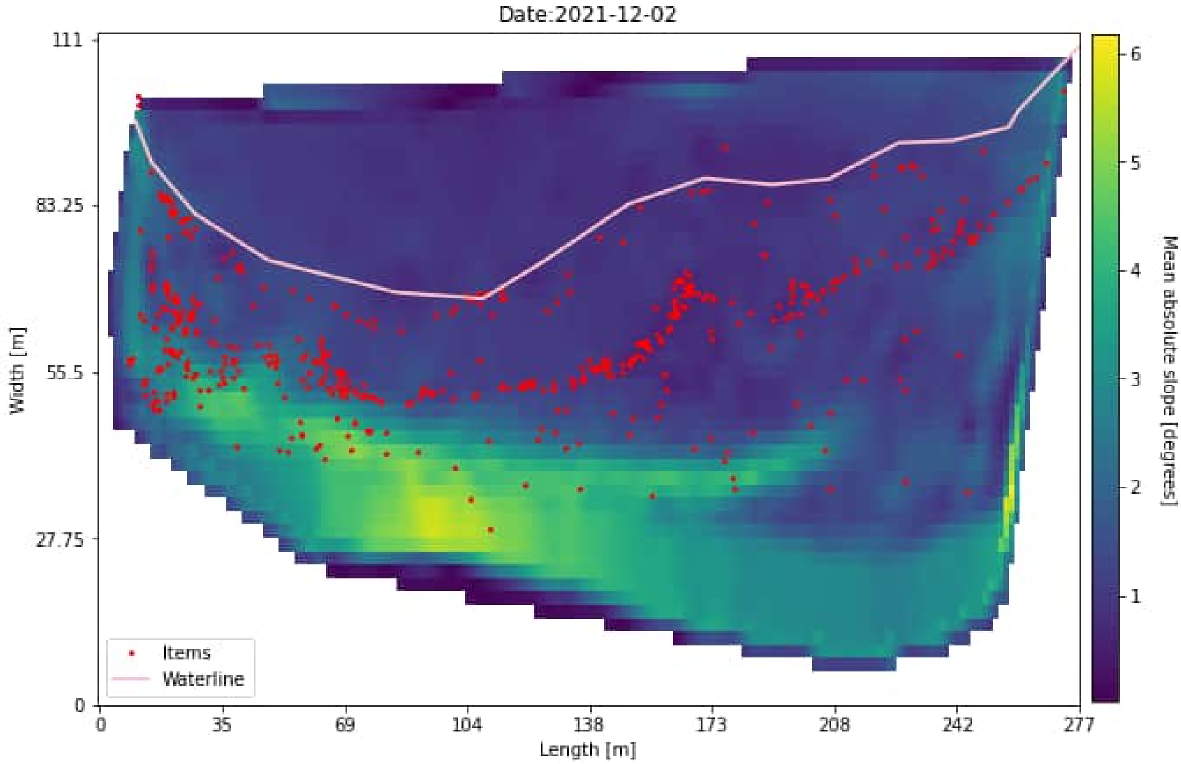
Length [m]
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(d)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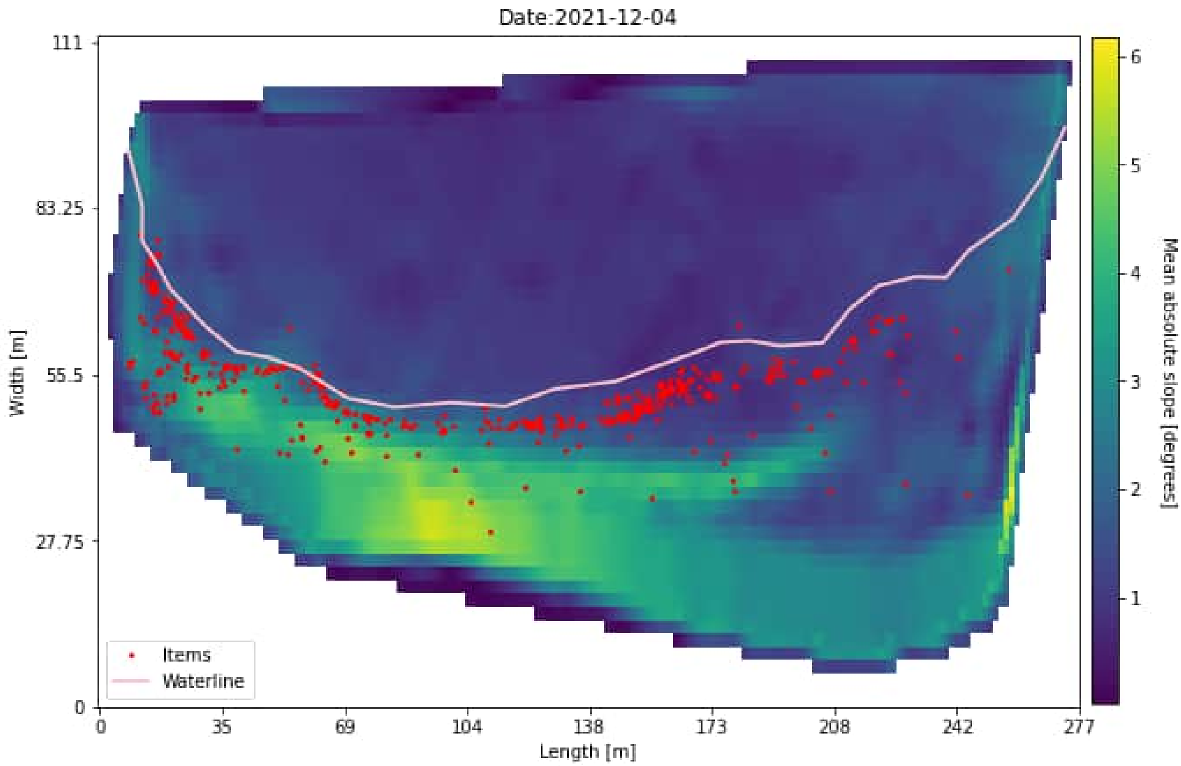
277
6
5
4
3
2
1

(e)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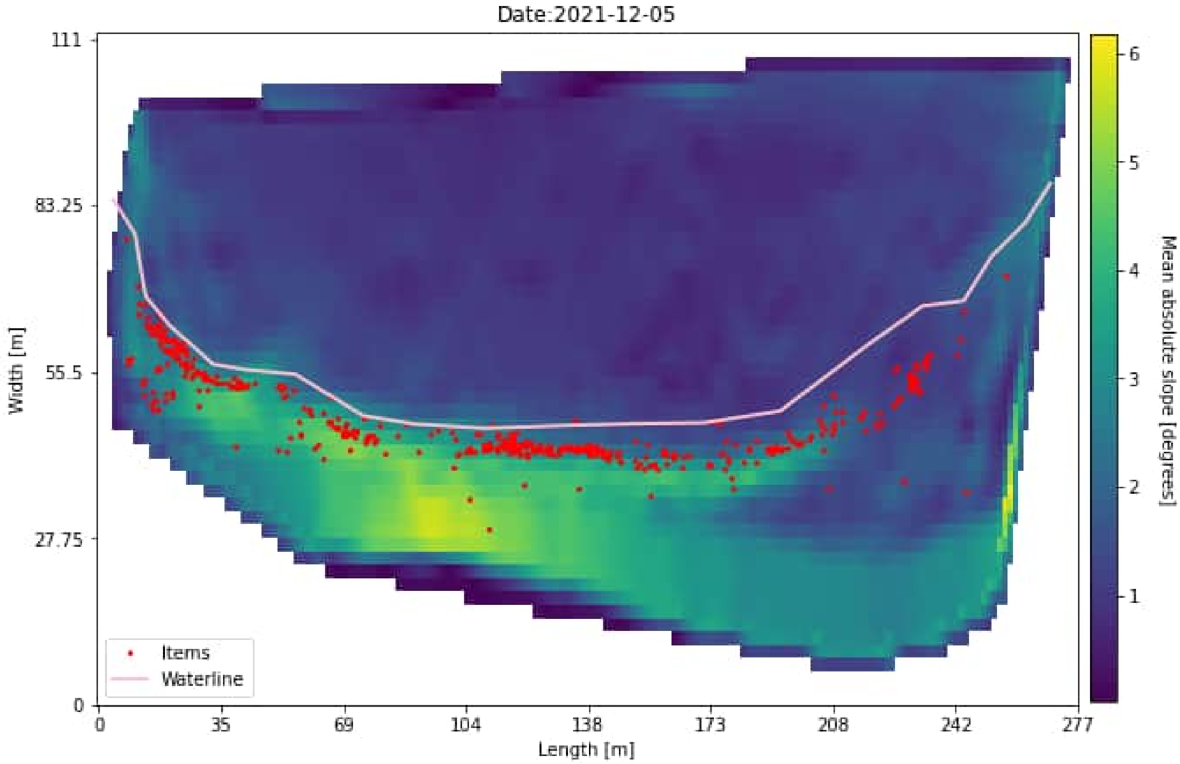
277
6
5
4
3
2
1

(f)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Length [m]
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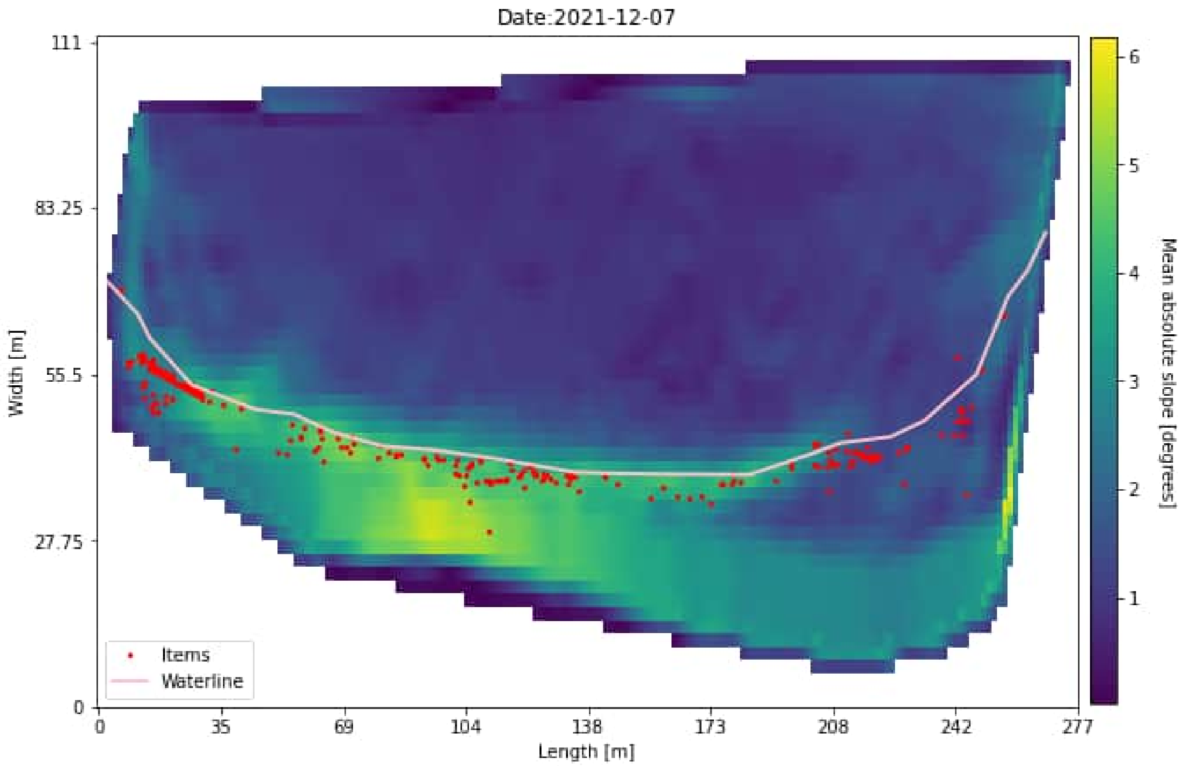
5
4
3
2
1
Mean absolute slope [degrees]

(g)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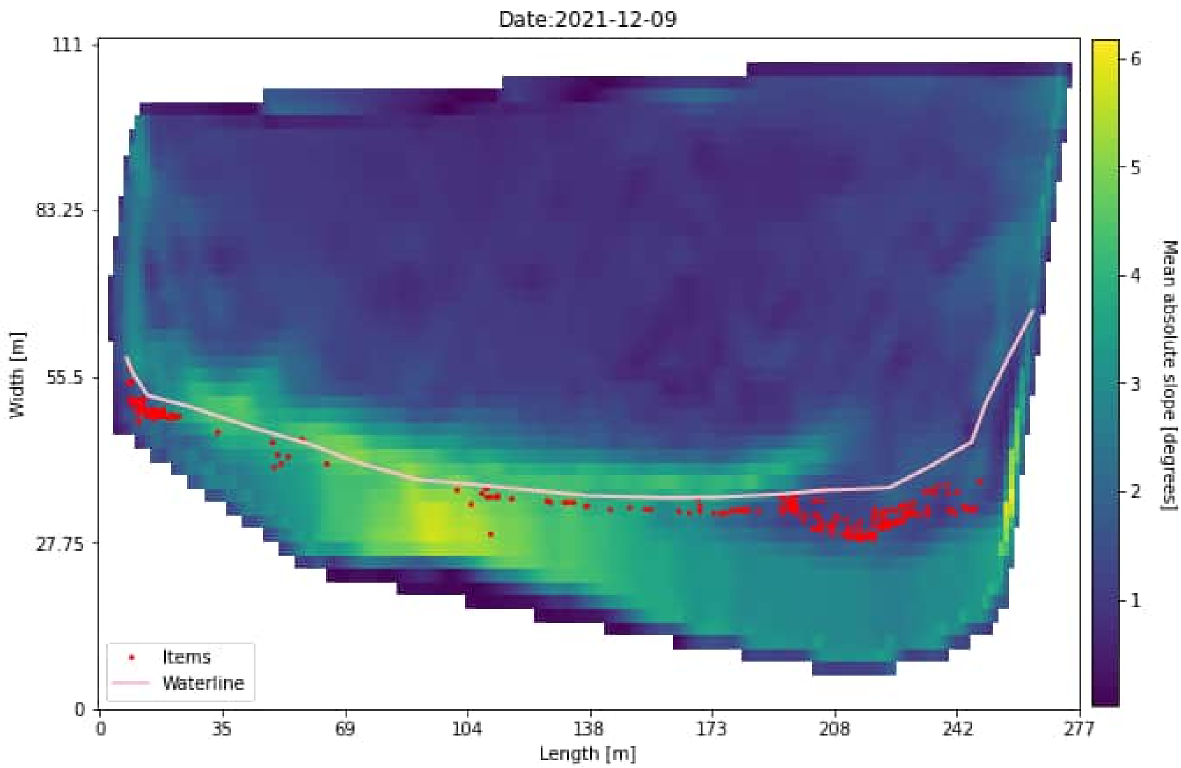
Length [m]
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(h)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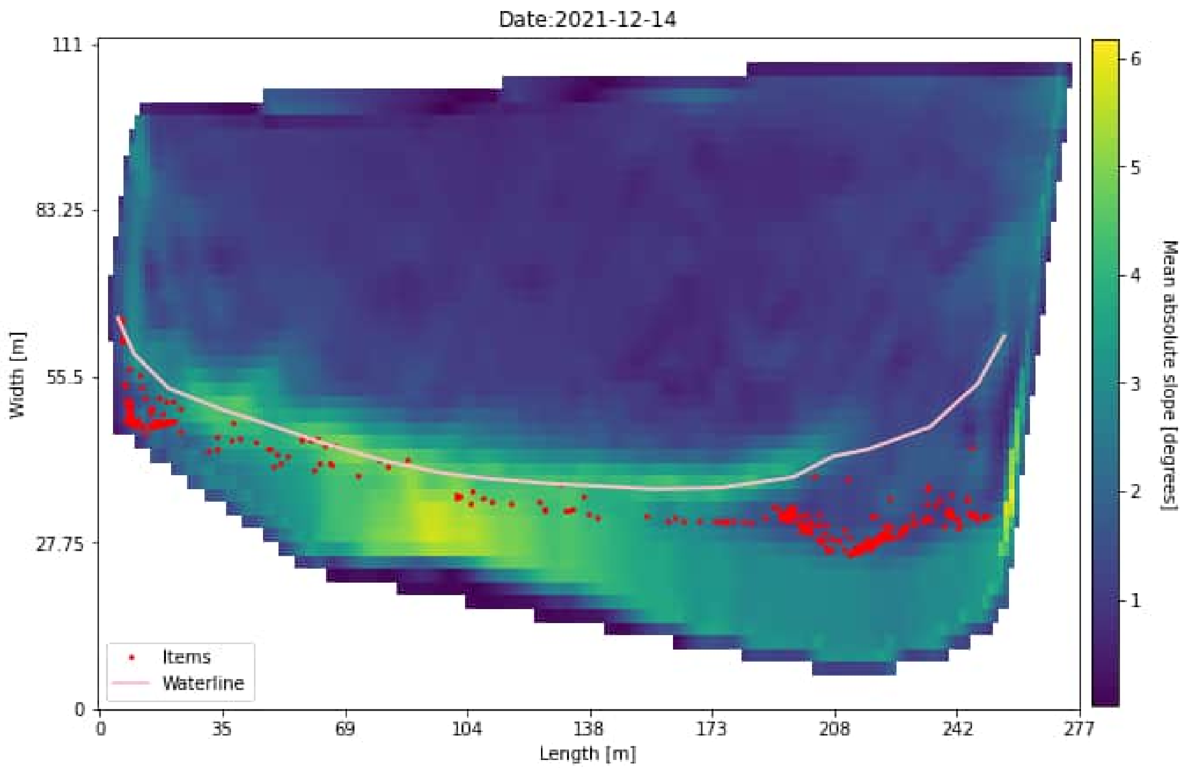
208
242
277
6
5
4
3
2
1

(i)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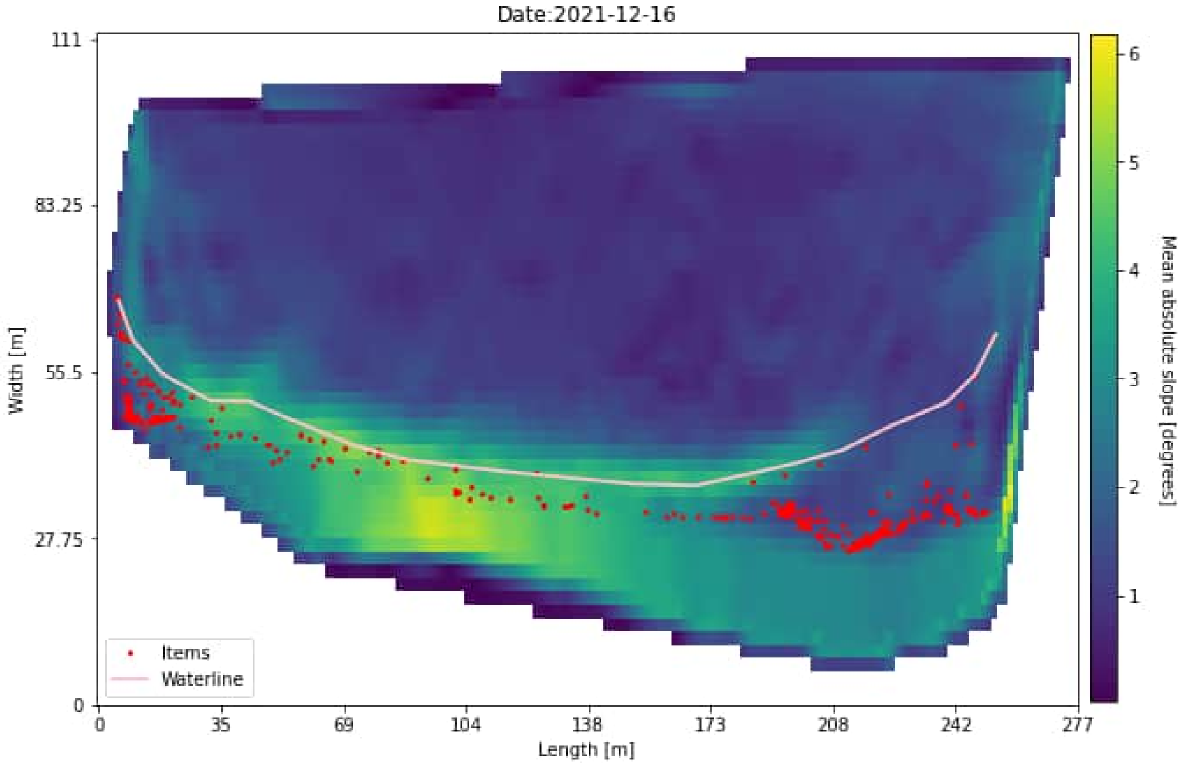
173
208
242
277
6
5
4
3
2
1

(j)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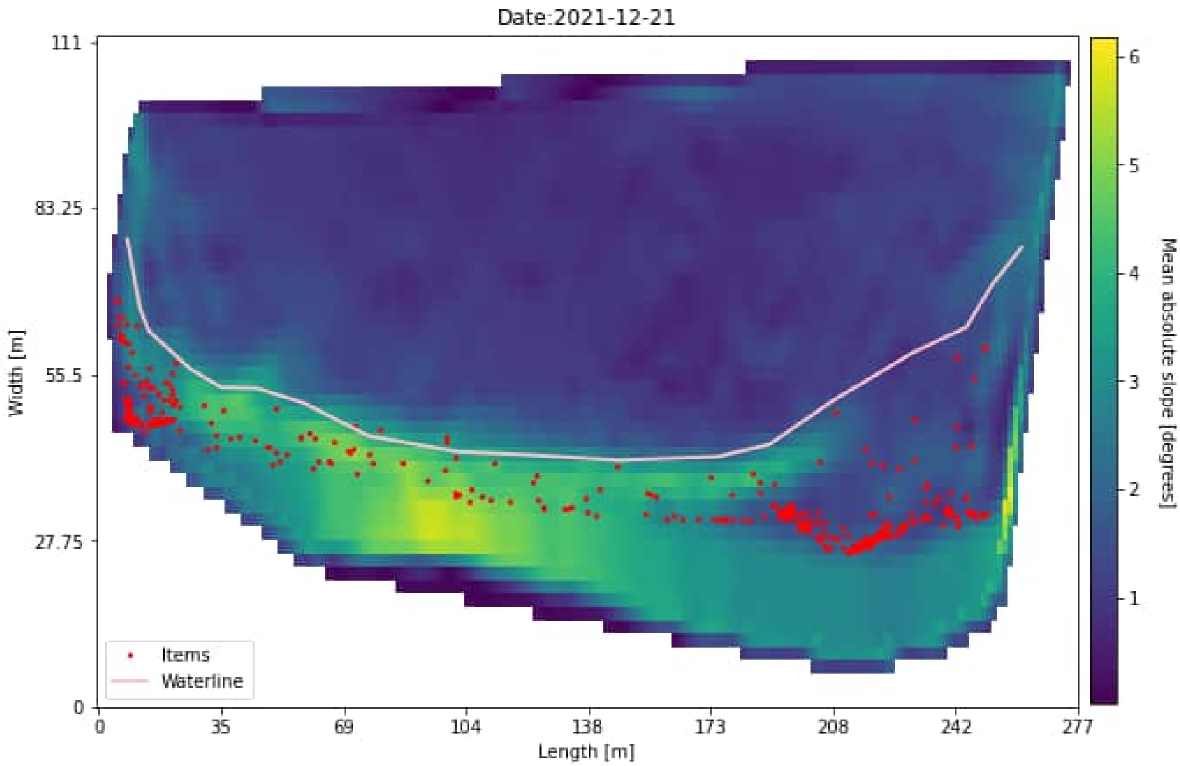
277
Length [m]
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(k)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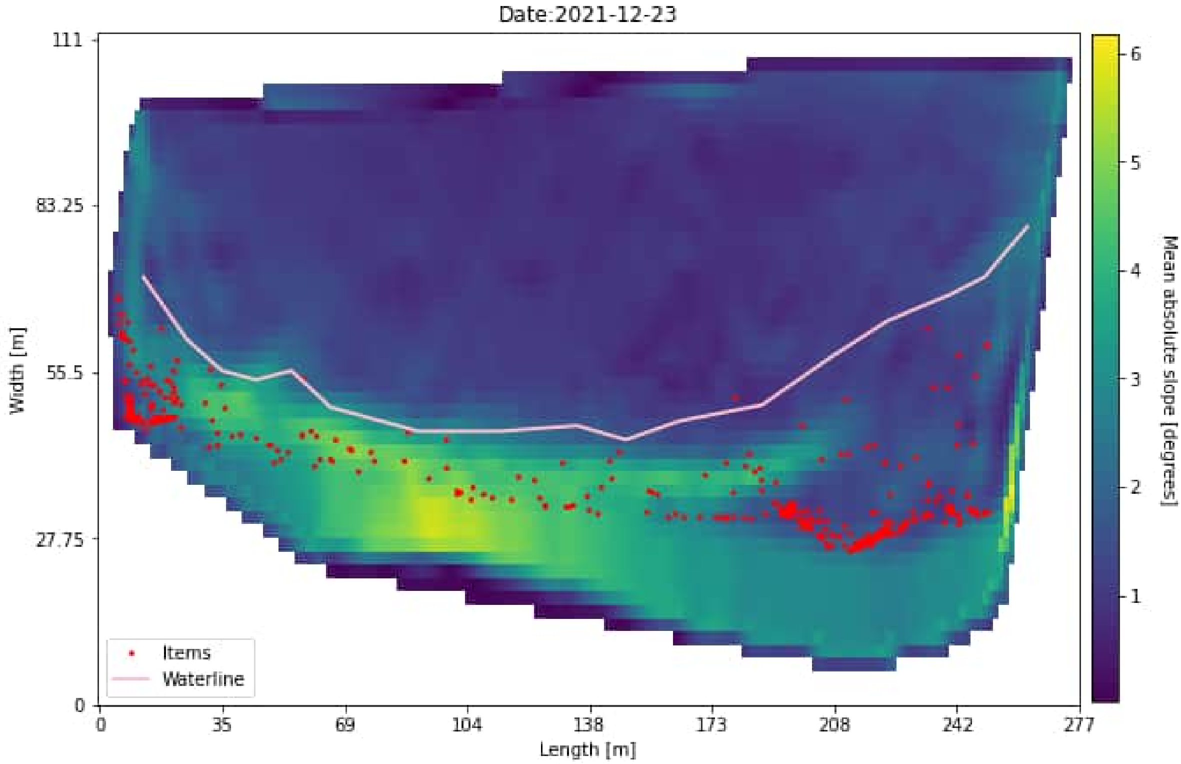
277
Length [m]
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(l)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Length [m]
Mean absolute slope [degrees]
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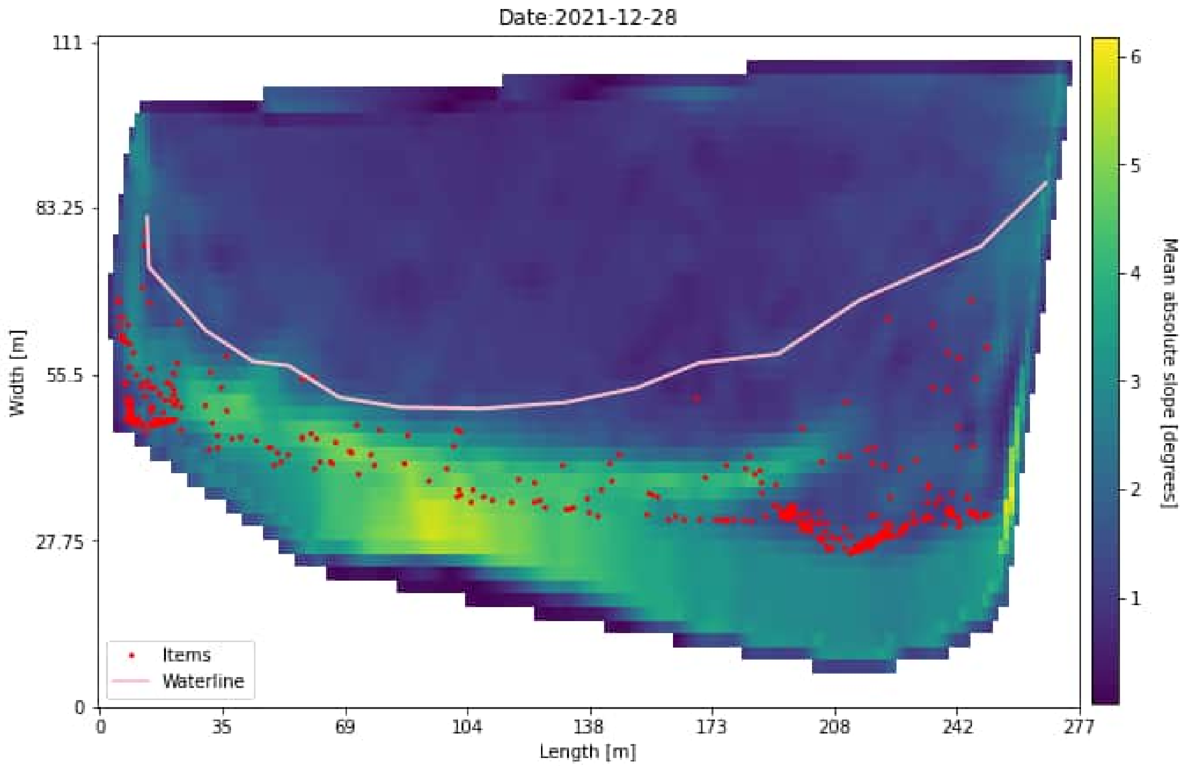
104
138
173
208
242
277
1
2
3
4
5
6

(m)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173
208
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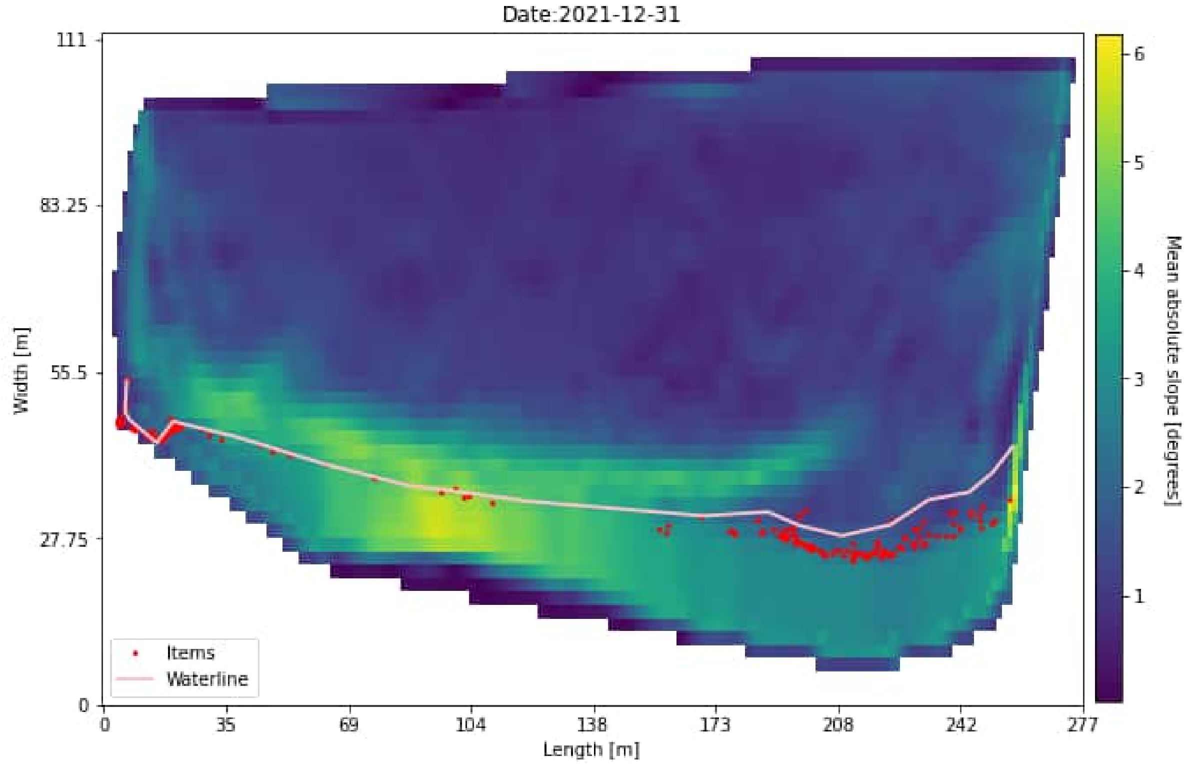
277
1
2
3
4
5
6

(n)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Waterline
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2
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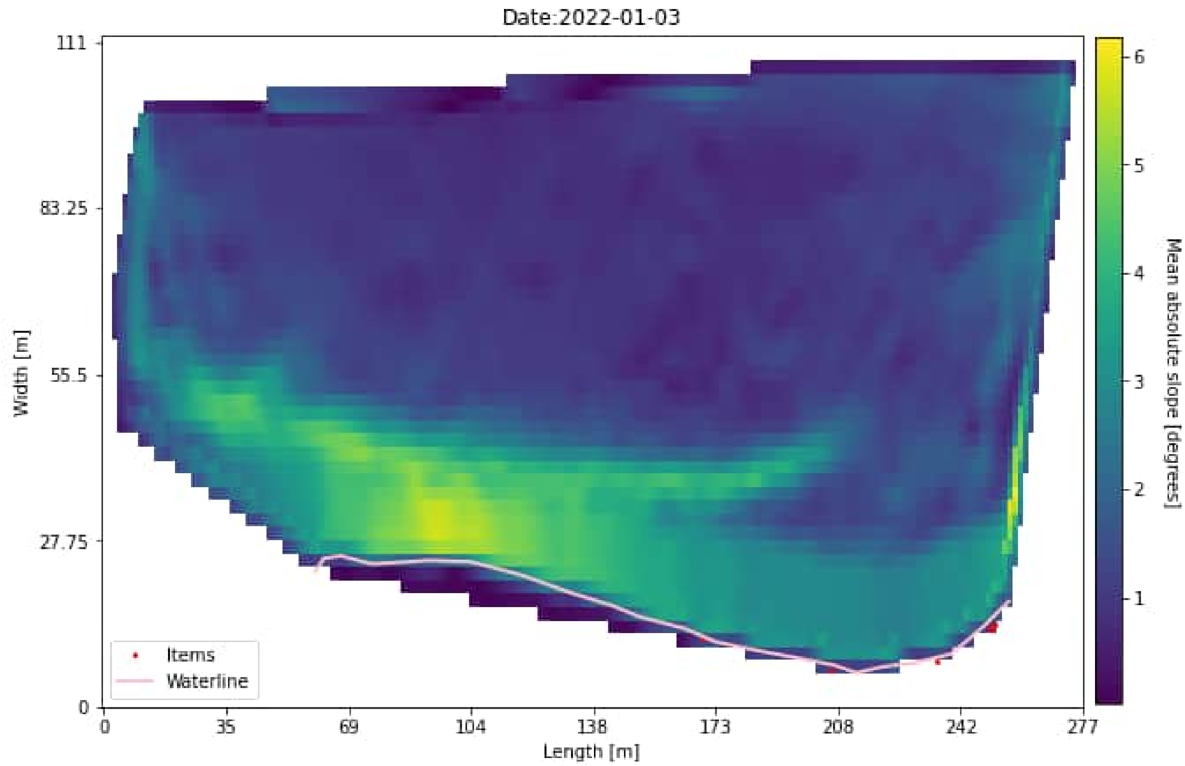
Mean absolute slope [degrees]

(o)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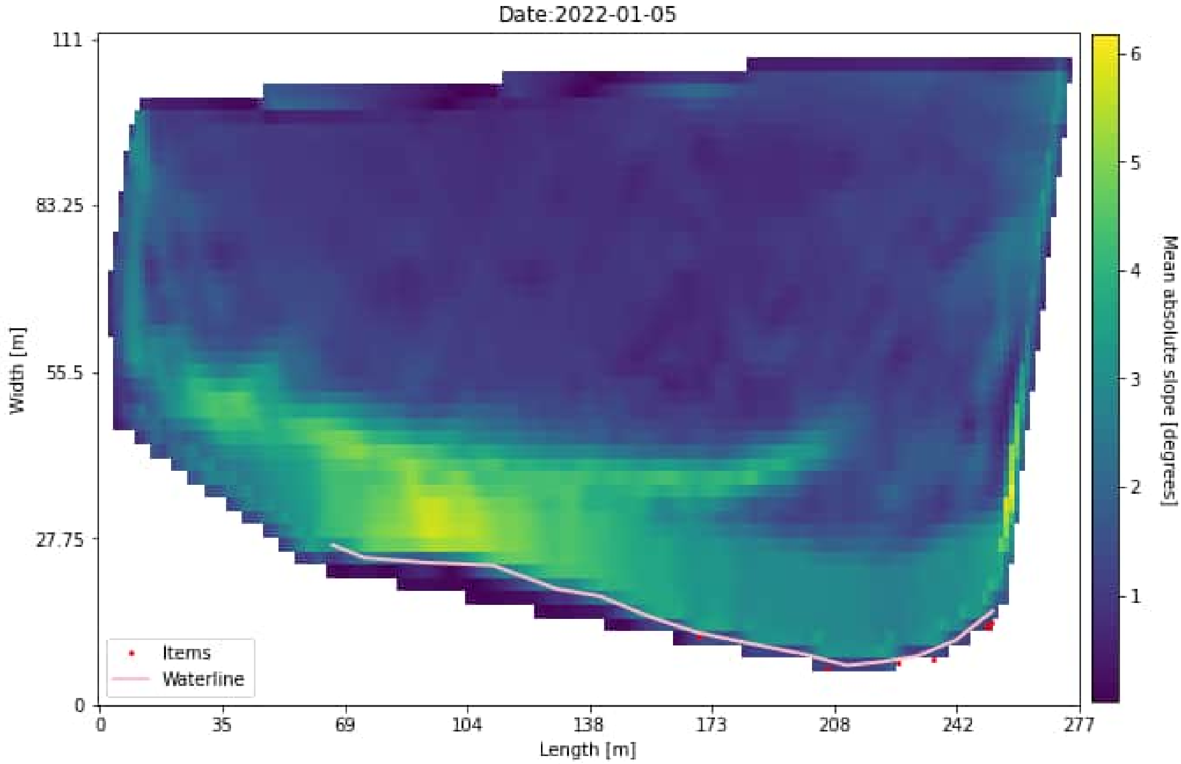
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(p)



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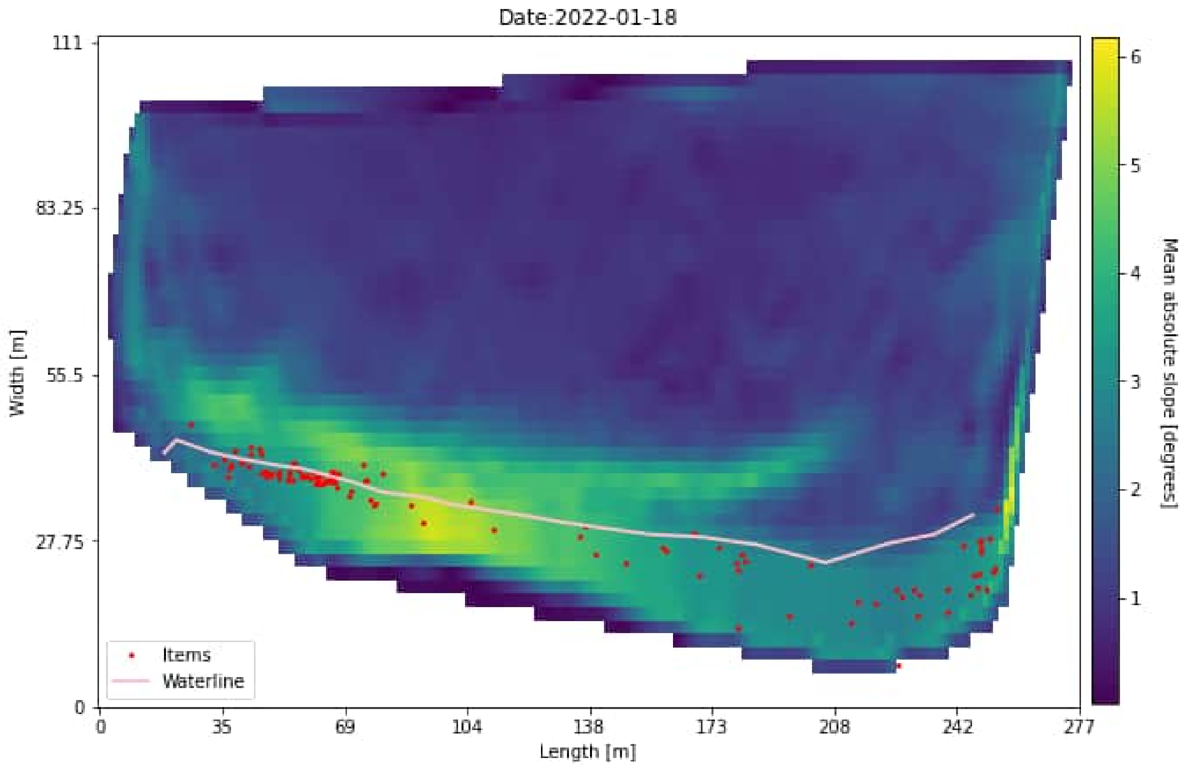
Length [m]
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(q)



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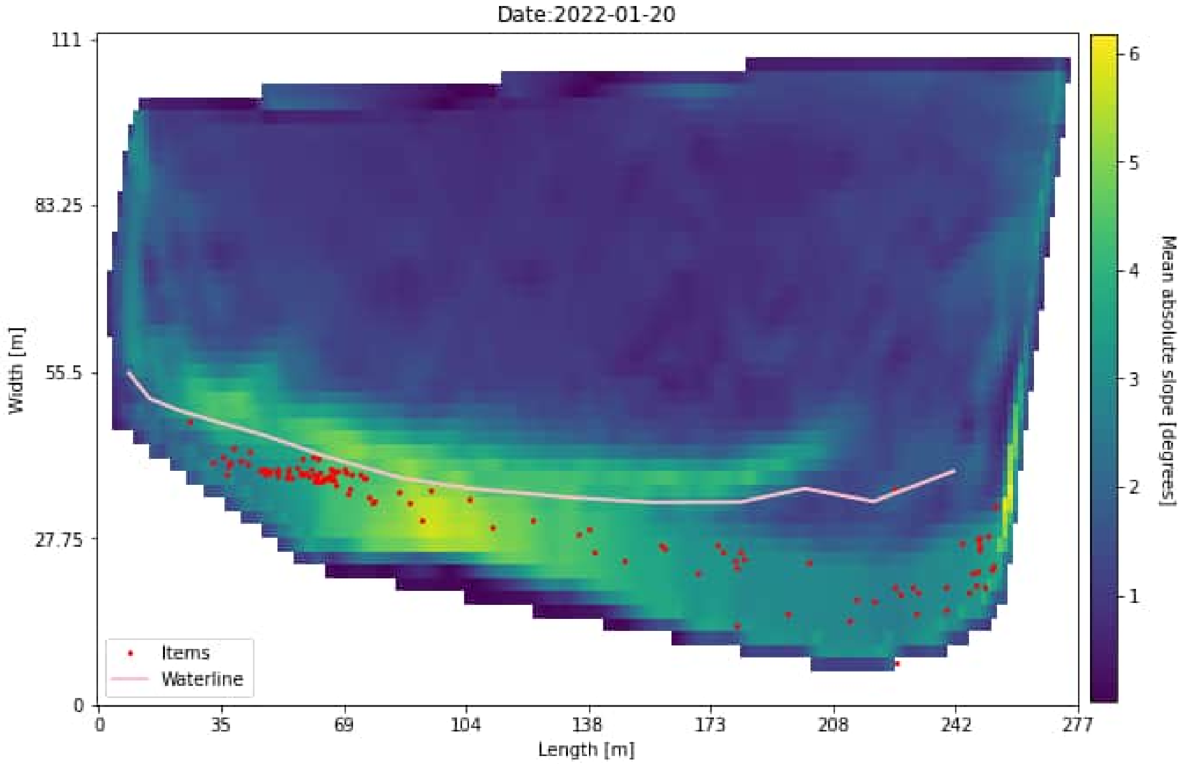
Length [m]
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(r)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69
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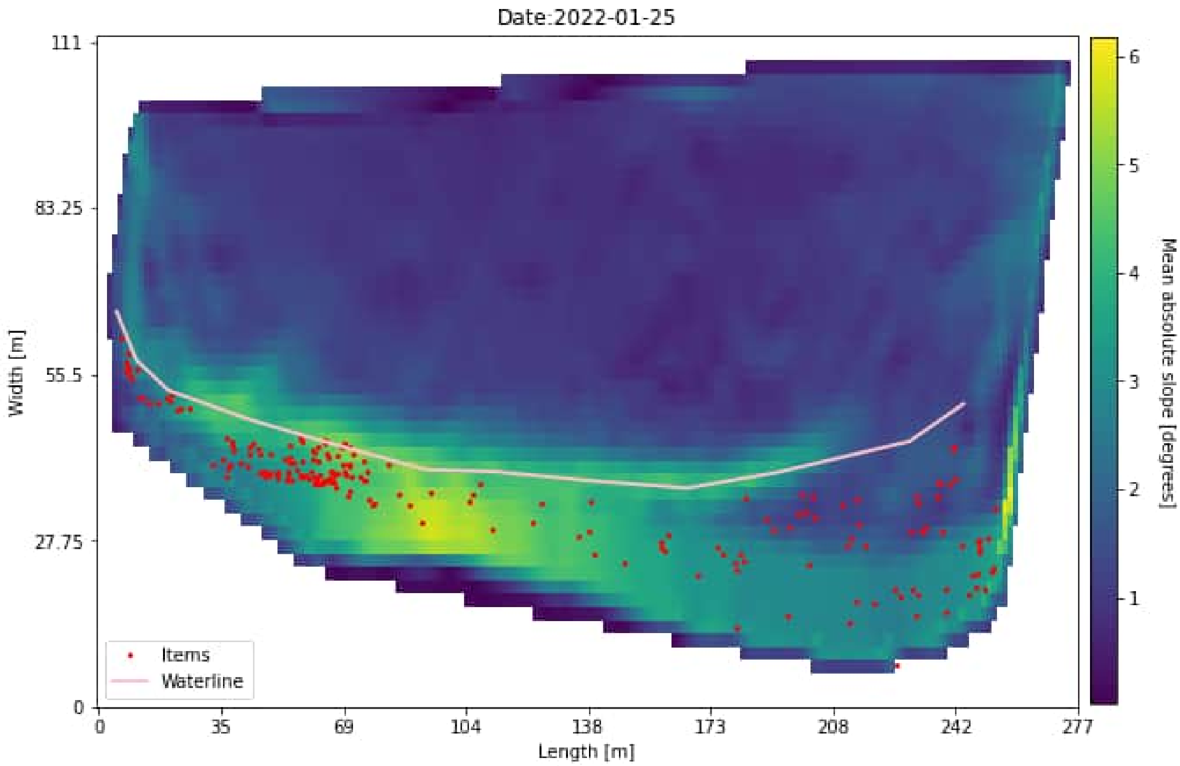
138
173
208
242
277
1
2
3
4
5
6

(s)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35
69
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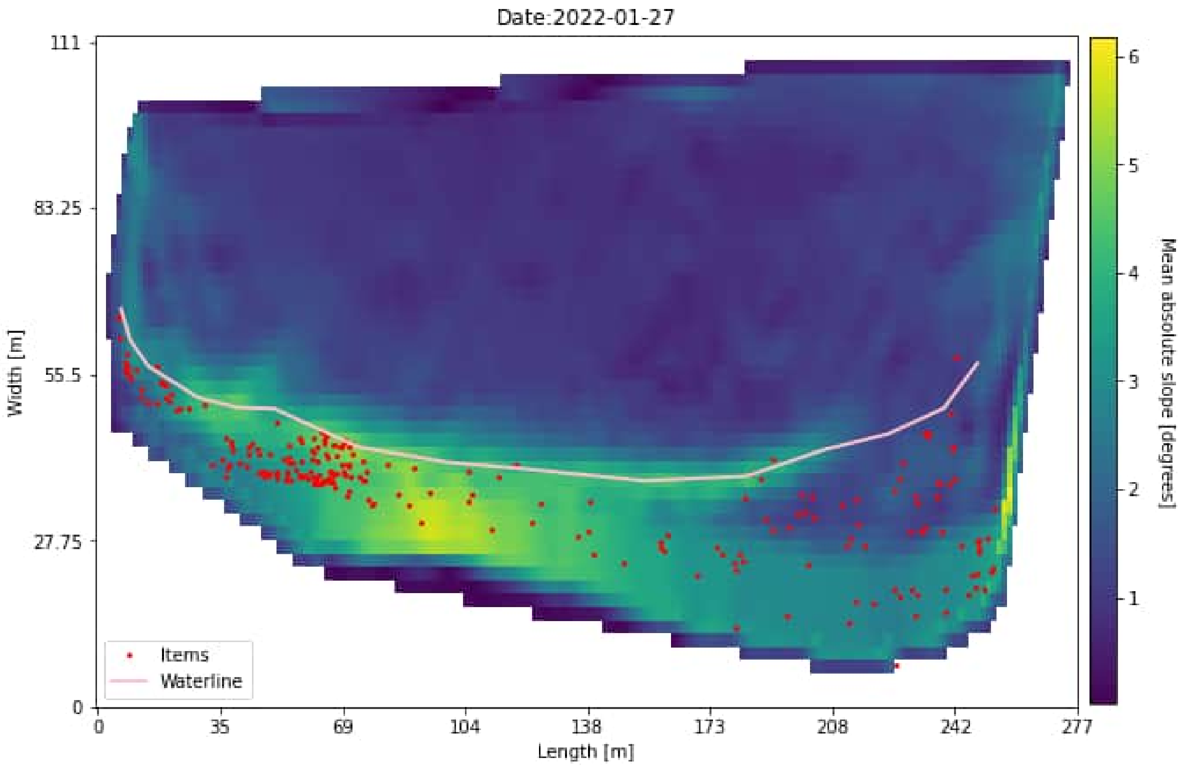
138
173
208
242
277
1
2
3
4
5
6

(t)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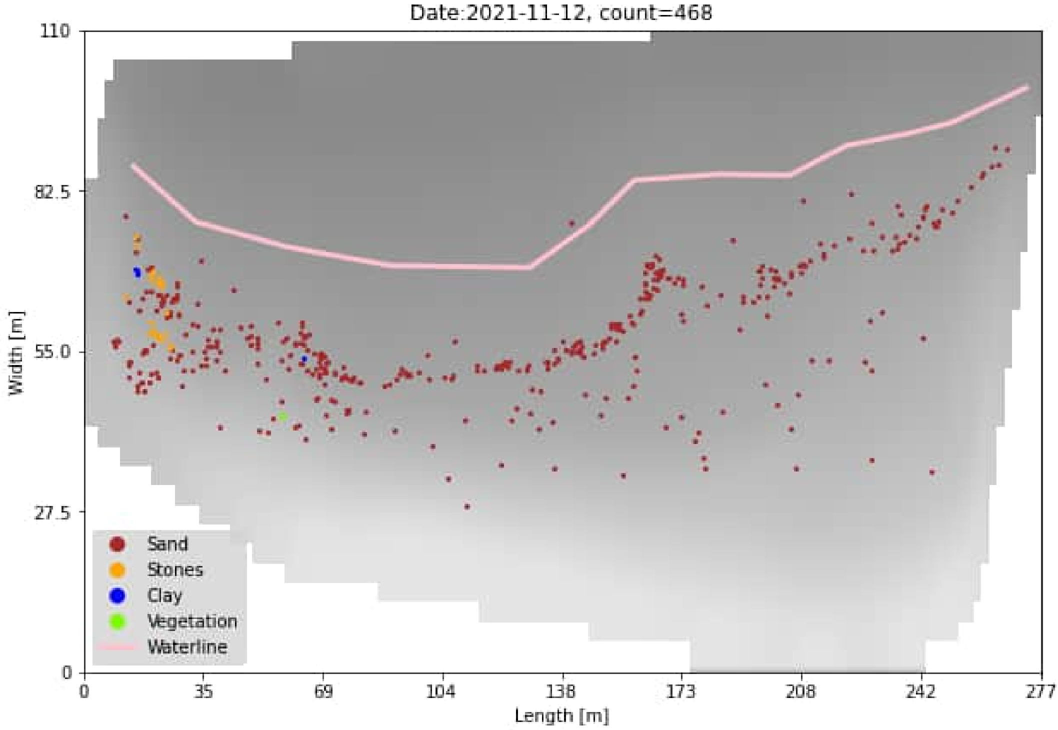
104
138
173
208
242
277
Length [m]
Items
Waterline
6
5
4
3
2
1
Mean absolute slope [degrees]

(u)

A.4. Daily surveys: item locations and substrate



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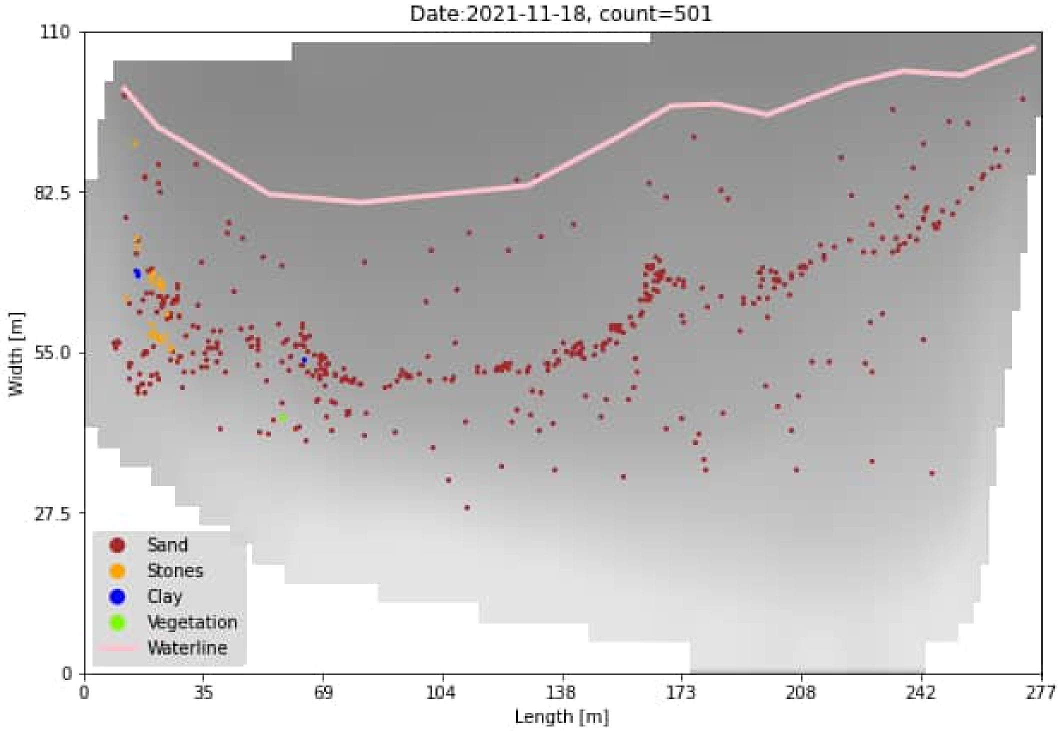

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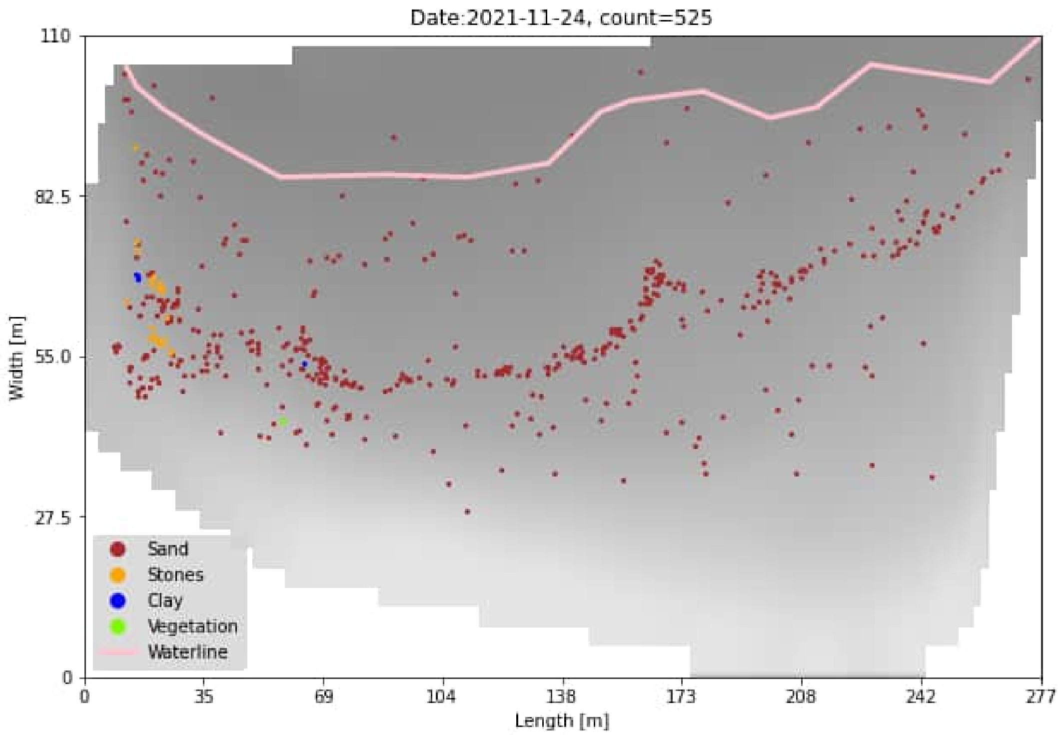
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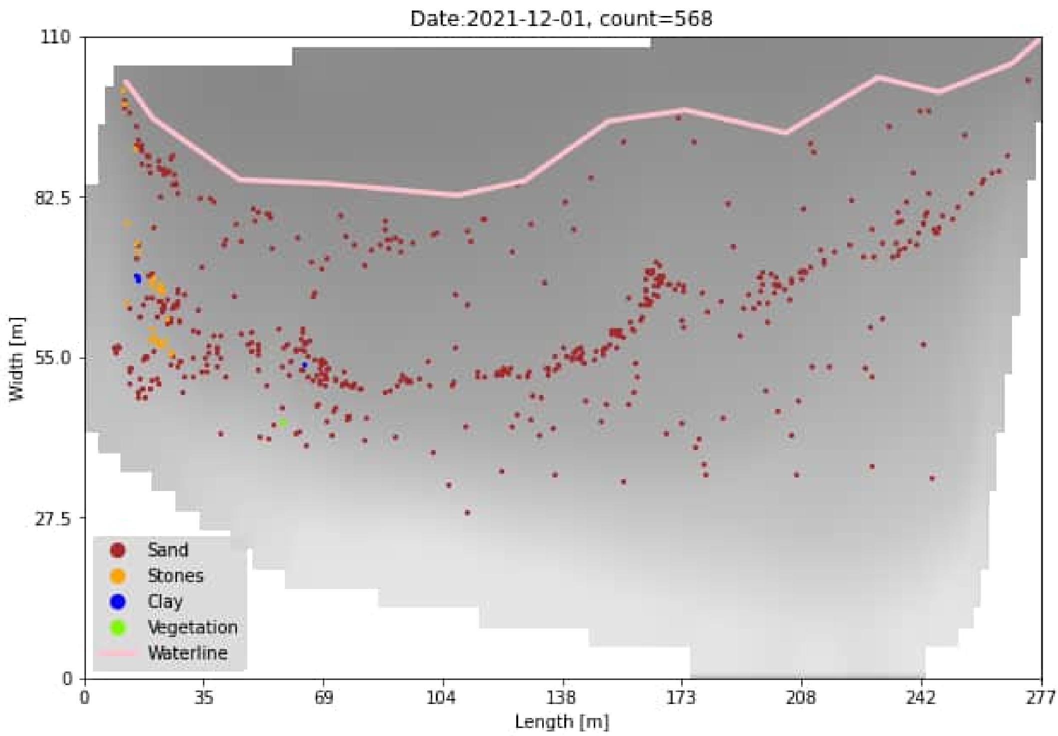
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(c)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138
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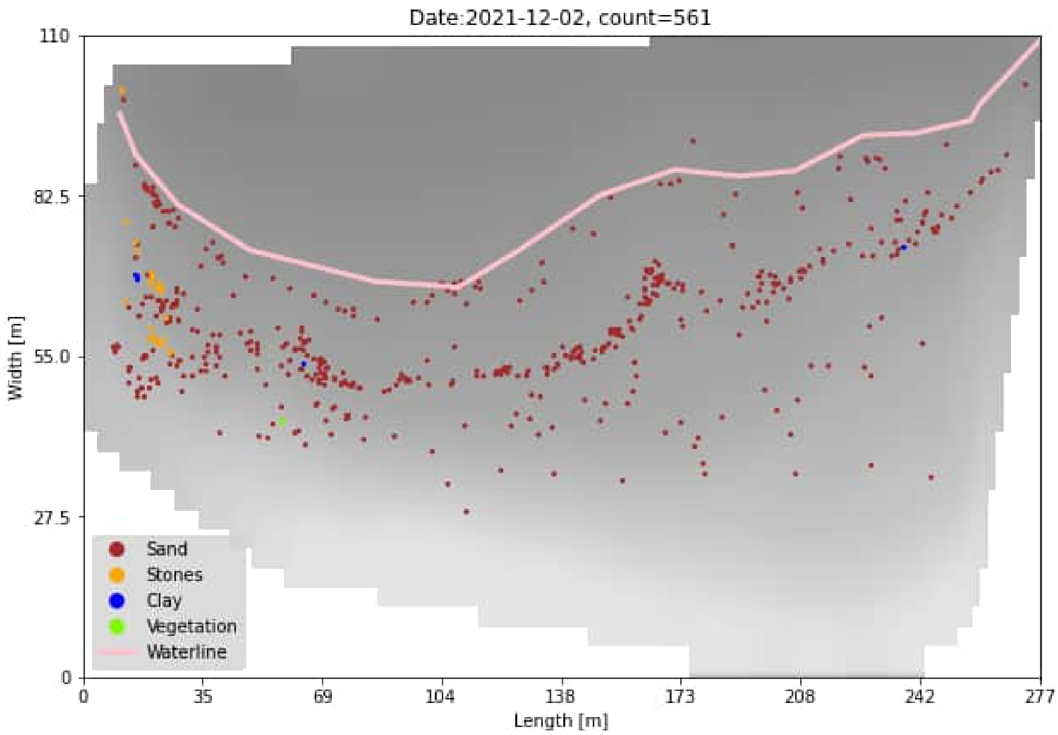
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(d)



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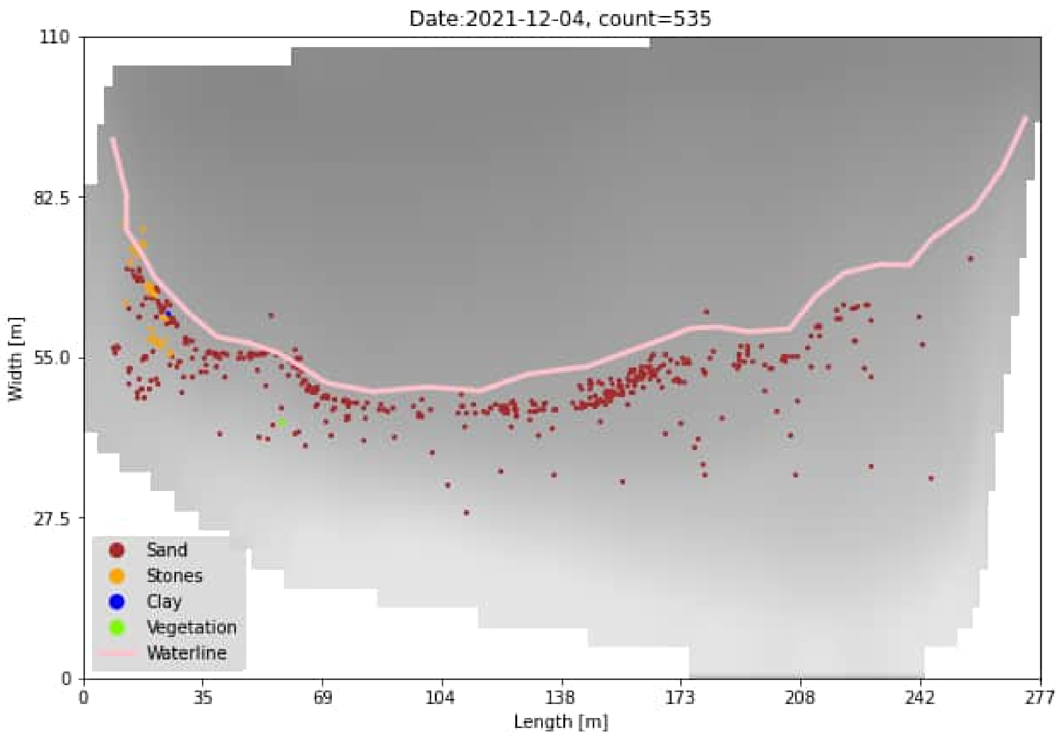
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(e)



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Width [m]
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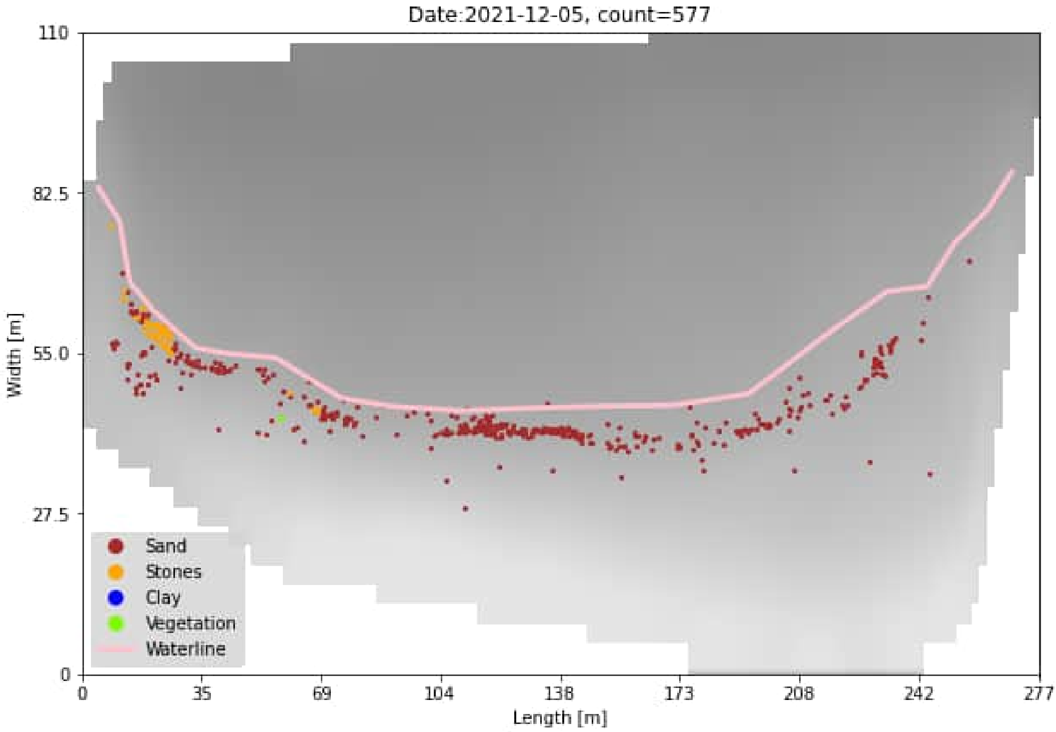
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(f)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27.5
0
Width [m]
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35
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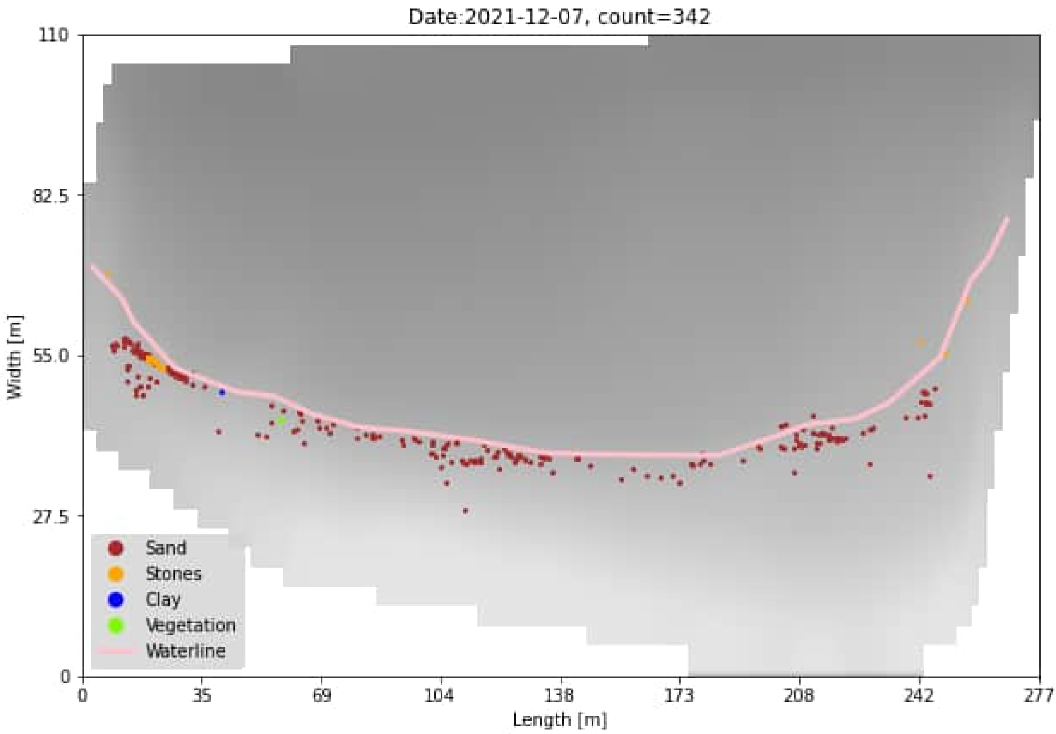
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(g)


Date:2021-12-07, count=342
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27.5
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Width [m]
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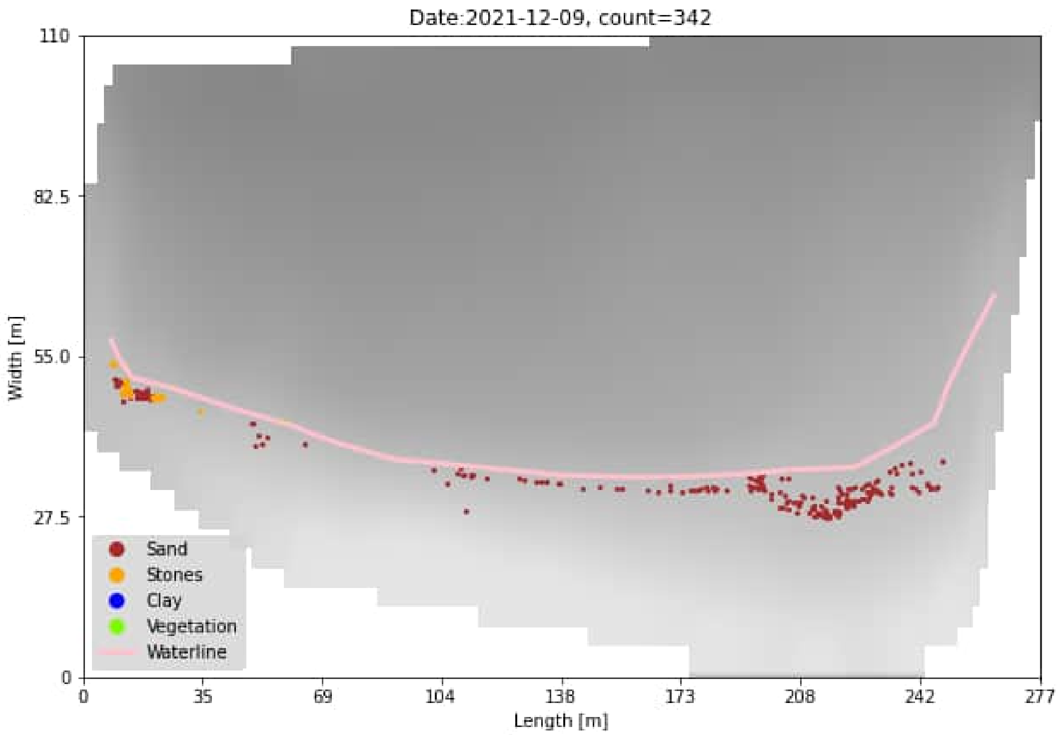
35
69
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(h)



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Width [m]
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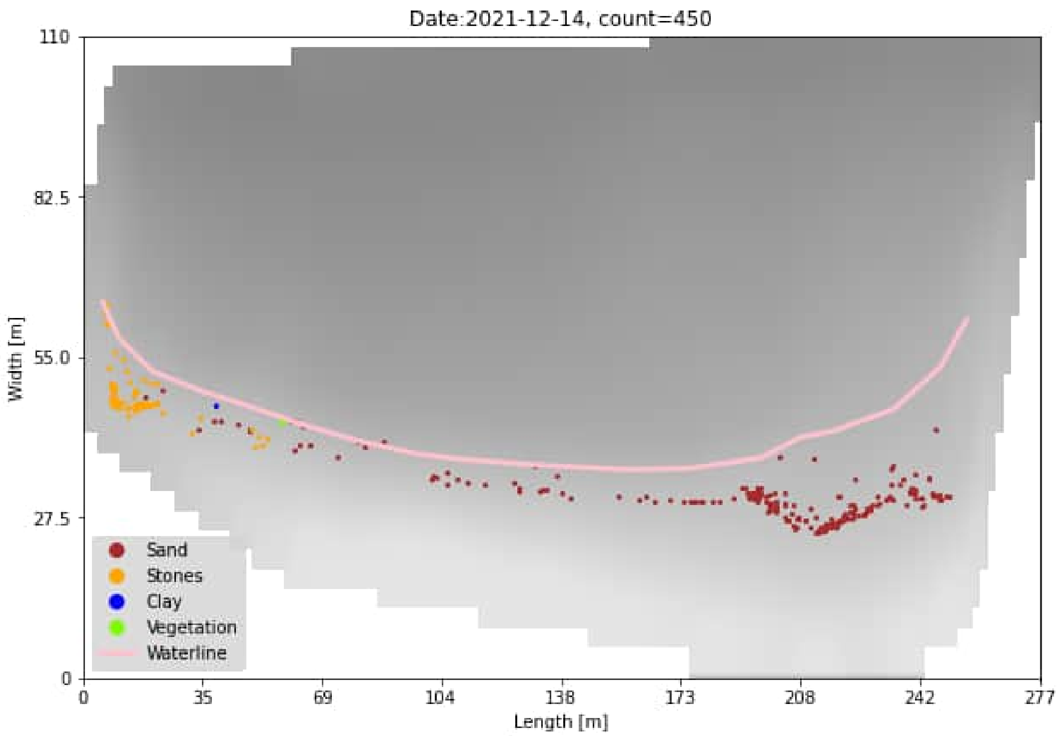
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(i)



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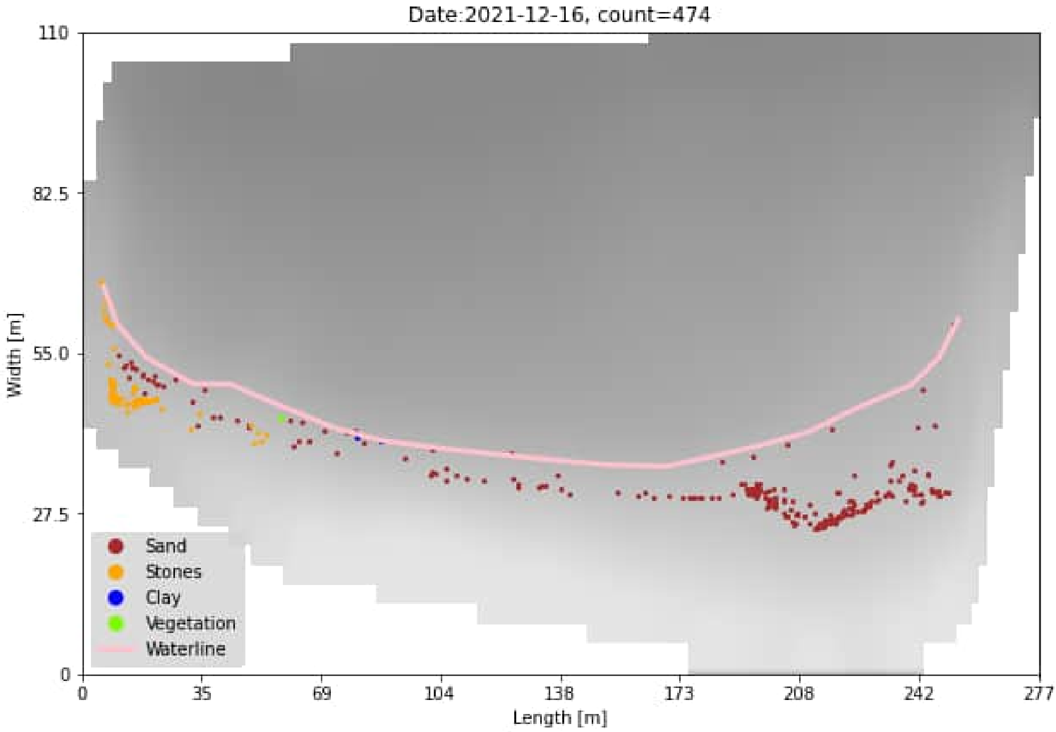
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(j)



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Width [m]
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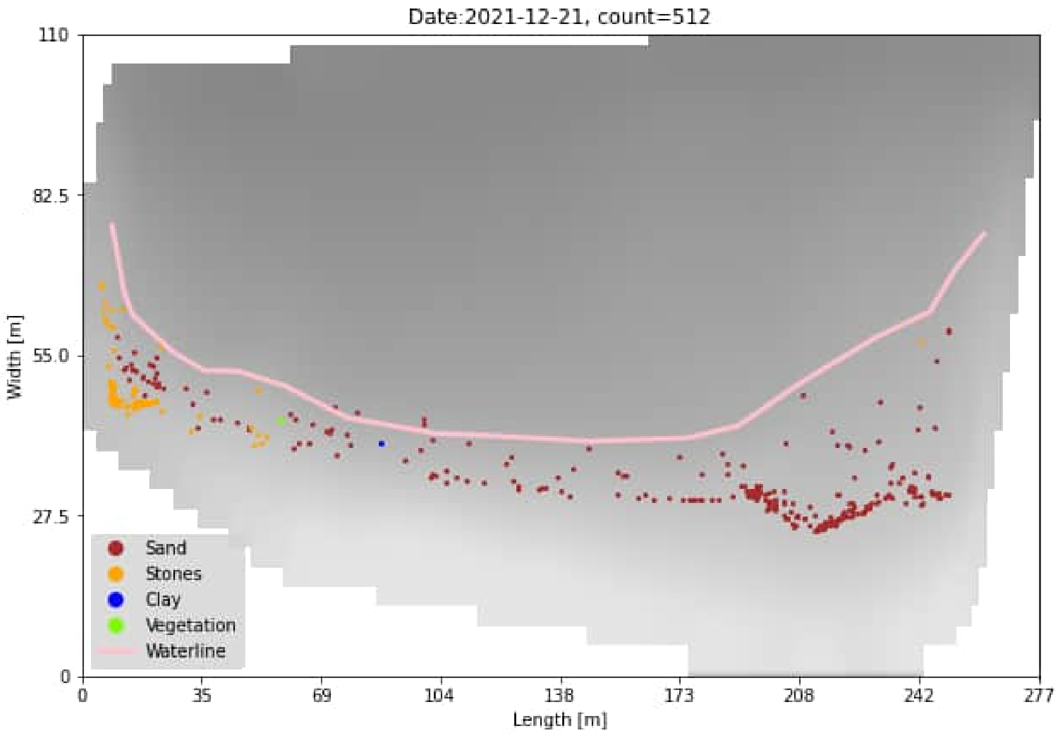
35
69
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(k)



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27.5
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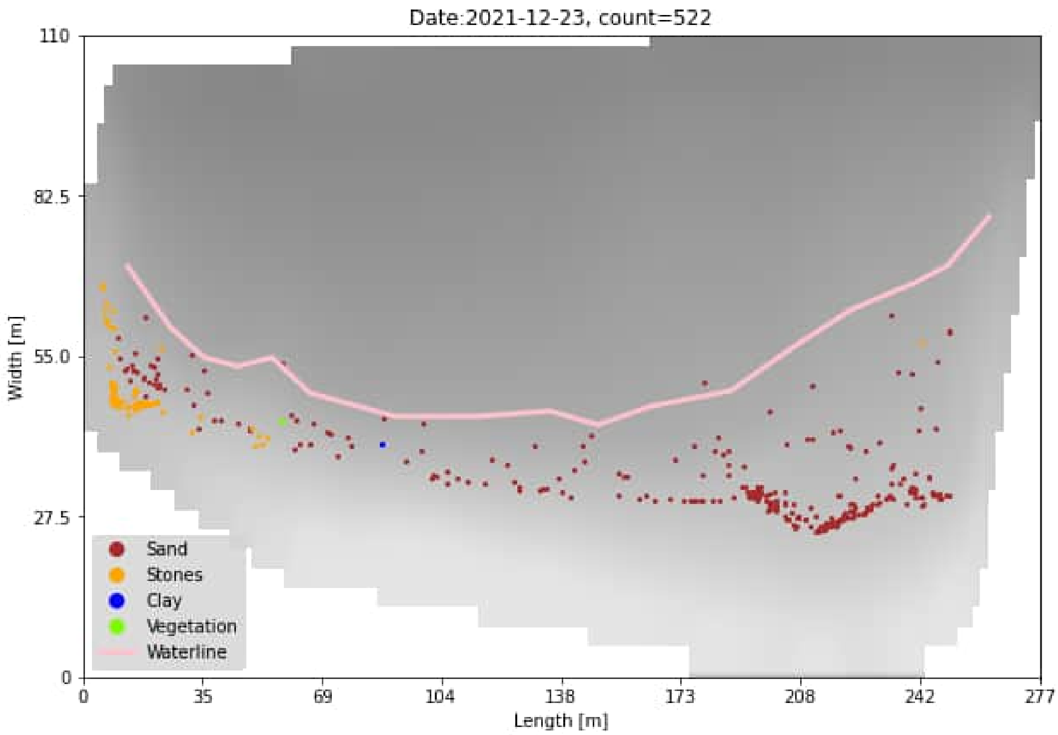
35
69
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(l)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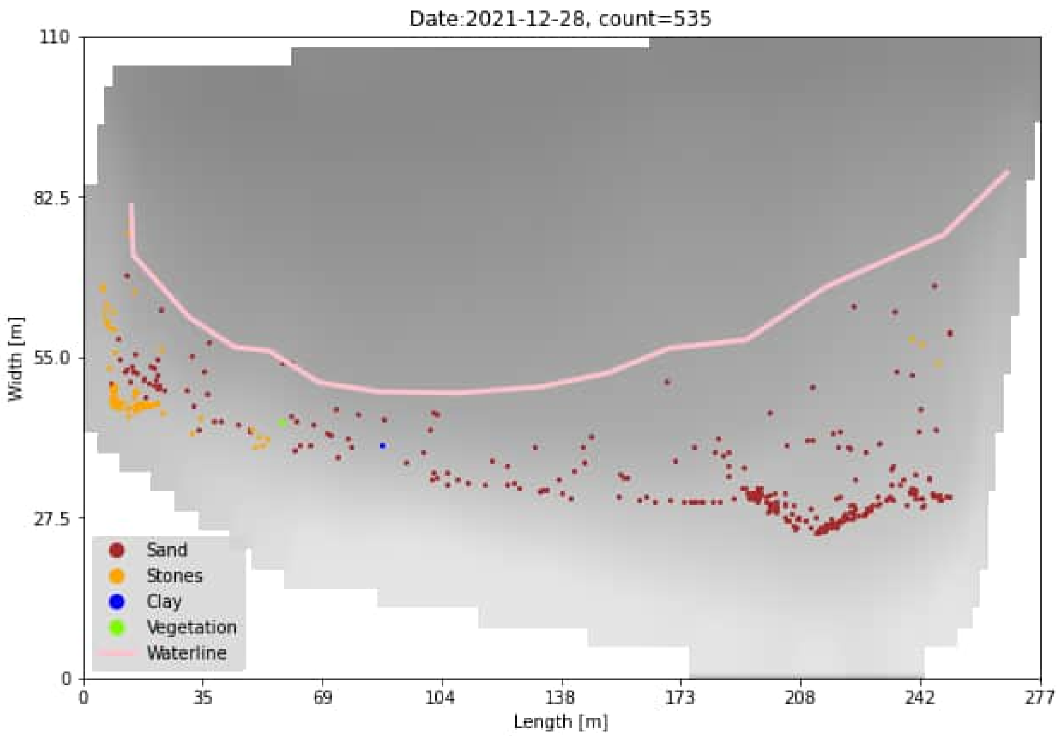
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(m)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104
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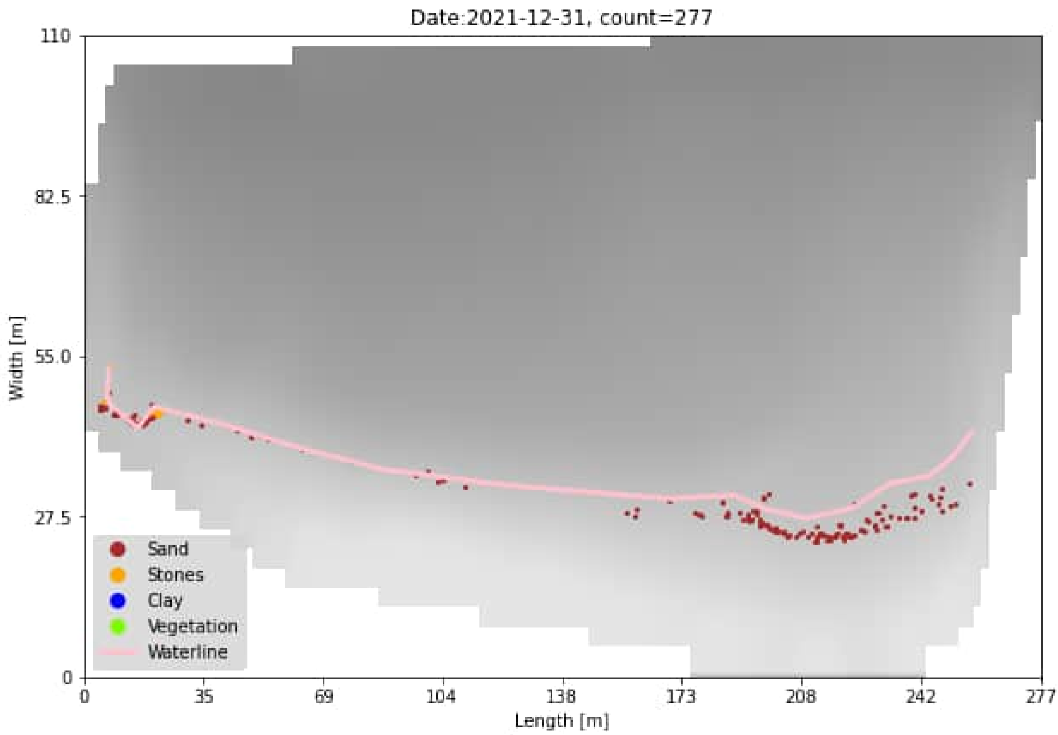
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(n)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104
138
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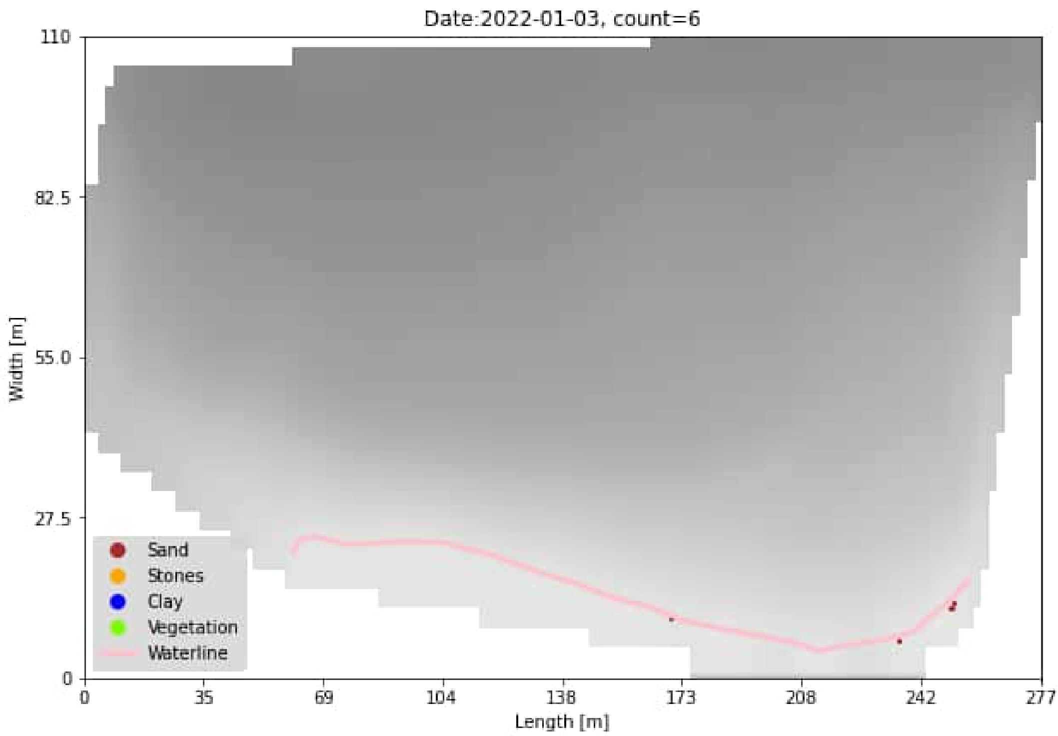
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(o)


Date:2022-01-03, count=6
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27.5
0
Width [m]
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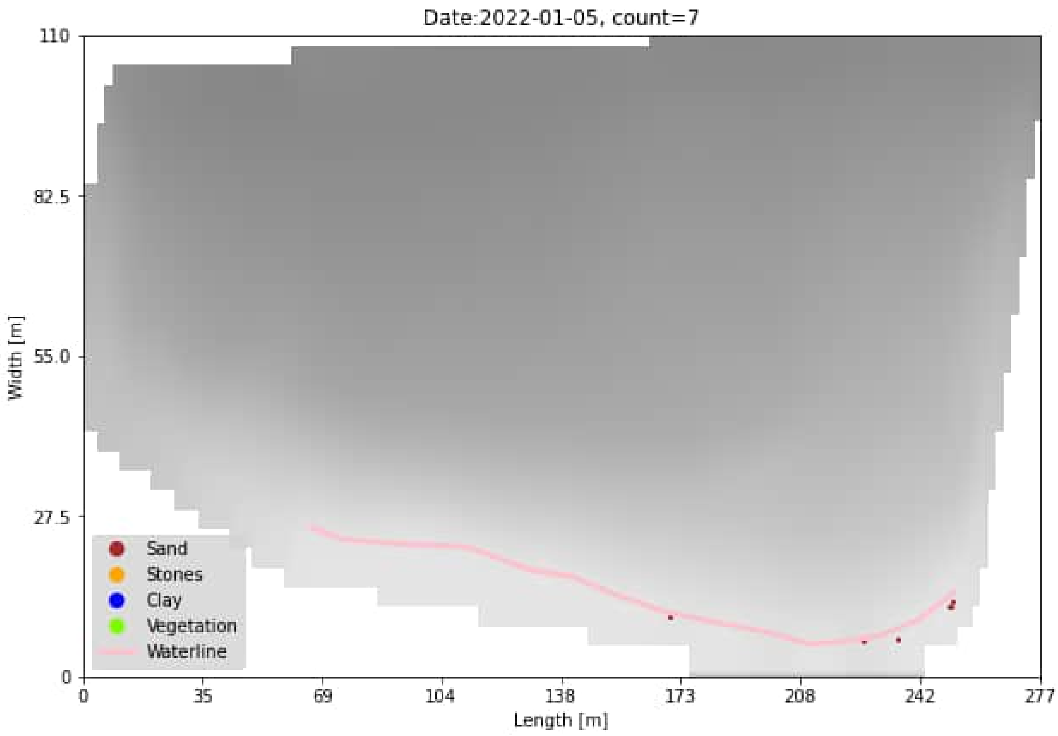
35
69
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(p)



Date:2022-01-05, count=7
110
82.5
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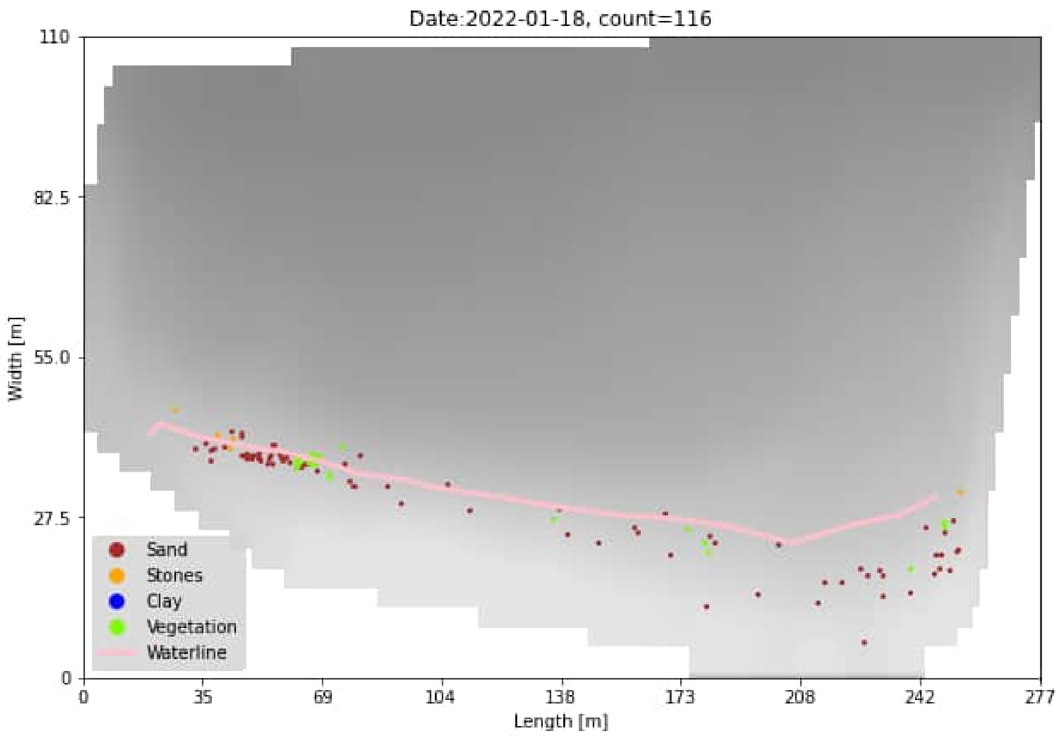
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(q)



Date:2022-01-18, count=116
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27.5
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Width [m]
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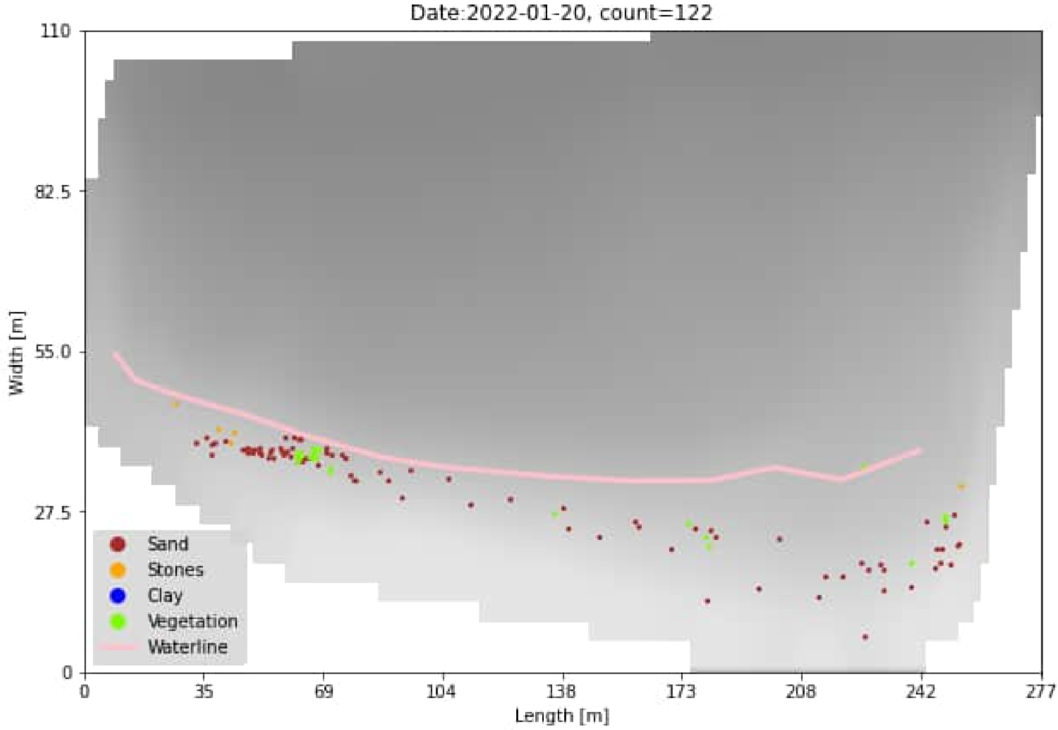
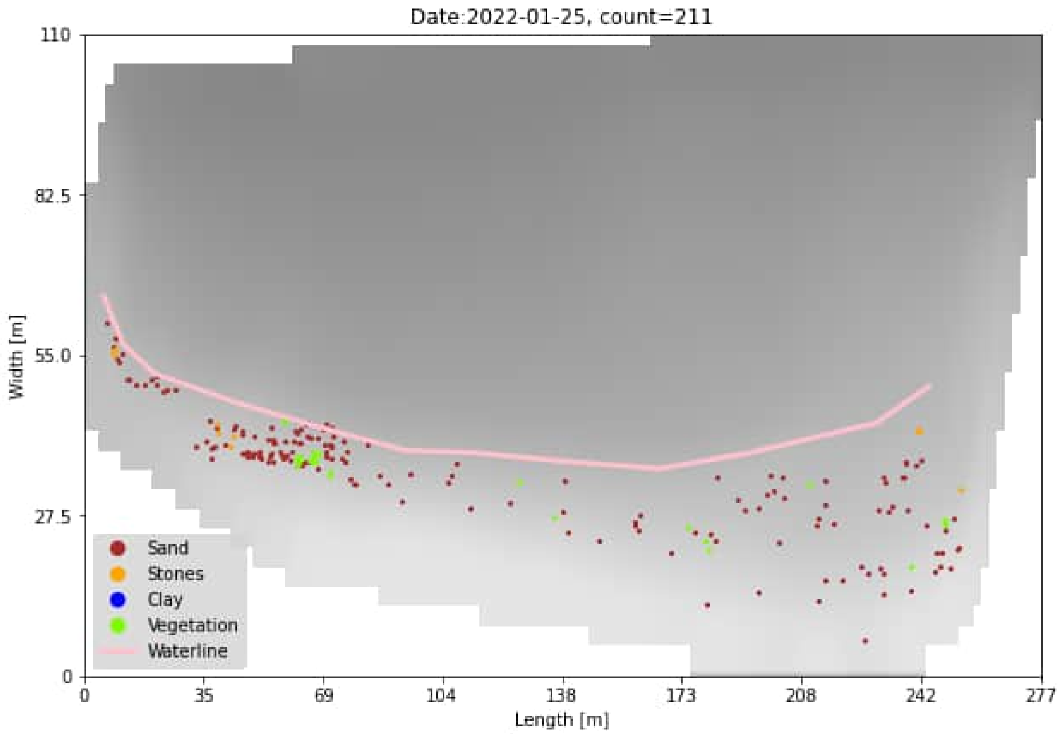
69
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(r)



Date:2022-01-20, count=122
Width [m]
Length [m]
110
82.5
55.0
27.5
0
0
35
69
104
138
173
208
242
277
Sand
Stones
Clay
Vegetation
Waterline

(s)



Date:2022-01-25, count=211
Width [m]
Length [m]
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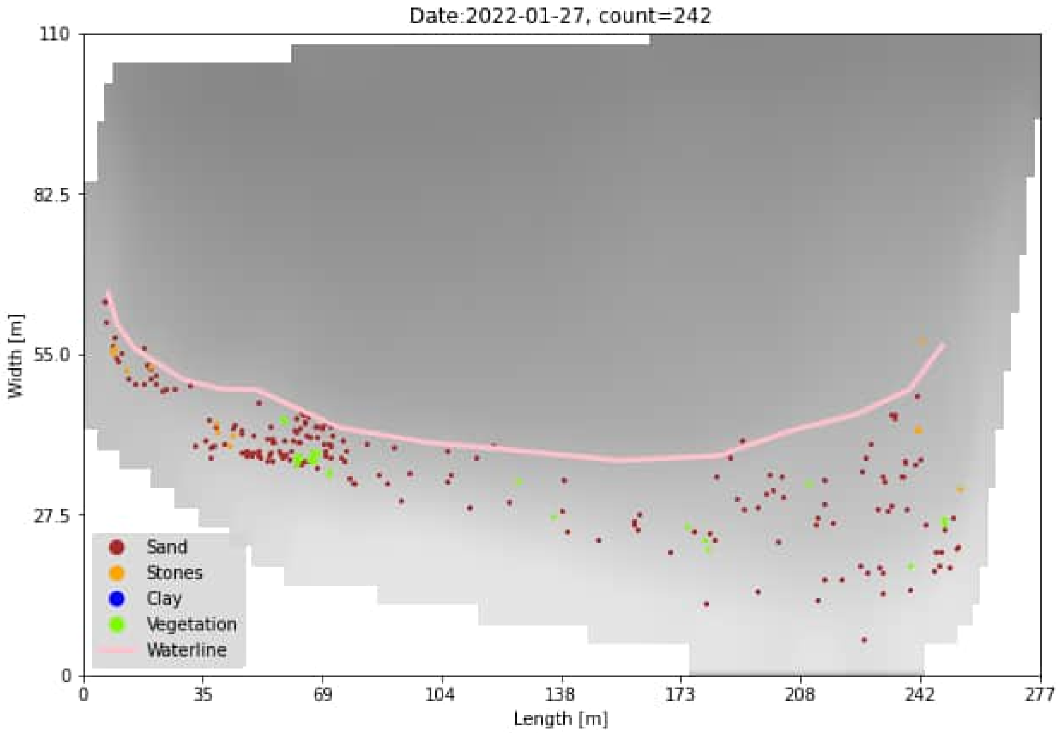
55.0
27.5
0
0
35
69
104
138
173
208
242
277
Sand
Stones
Clay
Vegetation
Waterline

(t)


Date:2022-01-27, count=242
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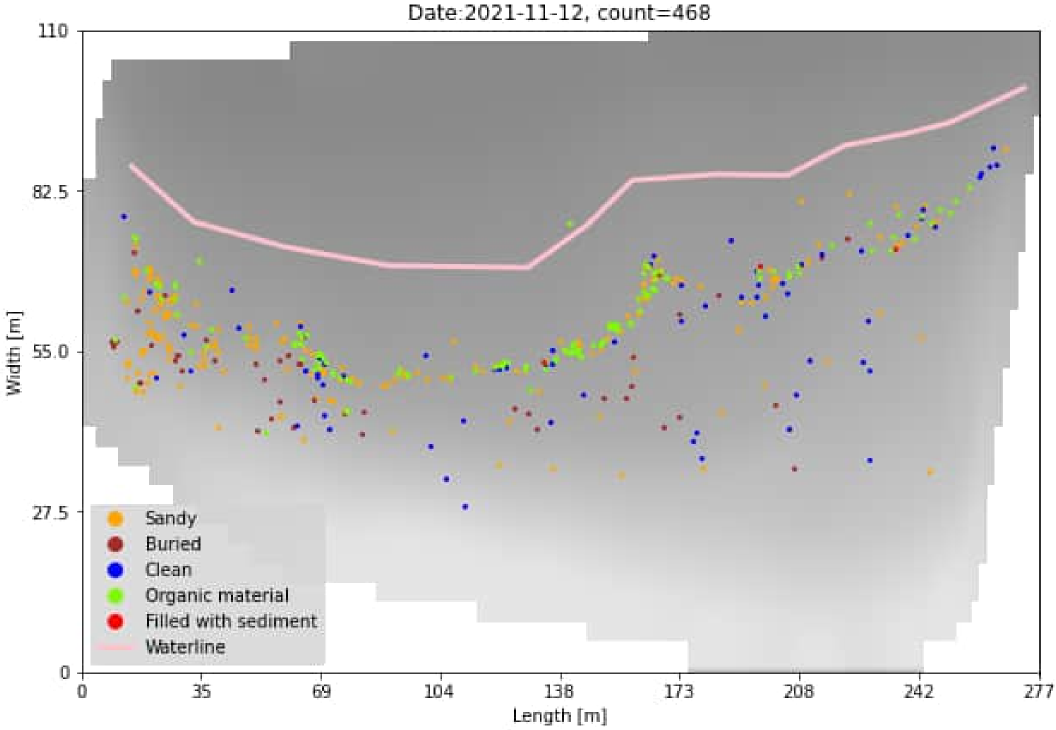
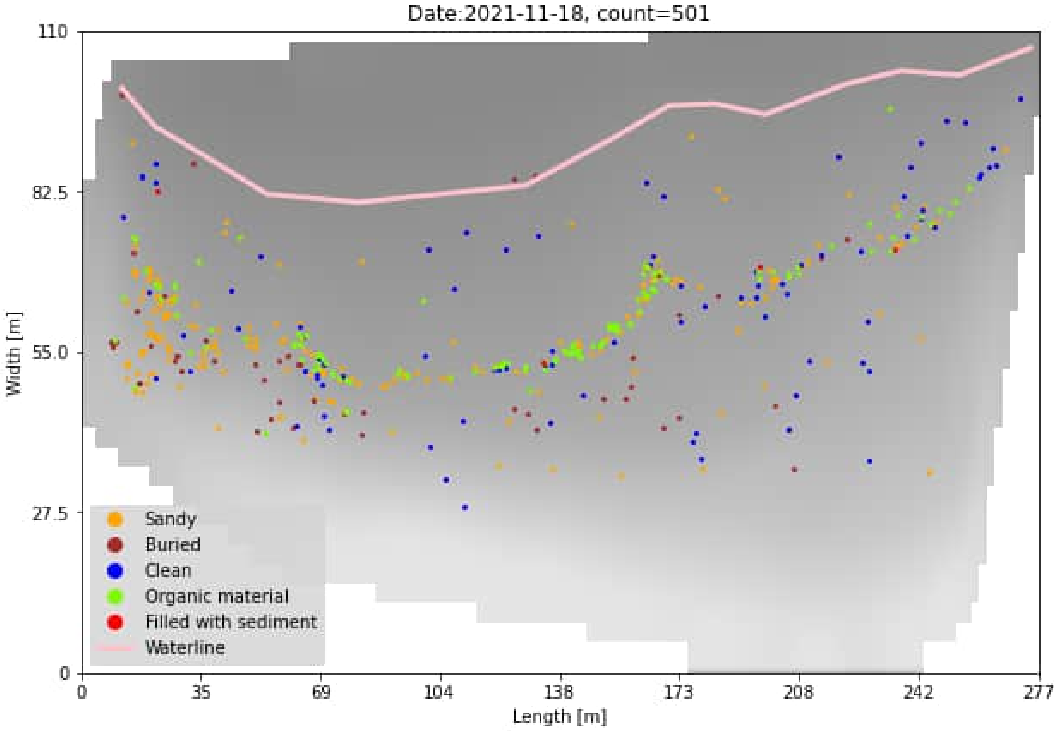
55.0
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sand
Stones
Clay
Vegetation
Waterline

(u)

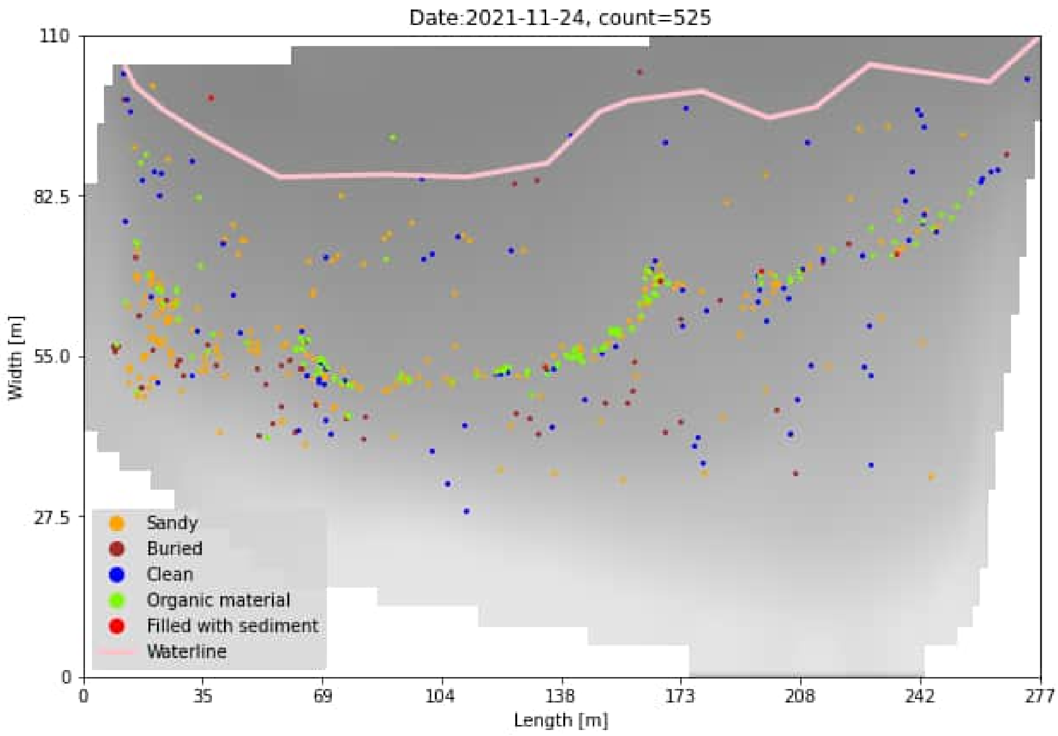
A.5. Daily surveys: item locations and position in sediment



(a)



(b)



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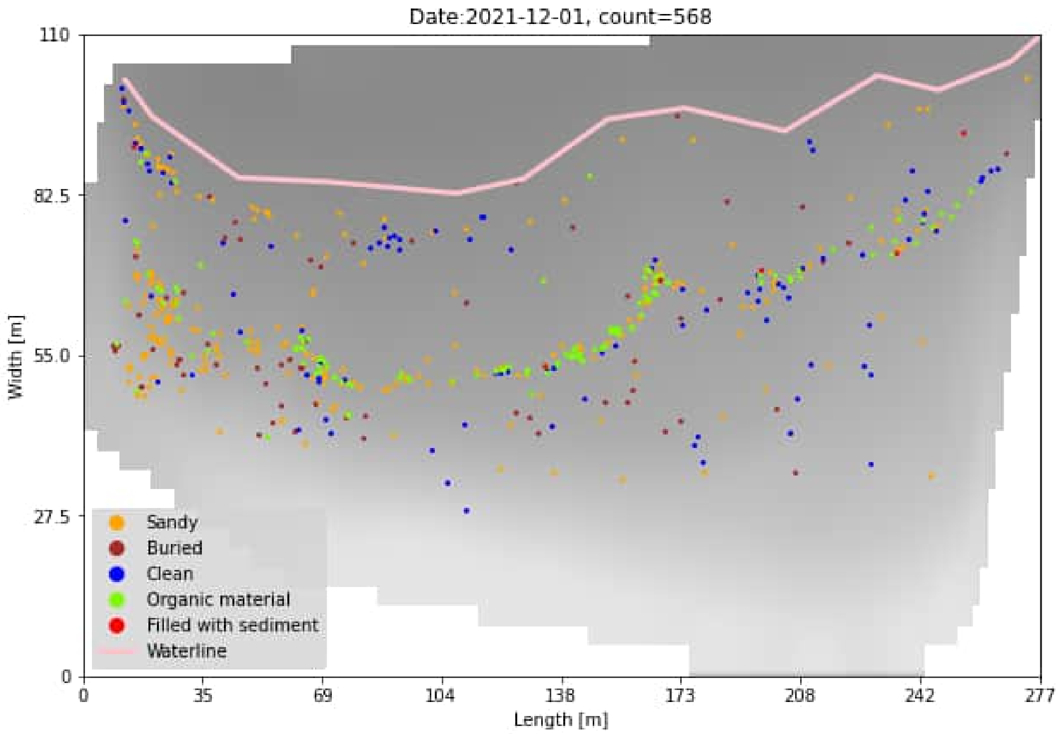
Length [m]
110
82.5
55.0
27.5
0
0
35
69
104
138
173
208
242
277
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(c)



Date:2021-12-01, count=568
Width [m]
Length [m]
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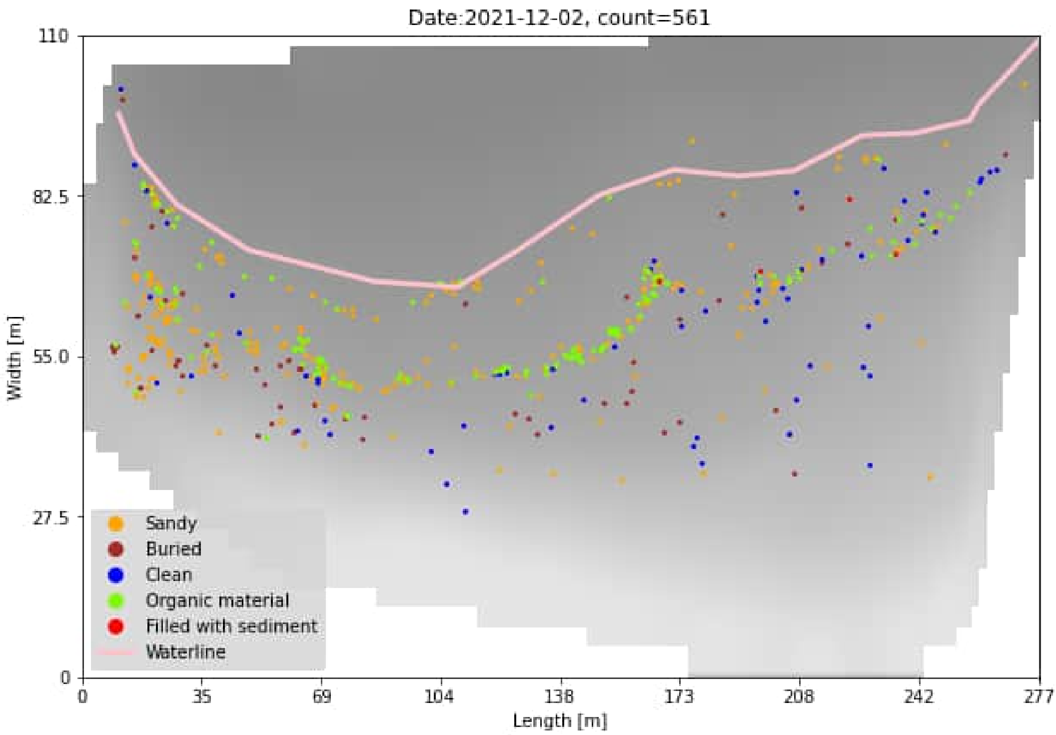
82.5
55.0
27.5
0
0
35
69
104
138
173
208
242
277
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(d)


Date:2021-12-02, count=561
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Length [m]
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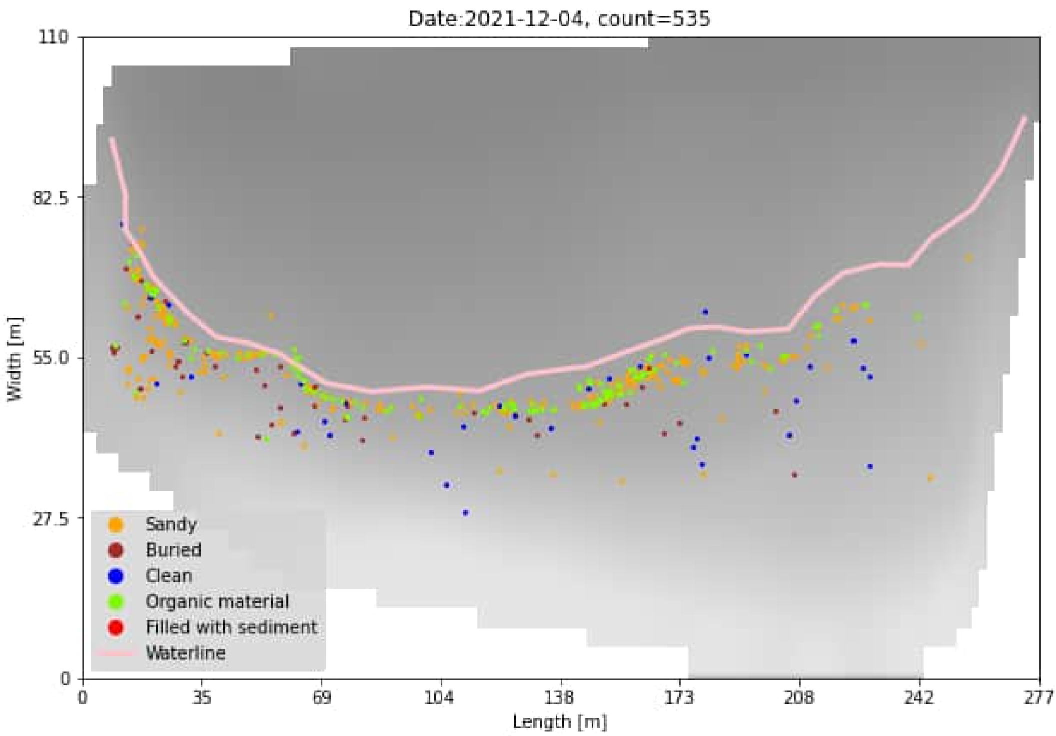
82.5
55.0
27.5
0
35
69
104
138
173
208
242
277
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(e)


Date:2021-12-04, count=535
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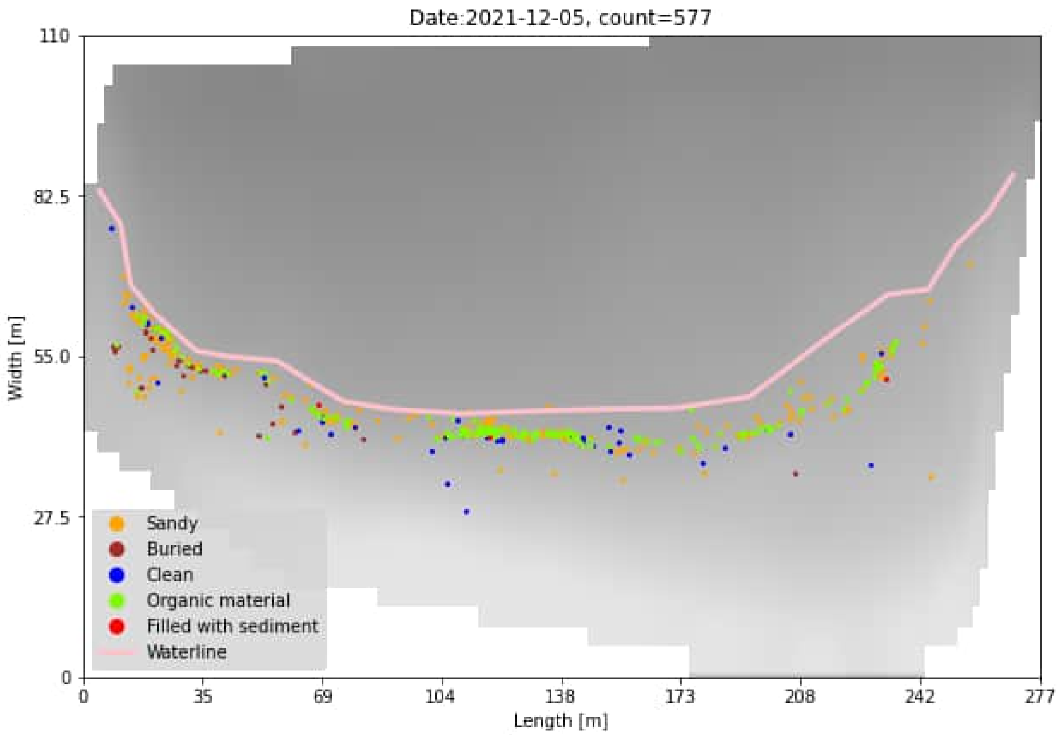
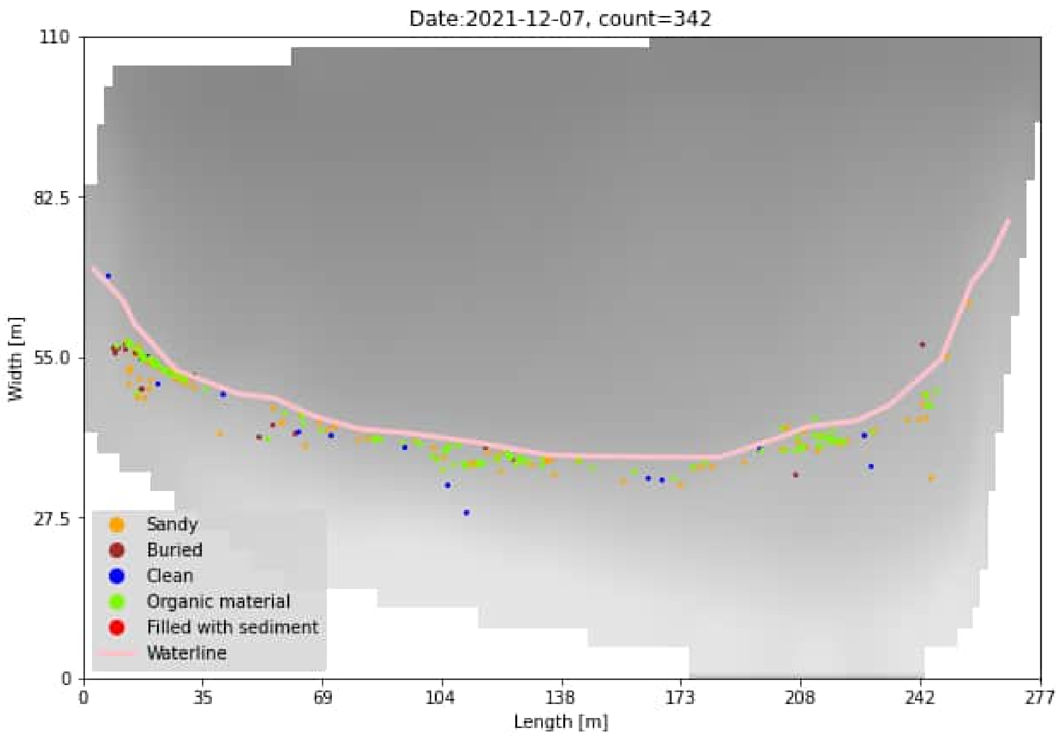
Length [m]
110
82.5
55.0
27.5
0
35
69
104
138
173
208
242
277
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

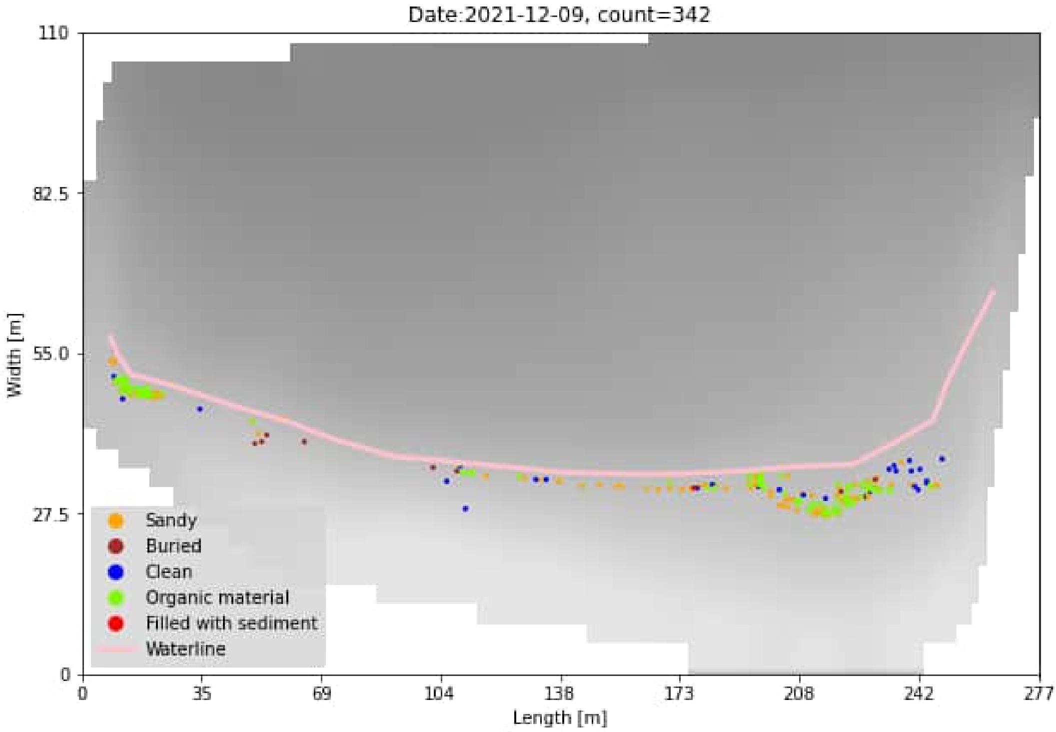
(f)


Date:2021-12-05, count=577
110
82.5
55.0
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

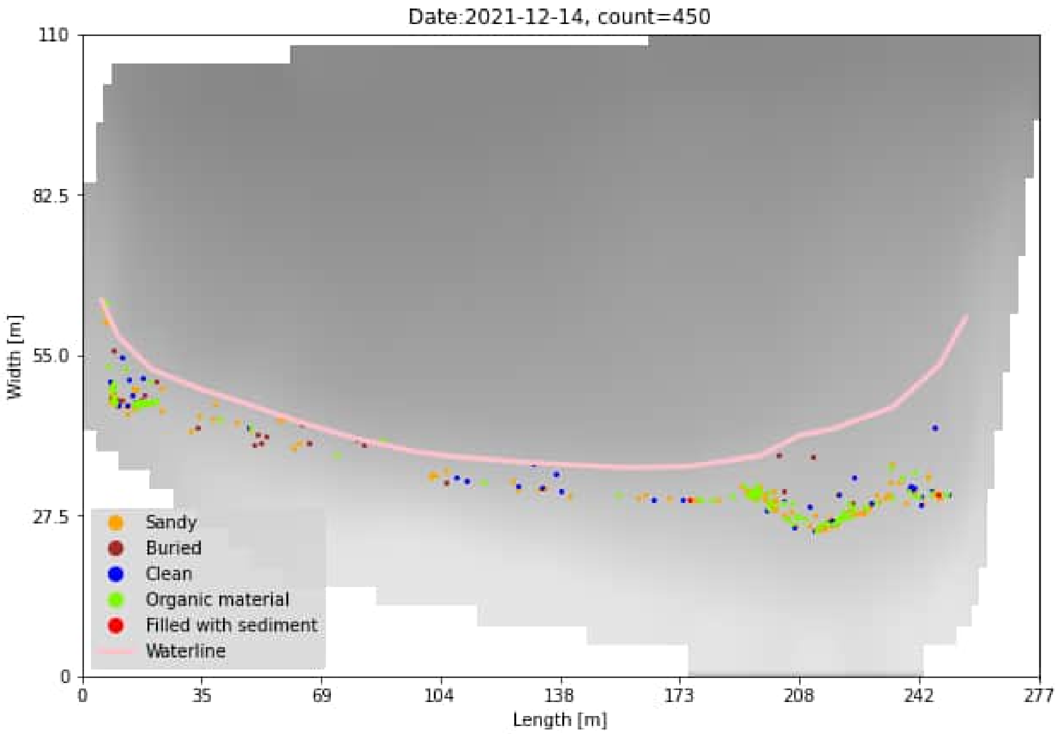
(g)


Date:2021-12-07, count=342
110
82.5
55.0
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

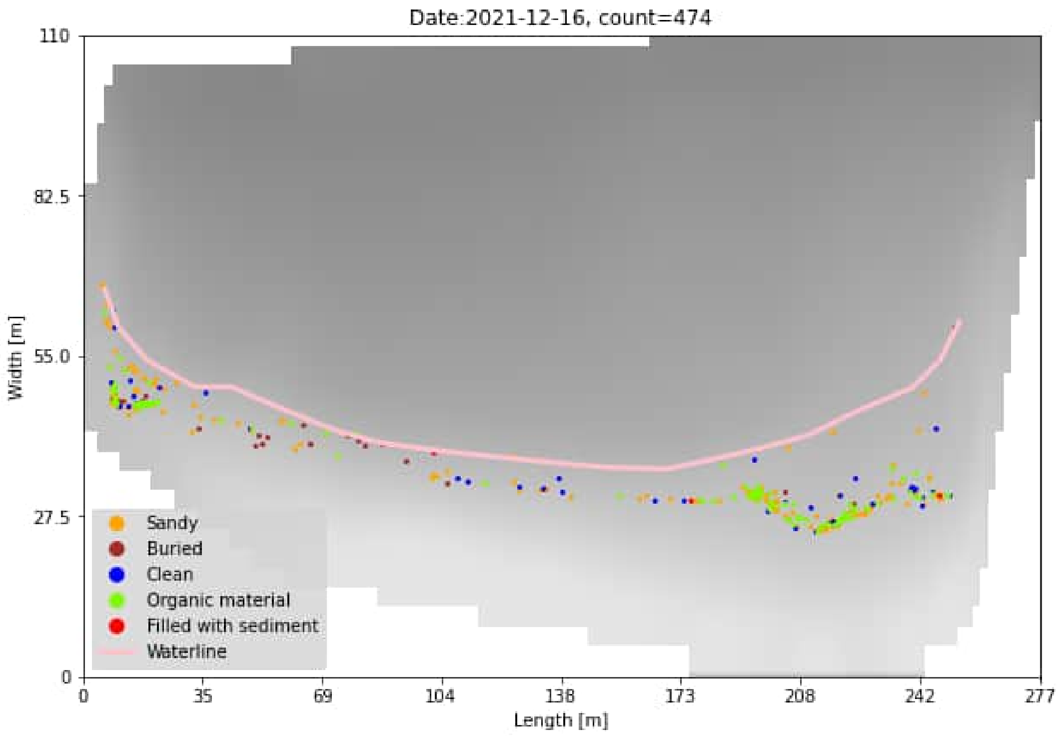
(h)


Date:2021-12-09, count=342
110
82.5
55.0
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(i)

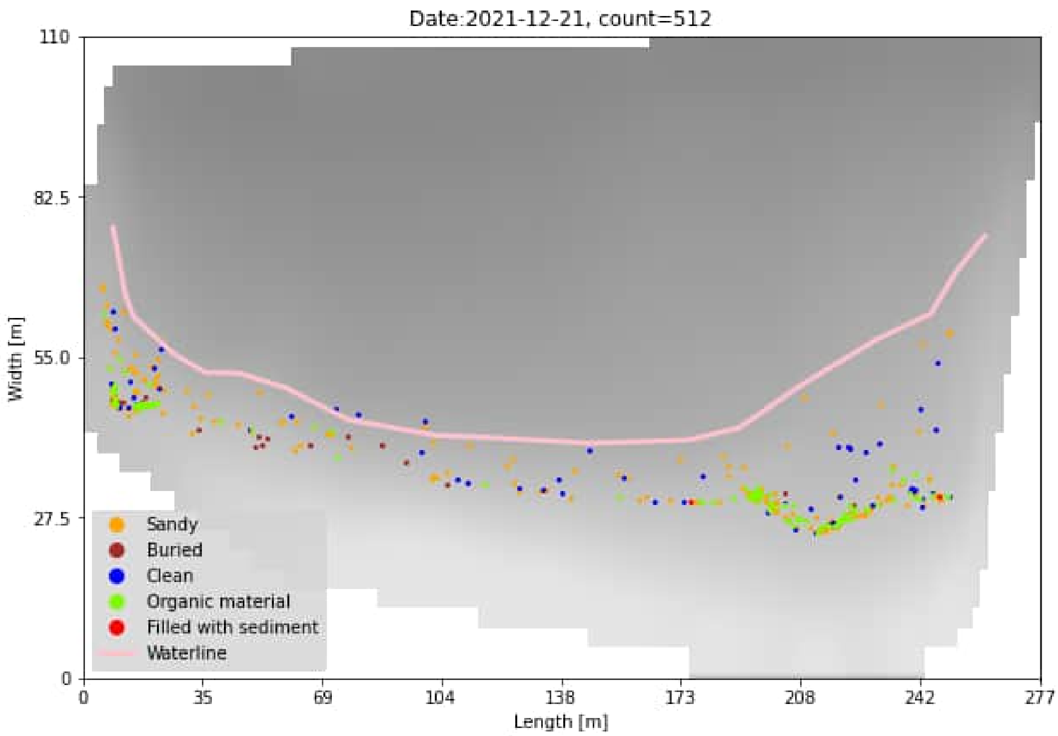

Date:2021-12-14, count=450
110
82.5
55.0
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(j)



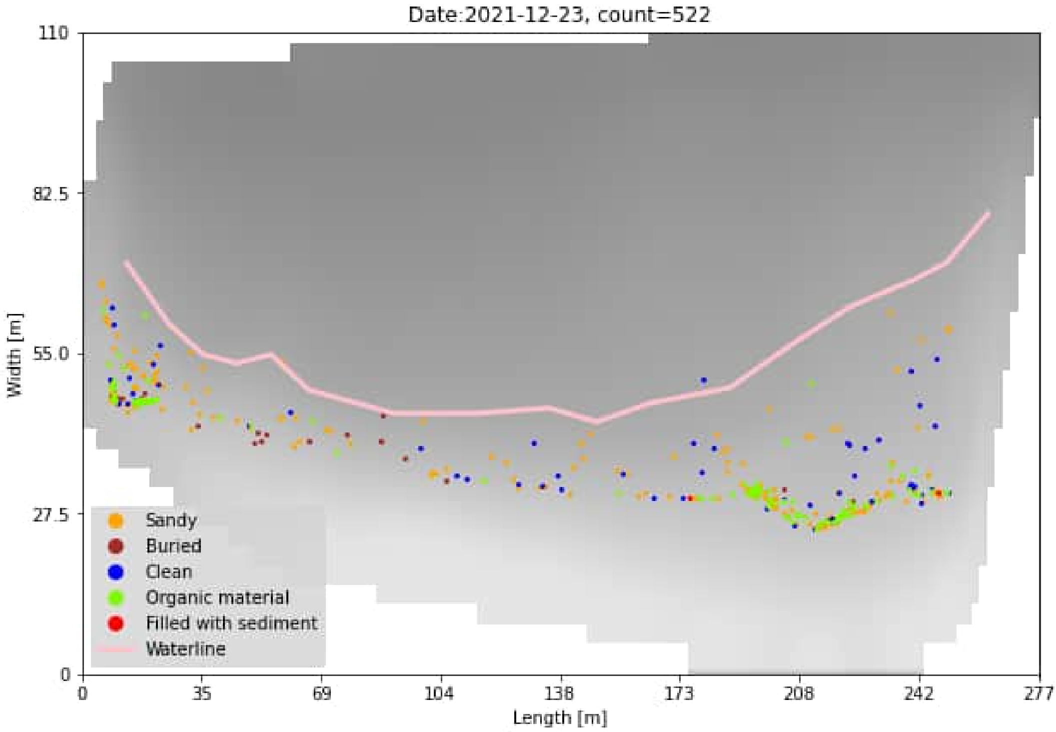
Date:2021-12-16, count=474
Width [m]
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(k)

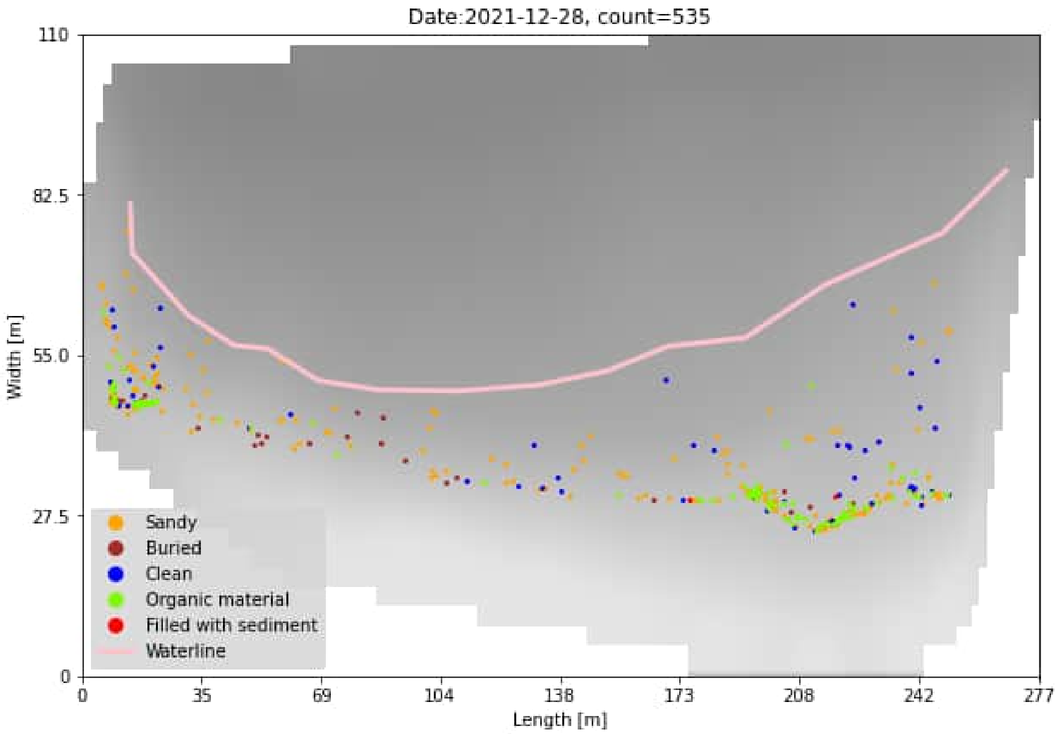


Date:2021-12-21, count=512
Width [m]
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(l)


Date:2021-12-23, count=522
Width [m]
Length [m]
110
82.5
55.0
27.5
0
0
35
69
104
138
173
208
242
277
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(m)


Date:2021-12-28, count=535
Width [m]
Length [m]
110
82.5
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27.5
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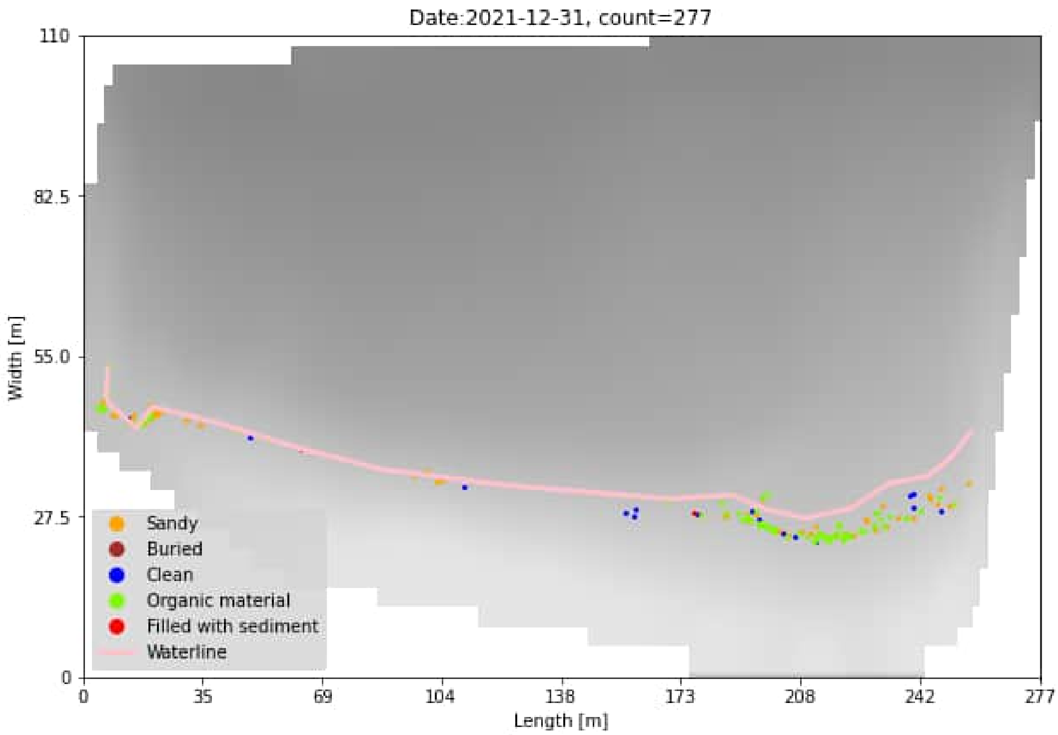
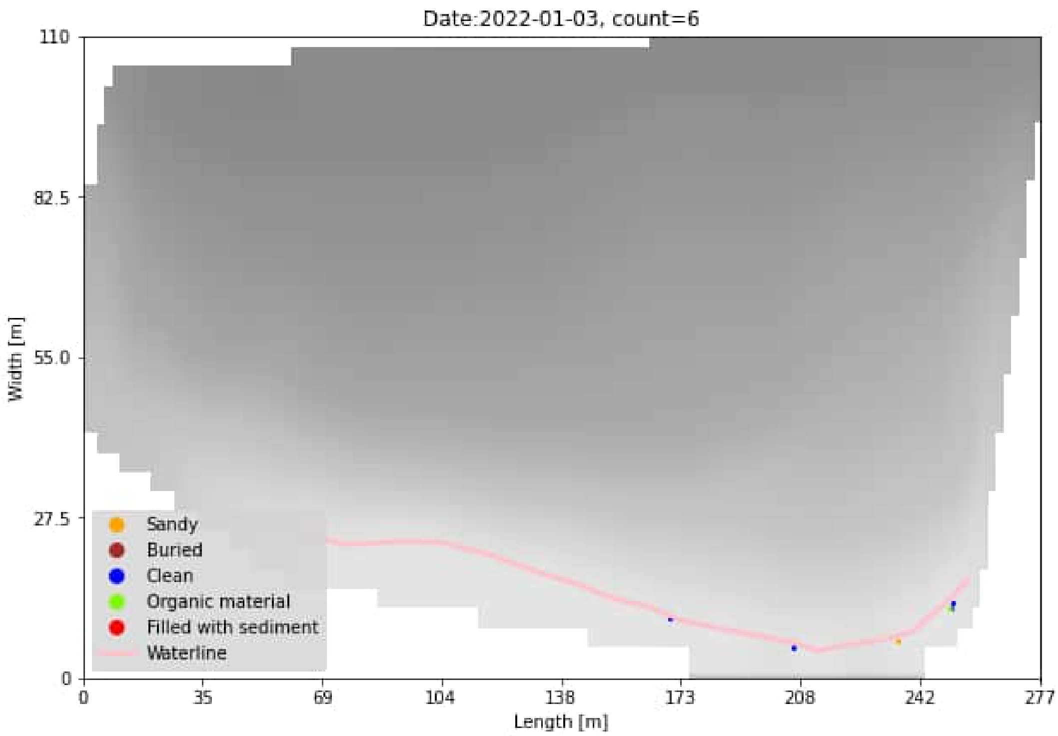
0
35
69
104
138
173
208
242
277
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(n)



Date:2021-12-31, count=277
110
82.5
55.0
27.5
0
Width [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline
0
35
69
104
138
173
208
242
277
Length [m]

(o)



Date:2022-01-03, count=6
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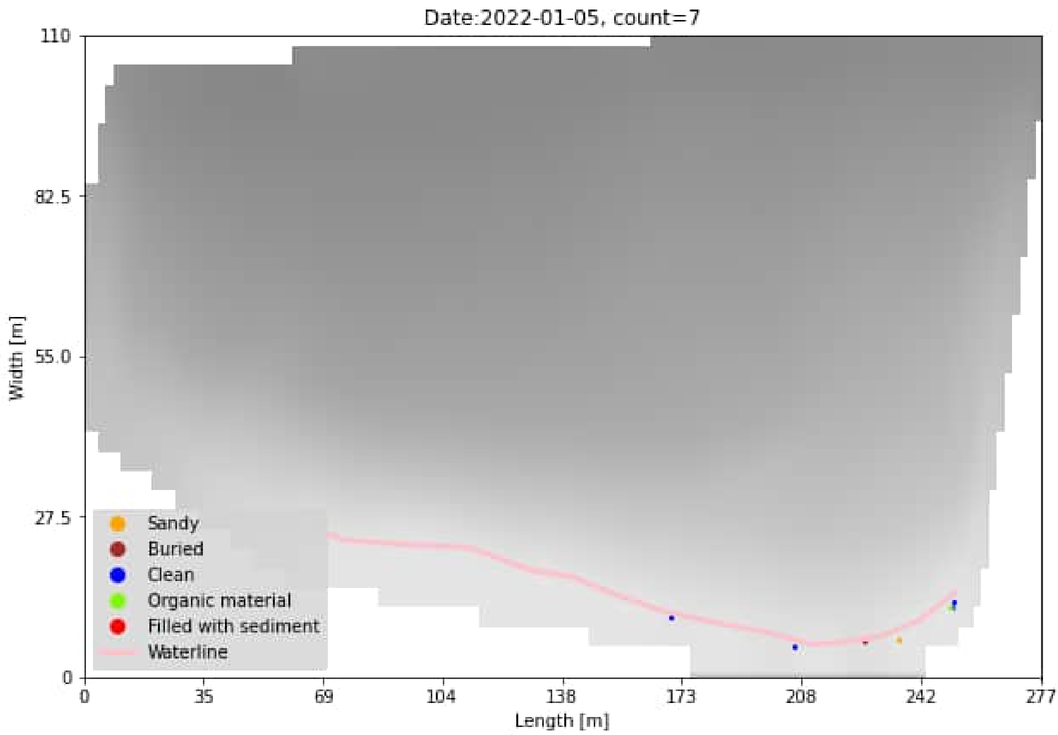
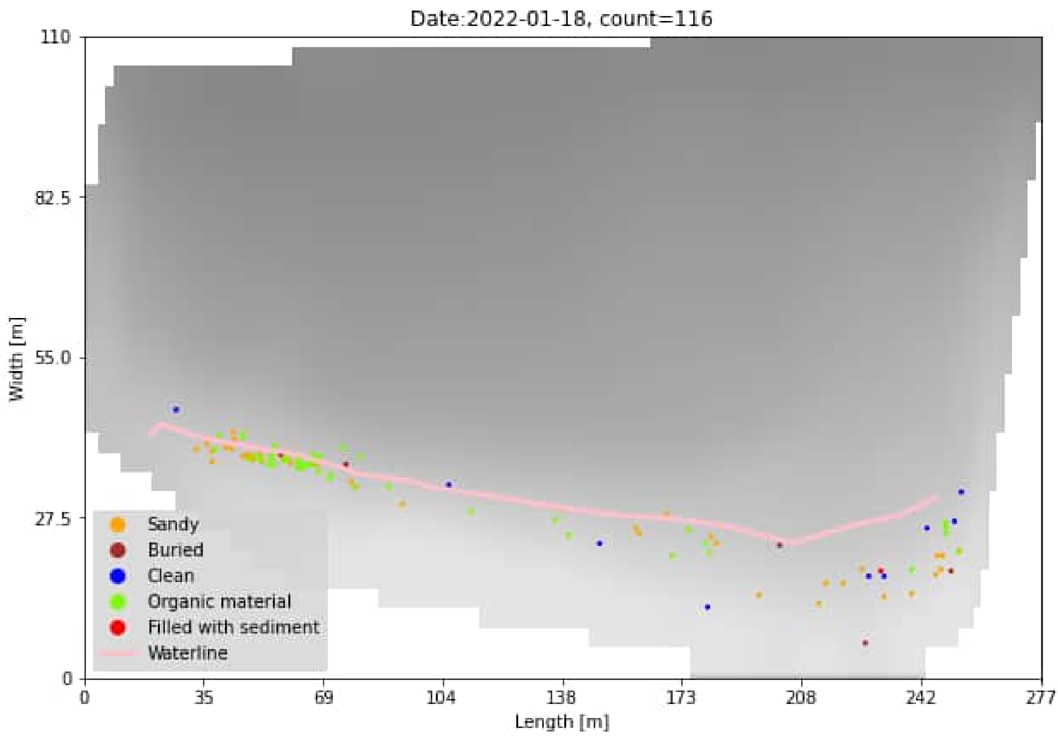
82.5
55.0
27.5
0
Width [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline
0
35
69
104
138
173
208
242
277
Length [m]

(p)



Date:2022-01-05, count=7
110
82.5
55.0
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(q)



Date:2022-01-18, count=116
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55.0
27.5
0
Width [m]
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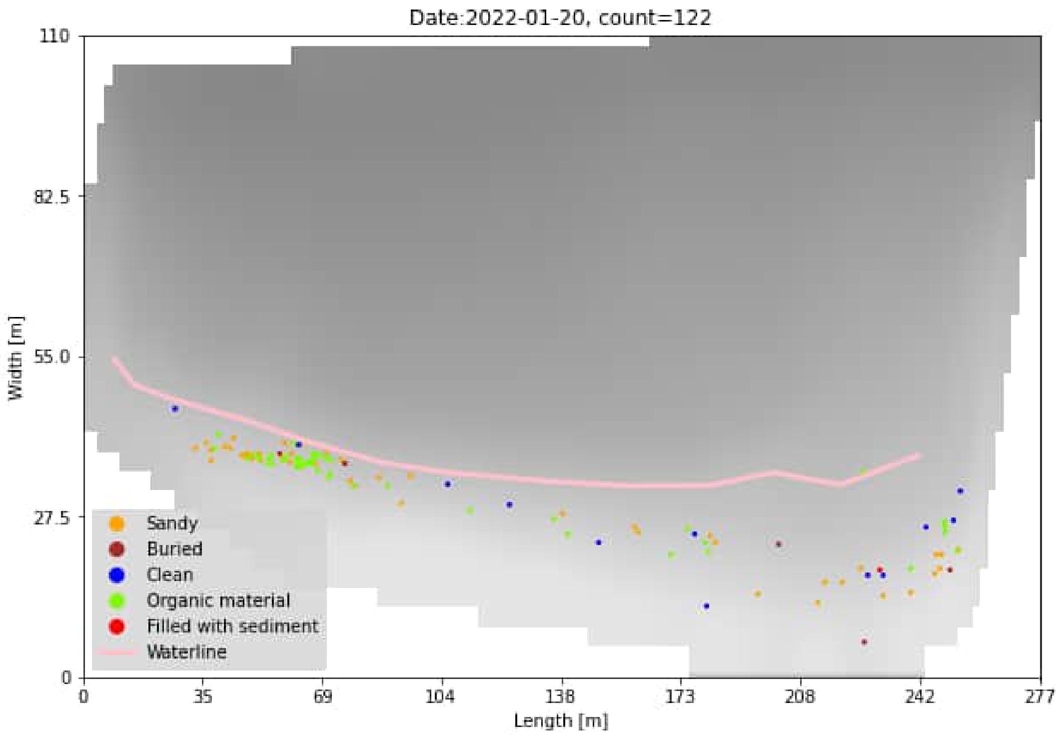
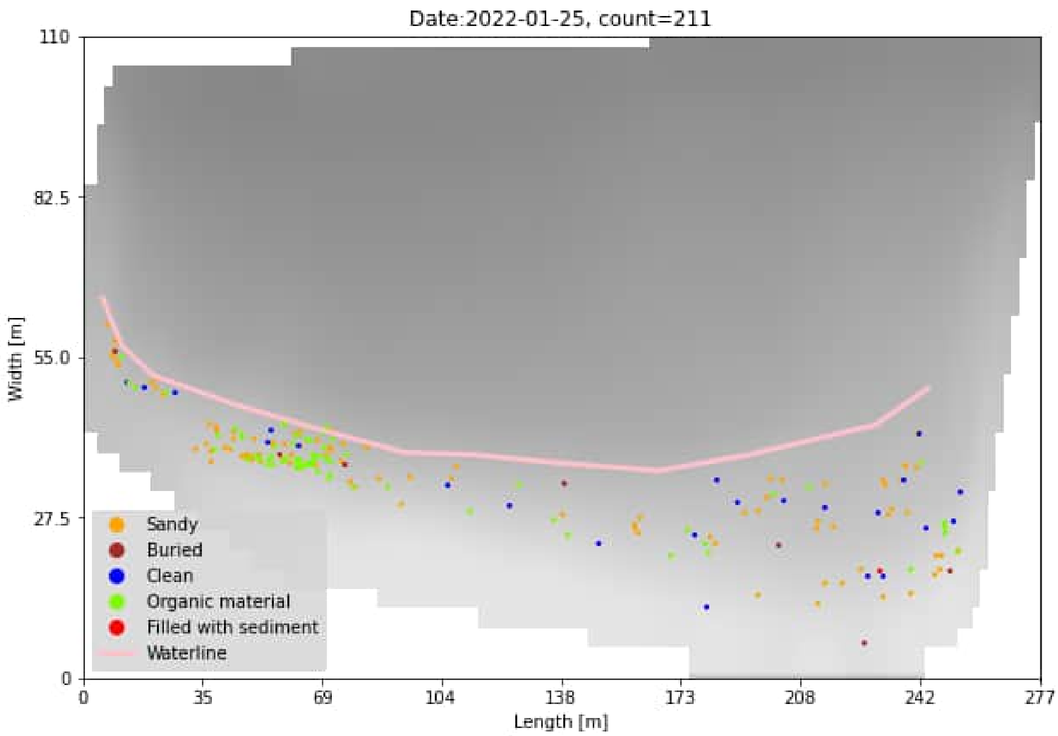
35
69
104
138
173
208
242
277
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

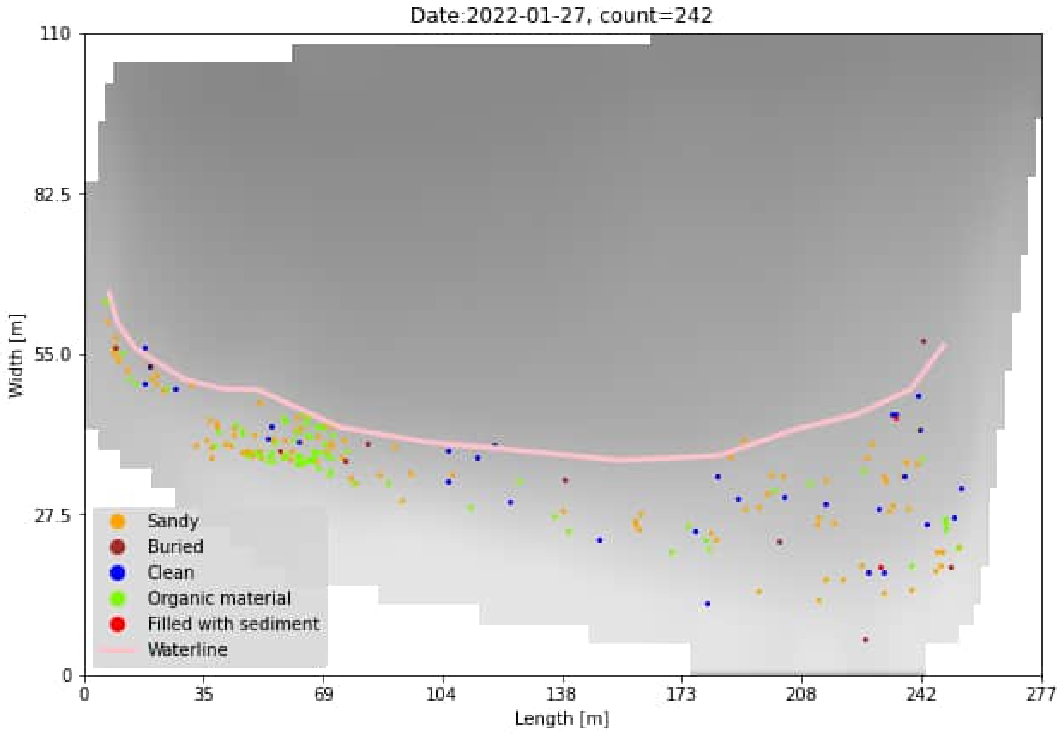
(r)


Date:2022-01-20, count=122
Width [m]
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline
110
82.5
55.0
27.5
0
0
35
69
104
138
173
208
242
277

(s)


Date:2022-01-25, count=211
Width [m]
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline
110
82.5
55.0
27.5
0
0
35
69
104
138
173
208
242
277

(t)


Date:2022-01-27, count=242
110
82.5
55.0
27.5
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Sandy
Buried
Clean
Organic material
Filled with sediment
Waterline

(u)

A.6. Tracked Items


(1) Aluminum wad


(2) Small PET bag


(3) Black cap


(4) Blue fishing rod


(5) Blue fork


(6) Blue cap


(7) Bottle (transparant)


(8) Fragment of bottle 2


(9) Bottle (brown plastic)


(10) Bubbleplastic


(11) Candybar wrapper


(12) Bottle (cleaner)


(13) Coffeemilk


(14) Bottle (cola)


(15) Crushed cup


(16) Cupping glass


(17) Sponge (dark)


(18) Bottle (dent)


(19) Face mask 1


(20) Face mask 2


(21) Foam (holed)


(22) Folded glove


(23) Food wrapper


(24) Freezer bag


(25) Geotextile 1


(26) Geotextile 2


(27) Small shoe


(28) Bottle head


(29) Bottle (green, small)


(30) Green table cloth


(31) Plastic hand grip


(32) Black plastic


(33) Hose


(34) Large strap


(35) Yoghurt package (large)


(36) Milk carton


(37) Fragment of bottle


(38) Beer crate fragment


(39) Leather piece


(40) Table top


(41) Plastic lunch bag


(42) Bottle (red cap)


(43) Bottle (red ring)


(44) Red sock


(45) Red table cloth


(46) Bottle (ripped)


(47) Bottle (ripped 2)


(48) Rubber glove


(49) Rusty scrap


(50) Sponge (round)


(51) Meal packaging


(52) Sandpaper


(53) Beer scrap


(54) Shower curtain


(55) Sponge (small clump)


(56) Bottle (small)


(57) Spinach bag


(58) Sponge (large clump)


(59) Bottle (small 2)


(60) Yoghurt package (small)


(61) Sponge (square)


(62) Sweater


(63) Thin white strap


(64) Toothpaste


(65) Piece of cola can


(66) Tube


(67) Piece of leather 2


(68) White cup


(69) White fork


(70) Bottle (white ring)


(71) White shopping bag


(72) Bottle head (wine)


(73) Wire


(74) Working glove


(75) Yellow foil plastic


(76) Piece of leather 3


(77) Razor


(78) Pill container


(79) Small plastic fragment


(80) Small piece

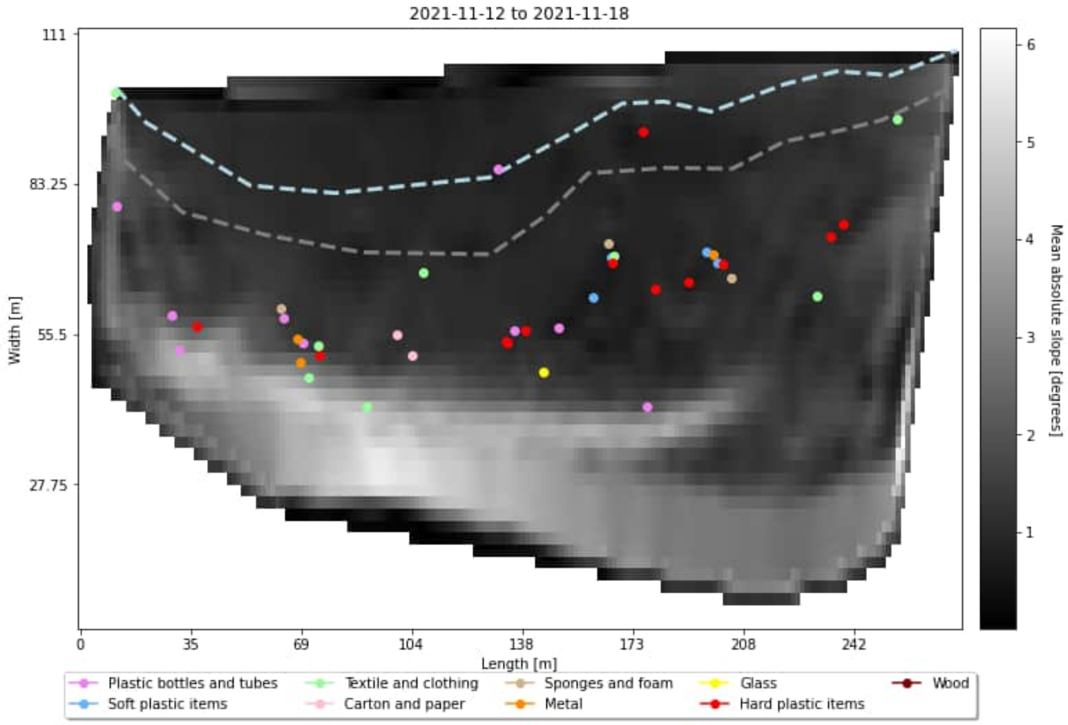

(81) Bottle head (beer)


(82) Metal cord


(83) Bottle (olive oil)

Figure A.6: Tagged item locations during and after the first discharge peak

A.7. Tracked item pathways



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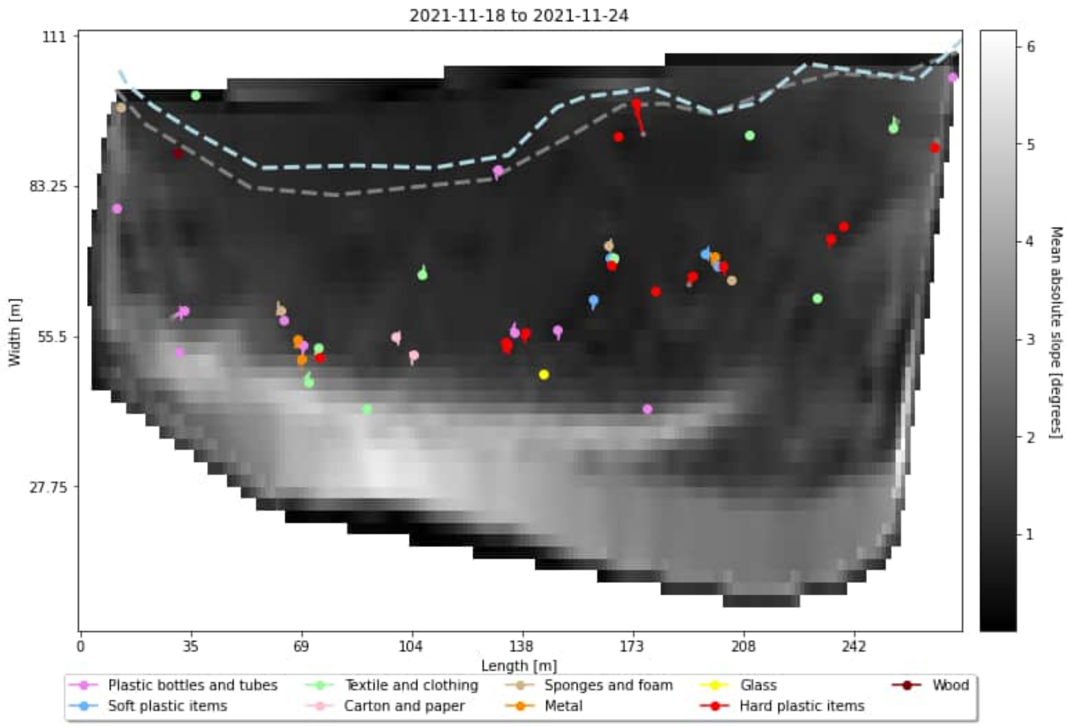
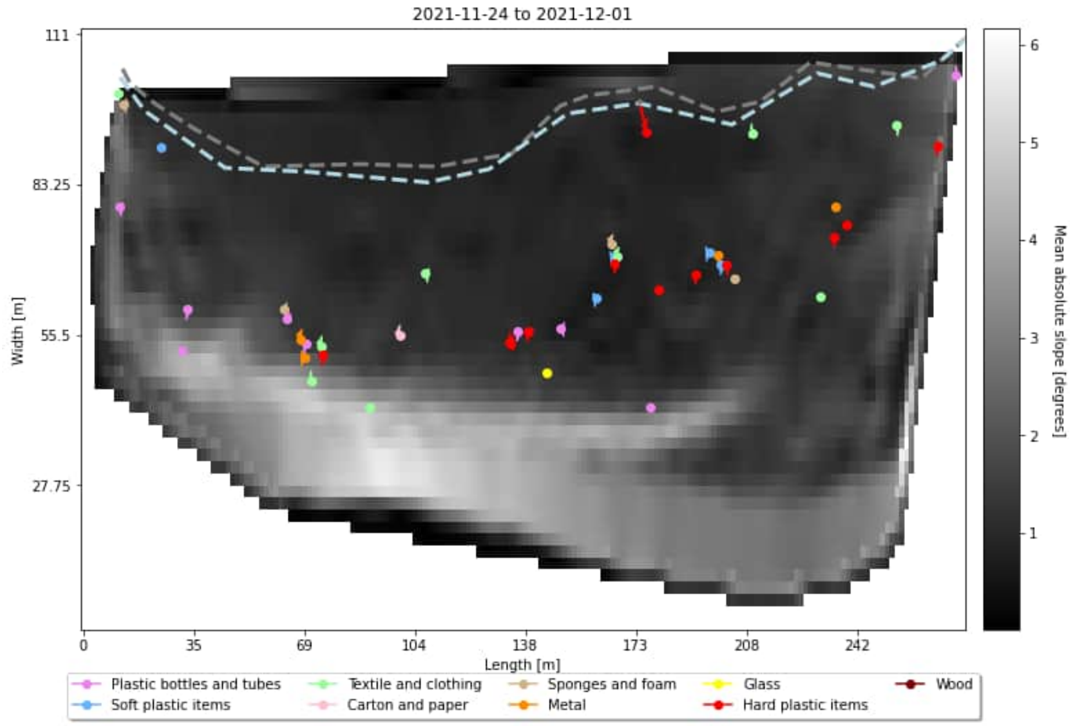
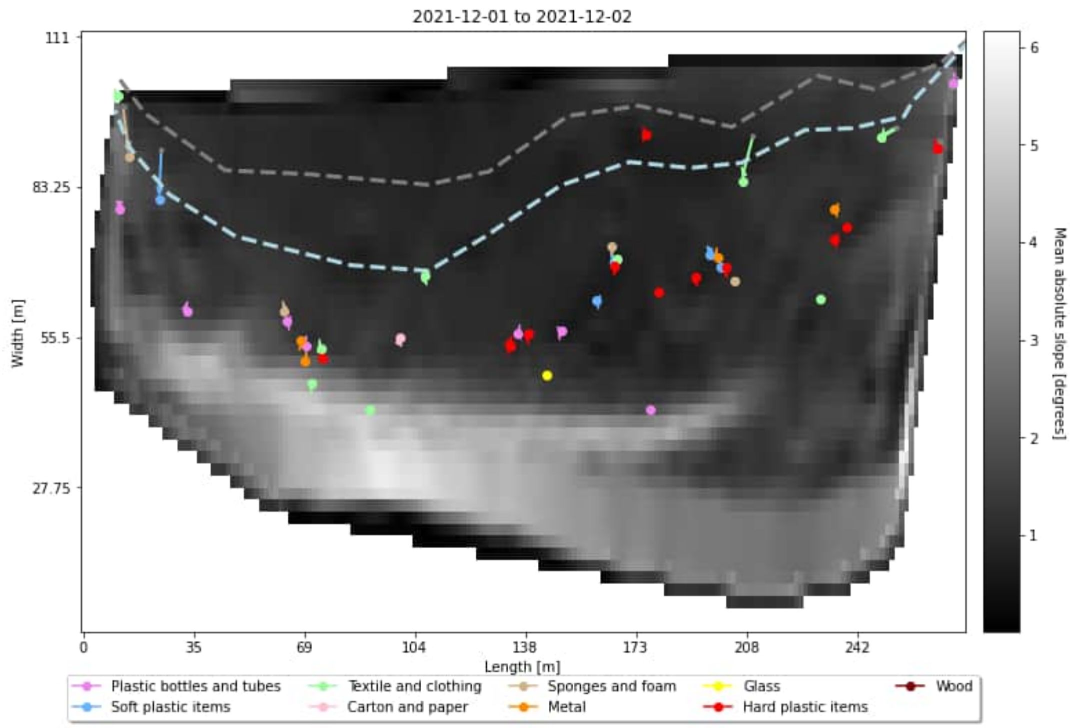


(2)


2021-11-24 to 2021-12-01
111
83.25
55.5
27.75
Width [m]
0
35
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
6
5
4
3
2
1
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(3)


2021-12-01 to 2021-12-02
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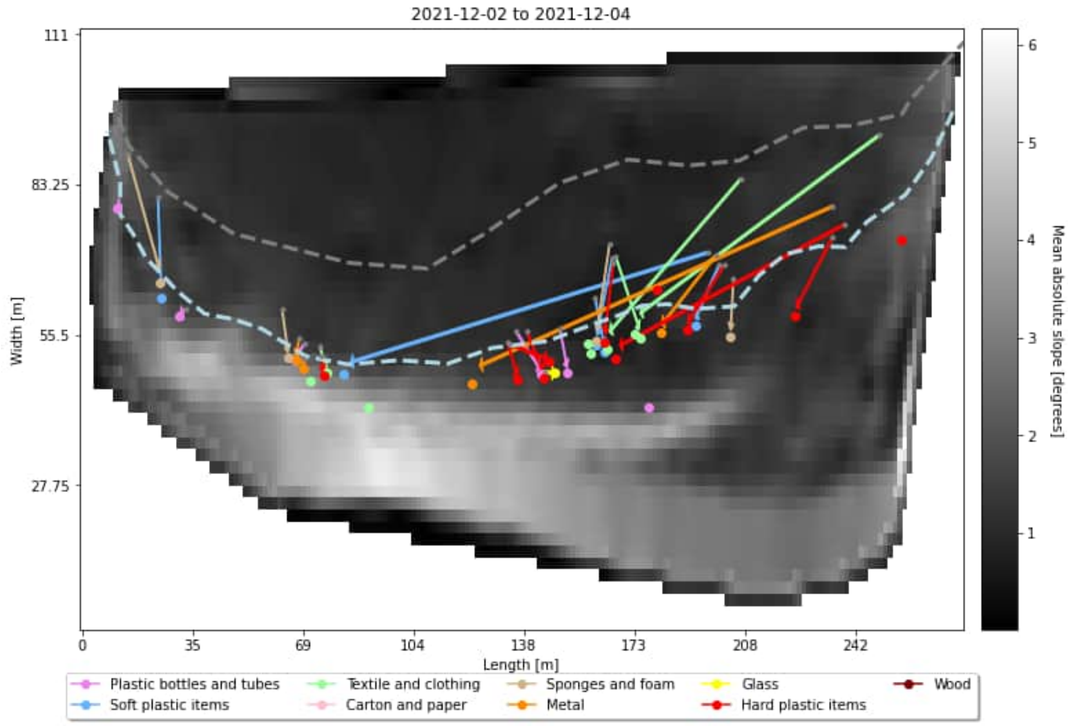
83.25
55.5
27.75
Width [m]
0
35
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
6
5
4
3
2
1
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(4)


2021-12-02 to 2021-12-04
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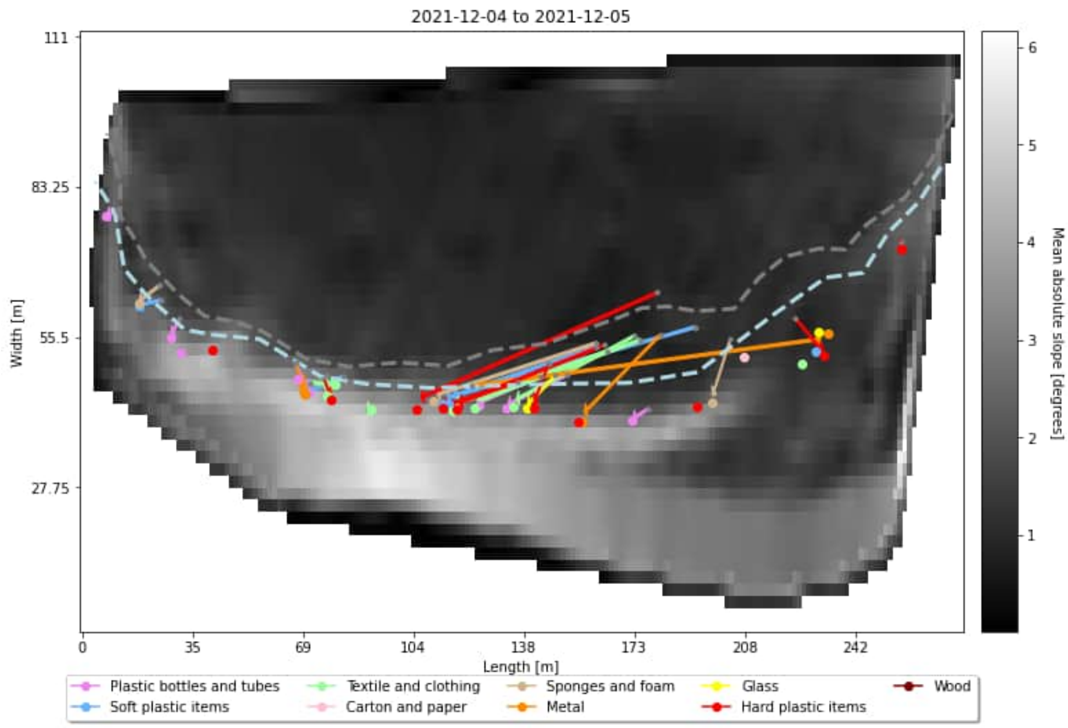
83.25
55.5
27.75
Width [m]
0
35
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(5)


2021-12-04 to 2021-12-05
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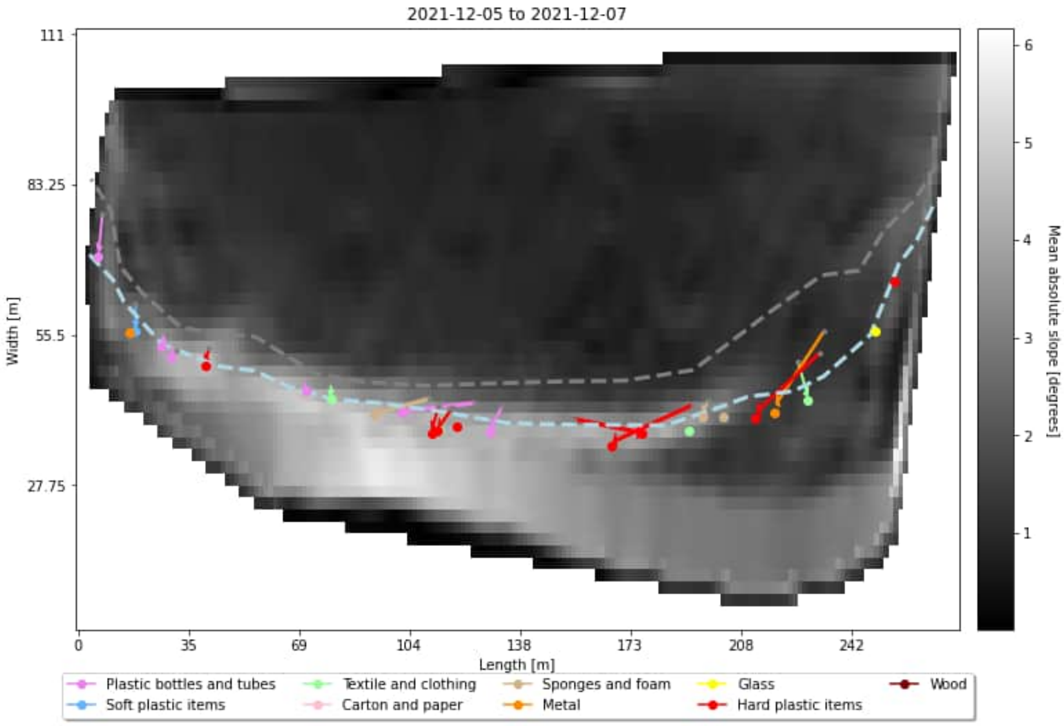
83.25
55.5
27.75
Width [m]
0
35
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(6)


2021-12-05 to 2021-12-07
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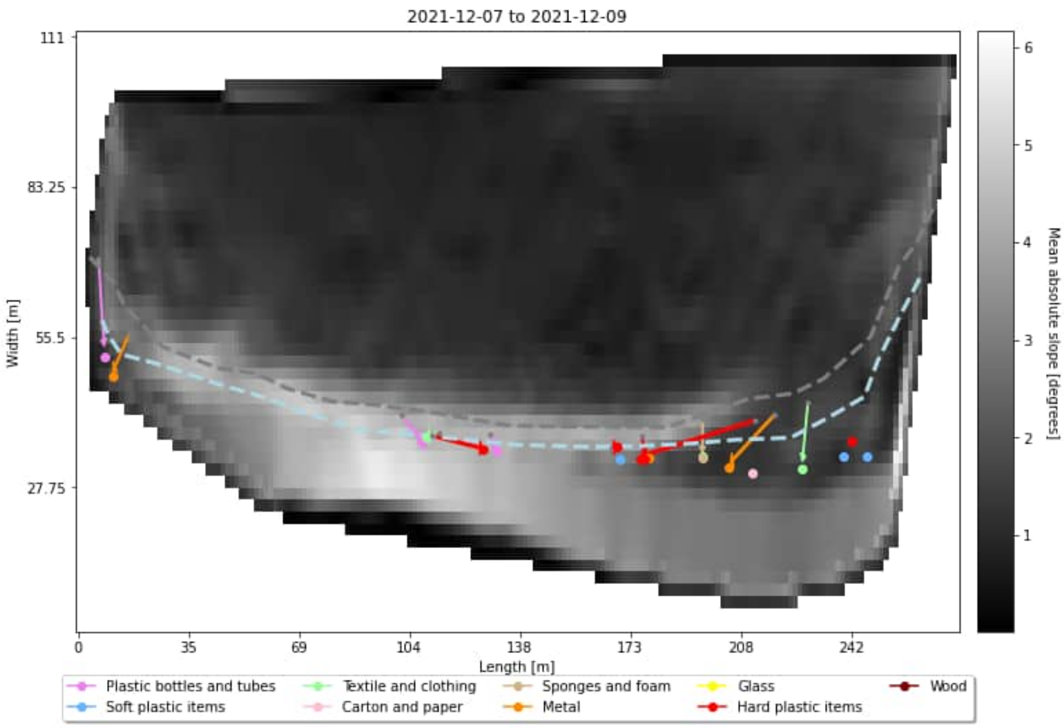
83.25
55.5
27.75
Width [m]
0
35
69
104
138
173
208
242
Length [m]
6
5
4
3
2
1
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(7)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55.5
27.75
Width [m]
0
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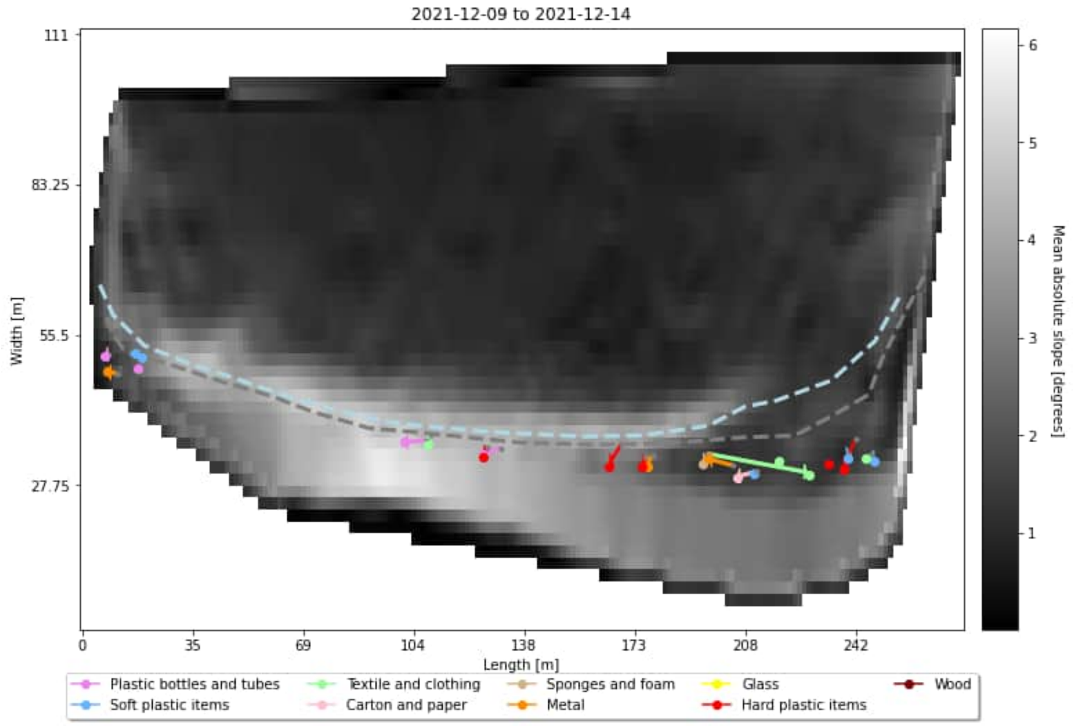
69
104
138
173
208
242
Length [m]
6
5
4
3
2
1
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(8)


2021-12-09 to 2021-12-14
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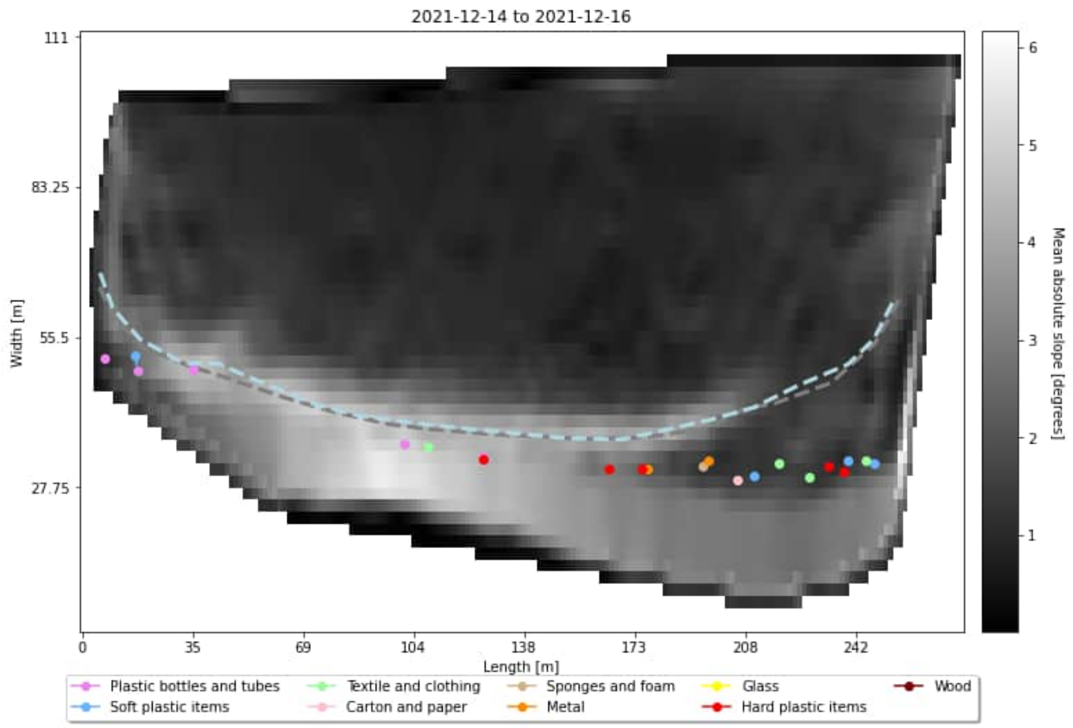
83.25
55.5
27.75
Width [m]
0
35
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
1
2
3
4
5
6
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(9)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27.75
Width [m]
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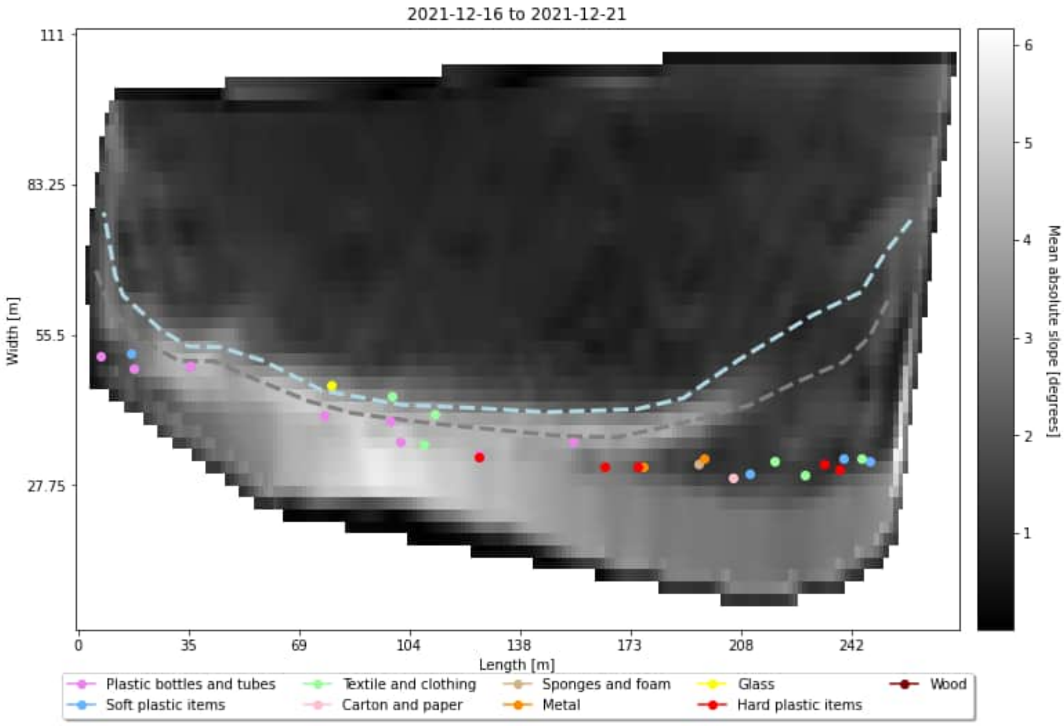
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
1
2
3
4
5
6
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(10)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27.75
Width [m]
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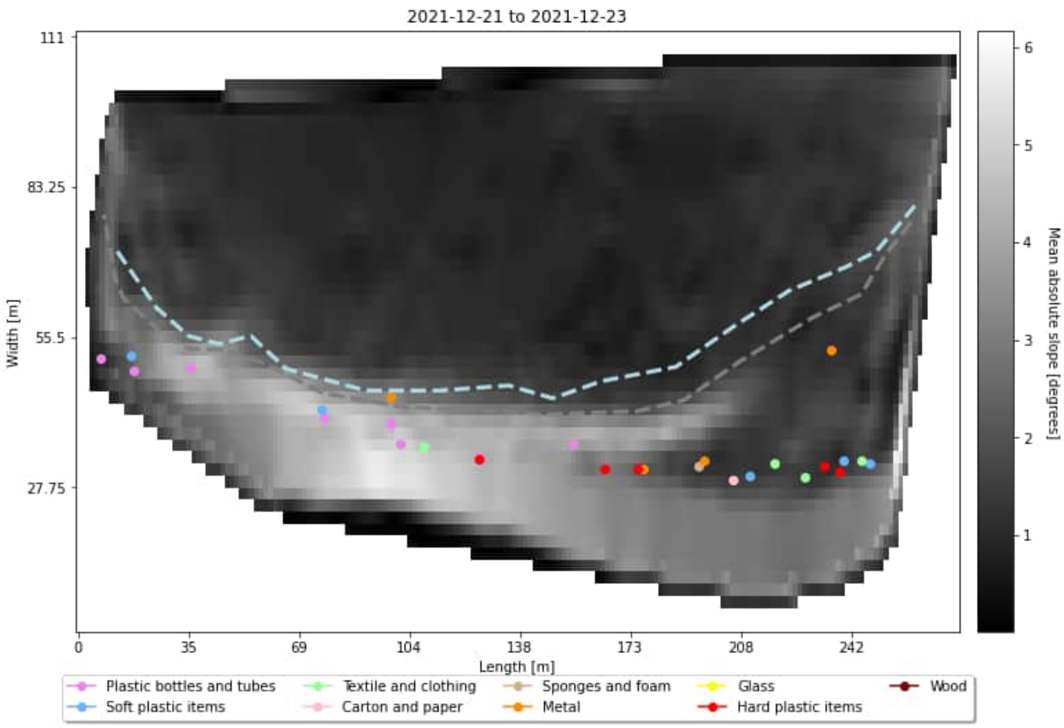
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
6
5
4
3
2
1
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(11)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55.5
27.75
Width [m]
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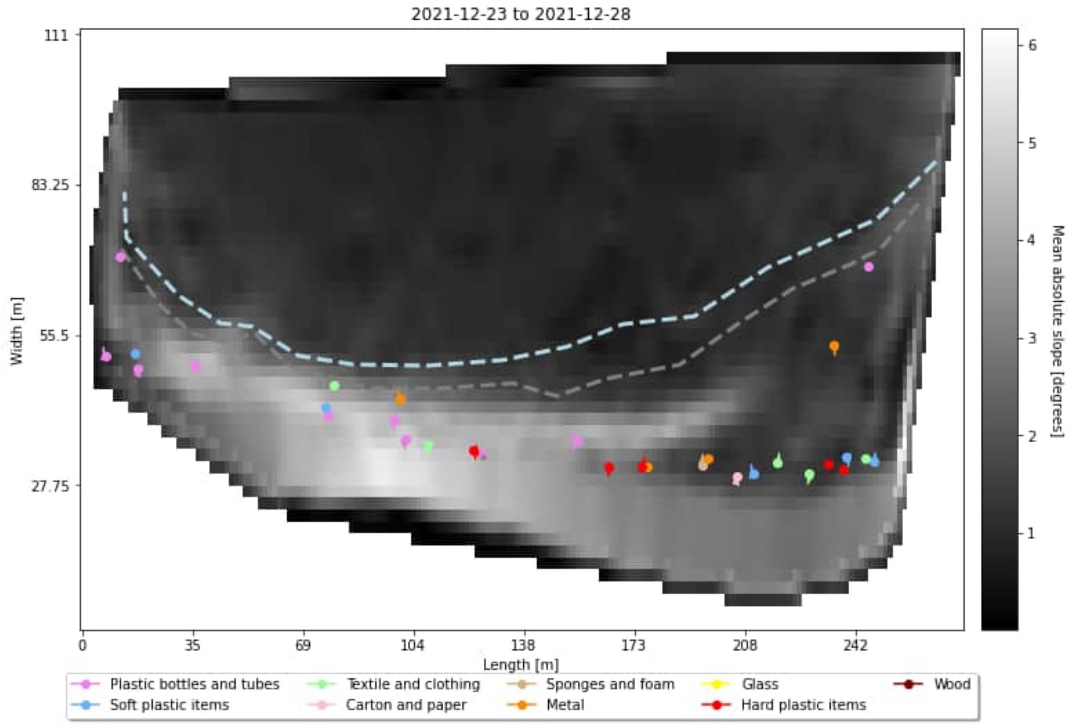
35
69
104
138
173
208
242
Length [m]
Mean absolute slope [degrees]
6
5
4
3
2
1
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(12)


2021-12-23 to 2021-12-28
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27.75
Width [m]
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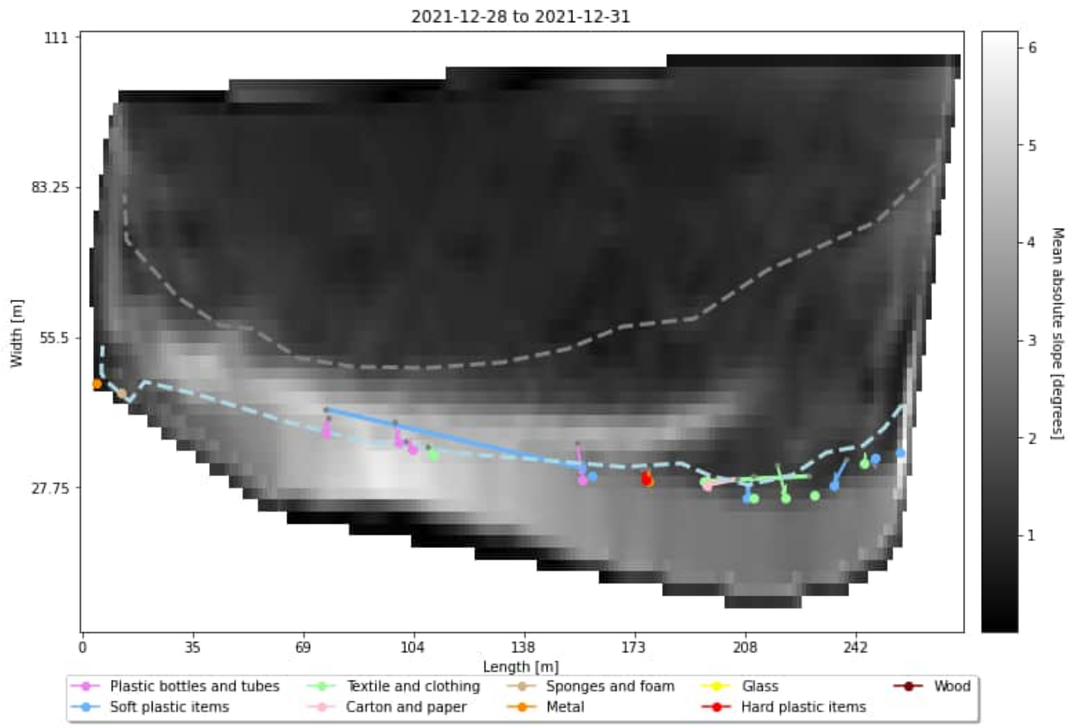
69
104
138
173
208
242
Length [m]
6
5
4
3
2
1
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(13)


2021-12-28 to 2021-12-31
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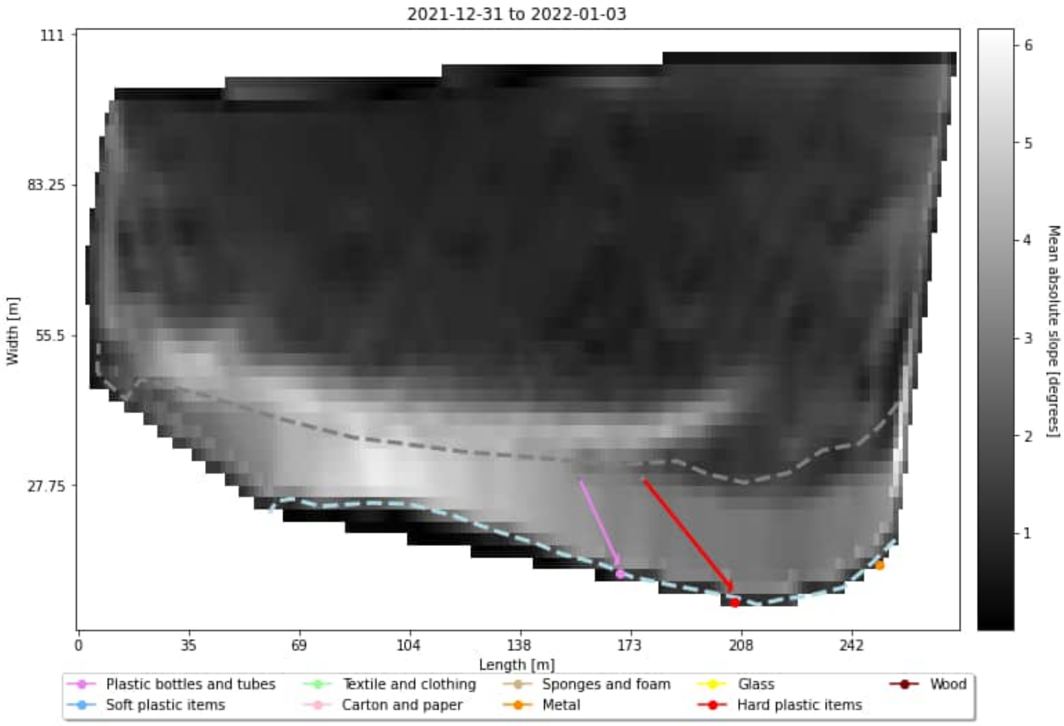
83.25
55.5
27.75
Width [m]
0
35
69
104
138
173
208
242
Length [m]
6
5
4
3
2
1
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(14)


2021-12-31 to 2022-01-03
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55.5
27.75
Width [m]
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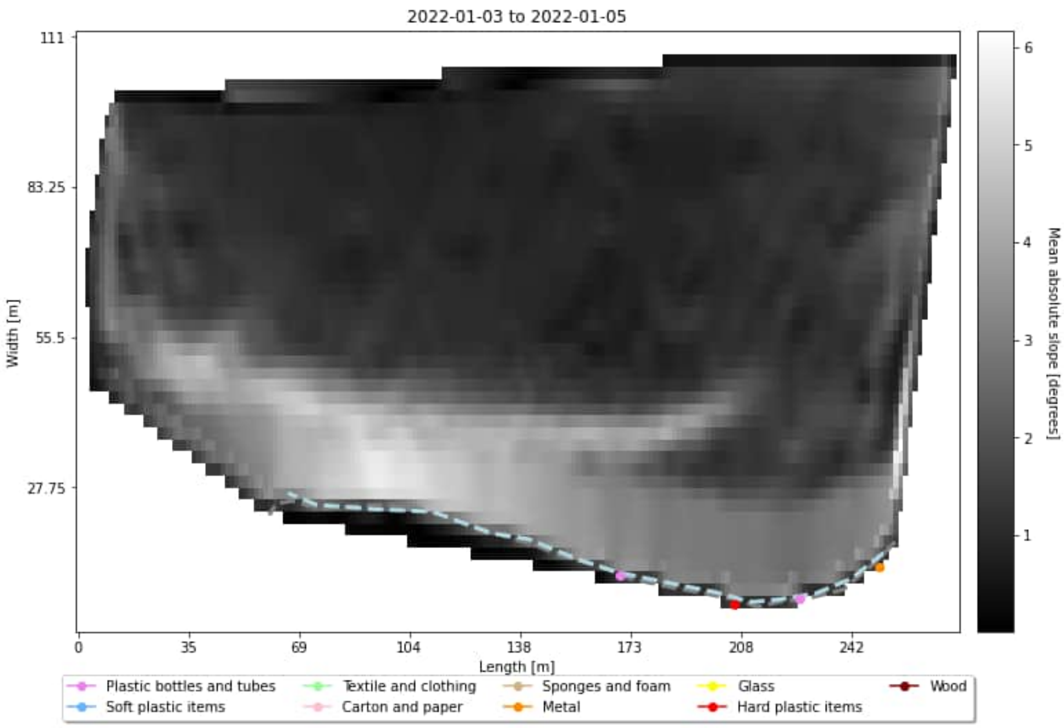
35
69
104
138
173
208
242
Length [m]
6
5
4
3
2
1
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(15)


2022-01-03 to 2022-01-05
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55.5
27.75
Width [m]
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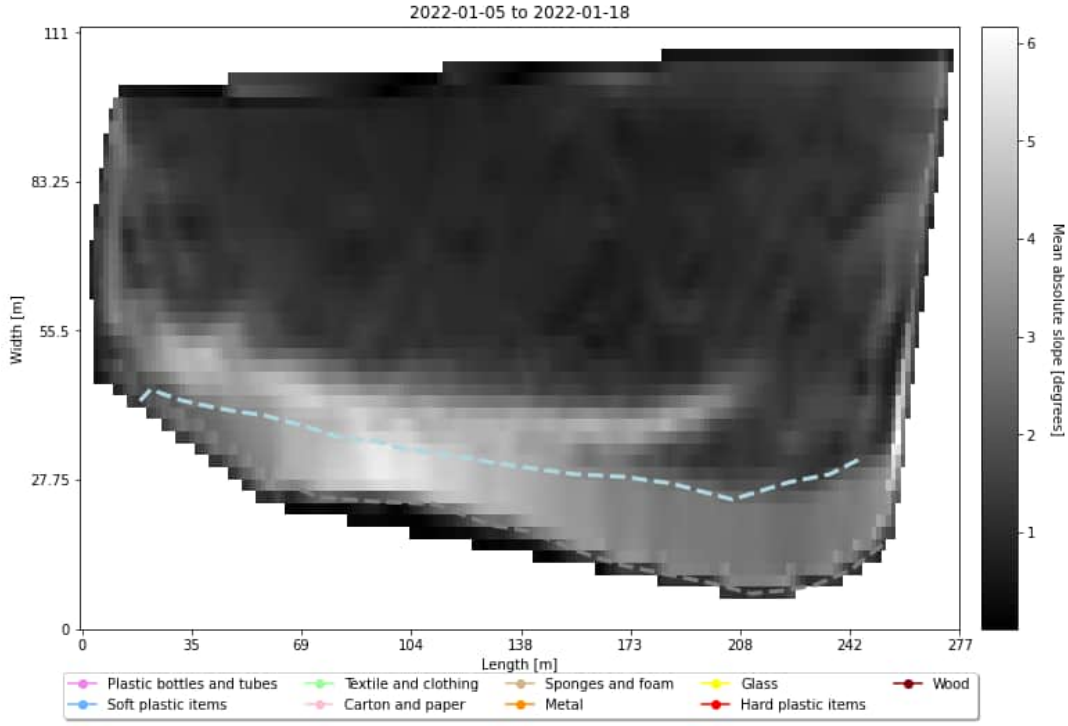
69
104
138
173
208
242
Length [m]
6
5
4
3
2
1
Mean absolute slope [degrees]
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(16)


2022-01-05 to 2022-01-18
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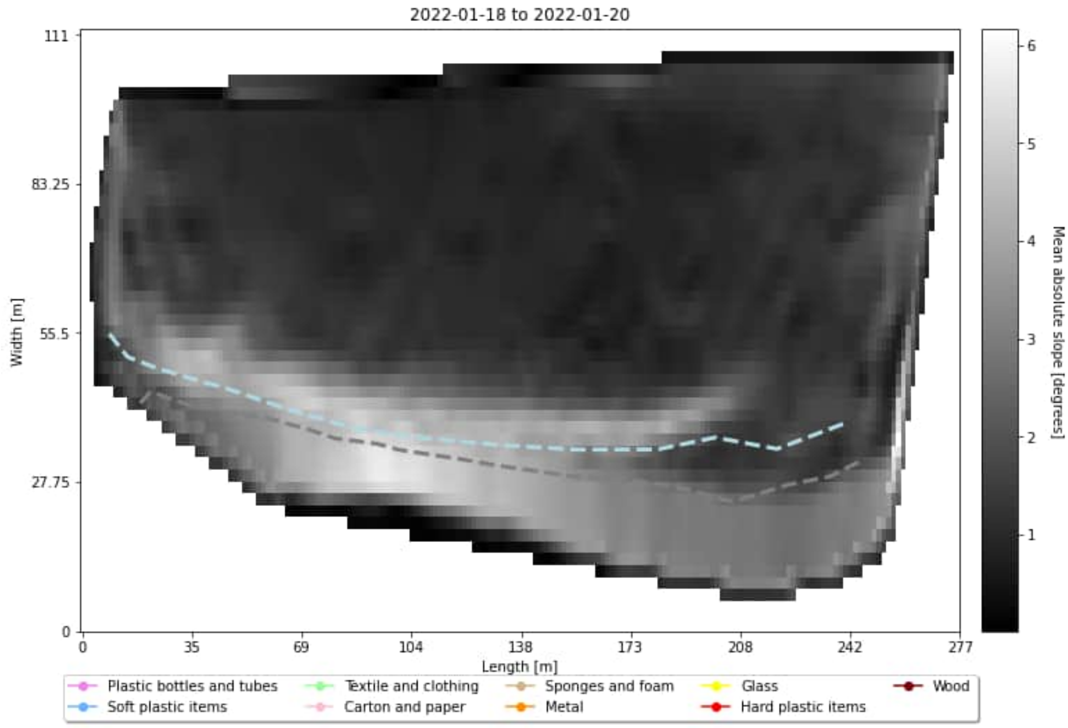
55.5
27.75
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Mean absolute slope [degrees]
6
5
4
3
2
1
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(17)


2022-01-18 to 2022-01-20
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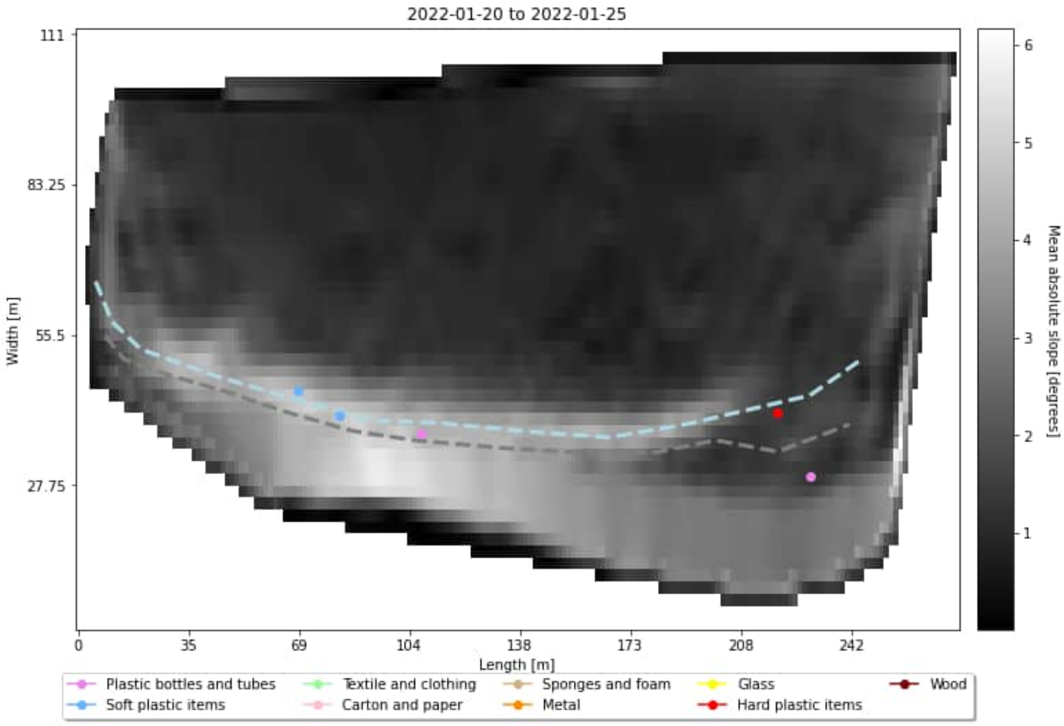
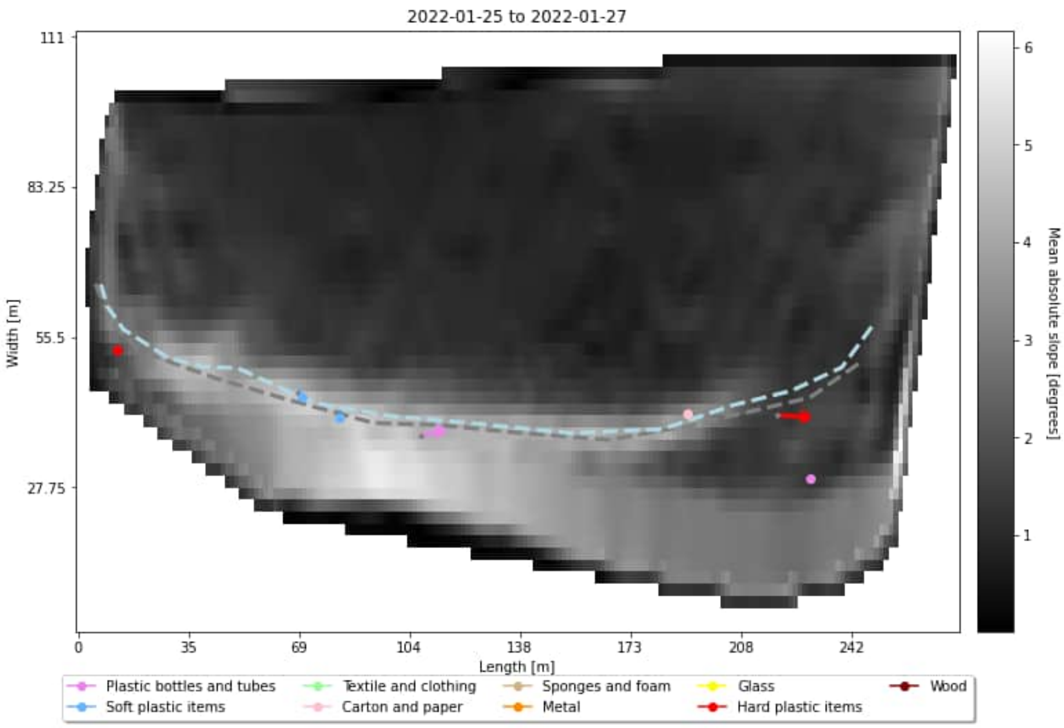
55.5
27.75
0
Width [m]
0
35
69
104
138
173
208
242
277
Length [m]
Mean absolute slope [degrees]
6
5
4
3
2
1
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(18)

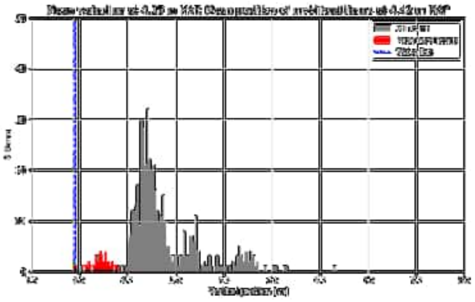

2022-01-20 to 2022-01-25
Width [m]
111
83.25
55.5
27.75
Length [m]
0
35
69
104
138
173
208
242
Mean absolute slope [degrees]
1
2
3
4
5
6
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(19)

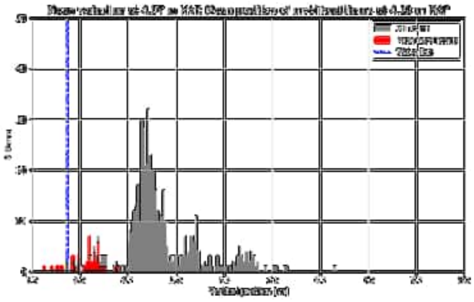

2022-01-25 to 2022-01-27
Width [m]
111
83.25
55.5
27.75
Length [m]
0
35
69
104
138
173
208
242
Mean absolute slope [degrees]
1
2
3
4
5
6
Plastic bottles and tubes
Soft plastic items
Textile and clothing
Carton and paper
Sponges and foam
Metal
Glass
Hard plastic items
Wood

(20)

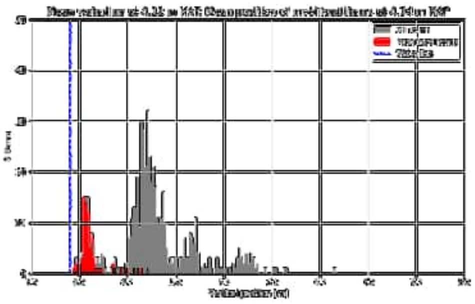
A.8. Vertical macrolitter distribution



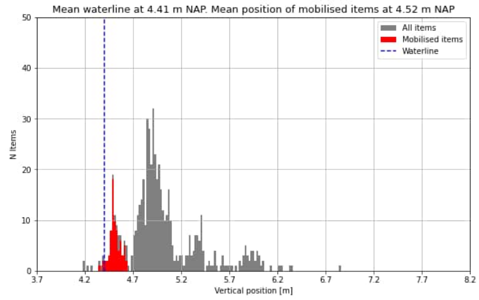
(1) 2021-11-18



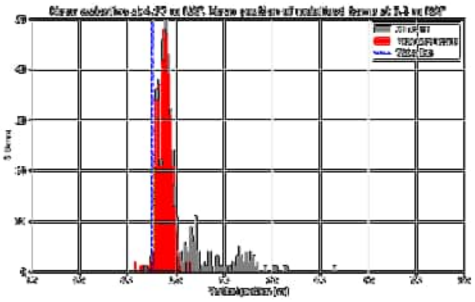
(2) 2021-11-24



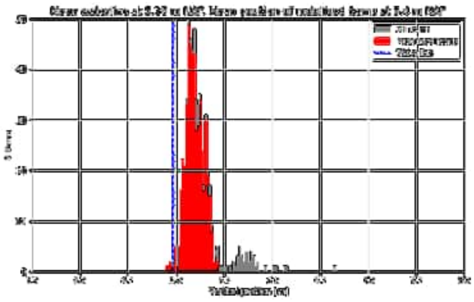
(3) 2021-12-01



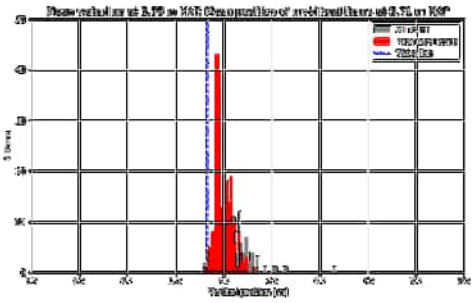
(4) 2021-12-02



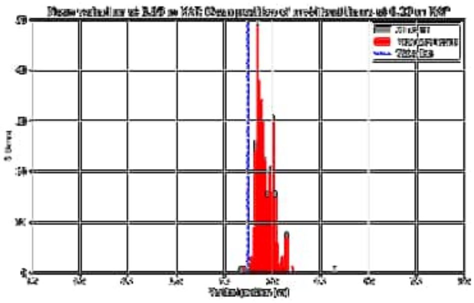
(5) 2021-12-04



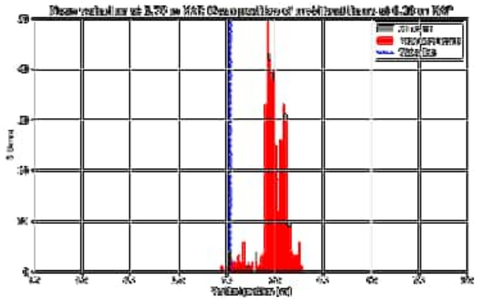
(6) 2021-12-05



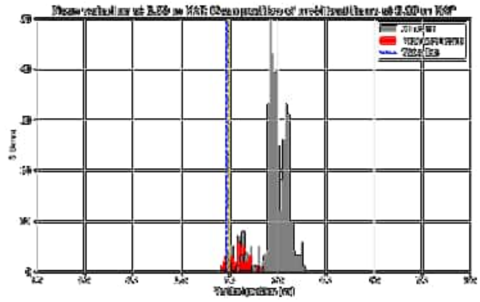
(7) 2021-12-07



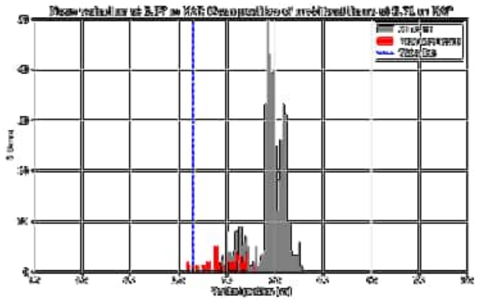
(8) 2021-12-09



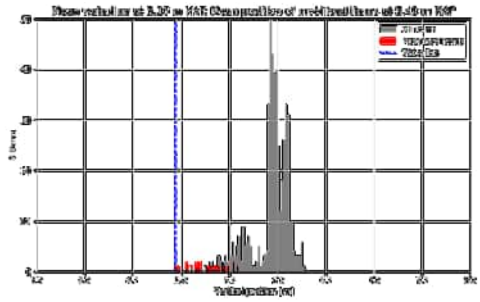
(9) 2021-12-14



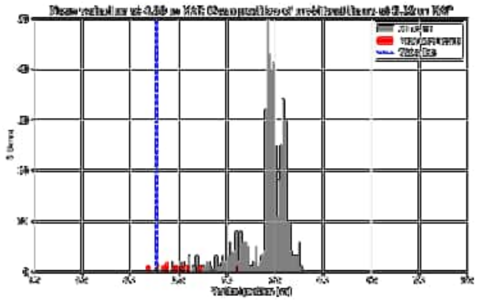
(10) 2021-12-16



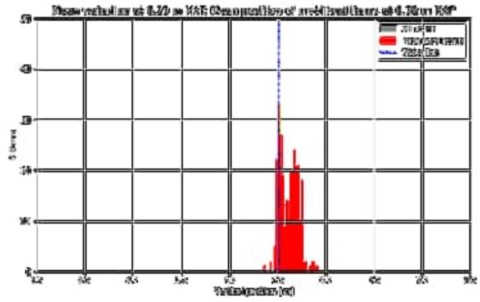
(11) 2021-12-21



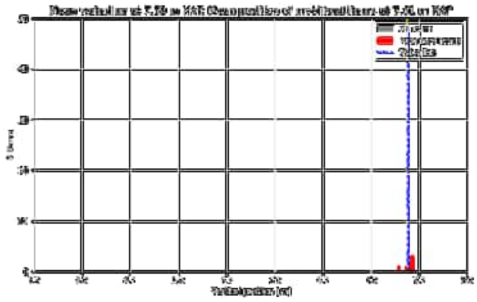
(12) 2021-12-23



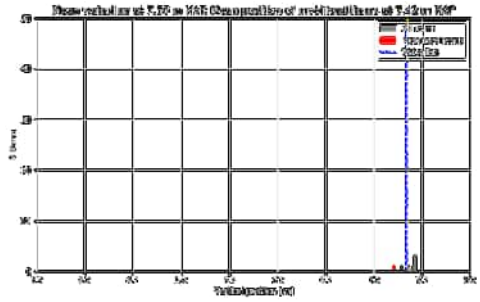
(13) 2021-12-28



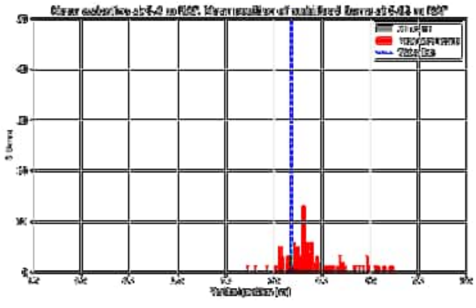
(14) 2021-12-31



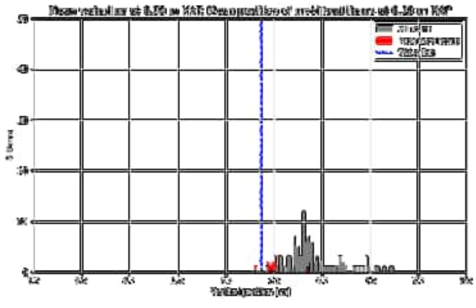
(15) 2022-01-03



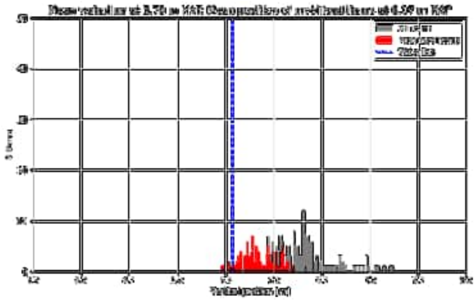
(16) 2022-01-05



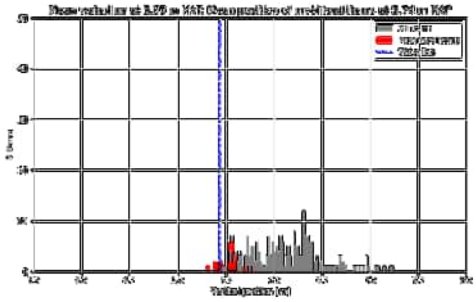
(17) 2022-01-18



(18) 2022-01-20



(19) 2021-01-25



(20) 2021-01-27

Figure A.8: Vertical item distribution

B

Additional imagery

B.1. Overland flow captured by wildlife camera

(1)

(2)

(3)

Figure B.1

Naam rivier	
Provincie	
Gebiedscode (Vul hier ontvangen code van het tracé in)	
Datum monitoring	
Starttijd	__ : __
Eindtijd	__ : __
Naam onderzoeker 1	
E-mail onderzoeker 1	
Naam onderzoeker 1	
E-mail onderzoeker 2	

Kon de meting worden uitgevoerd? Ja/ nee	Ja/Nee
Zo nee, beschrijf hier waarom	

Is er afgeweken van de vooraf bepaalde 100 meter? Geef lengte en breedte aan.	Ja/Nee
Zo ja, beschrijf hier waarom	

Waren er nog bijzonderheden? Noteer hier ook herkenbare items die niet op de lijst staan. (gelieve omschrijving per gevonden item en hoeveelheid)	

Ospar ID	**Plastic en piepschuim**	**Aantal**
15	Doppen en deksels	
4.2	Drankflessen < 1/2 liter	
4.1	Drankflessen > 1/2 liter	
40	Industriële verpakkingsmaterialen (o.a. plastic zeil, bouwplastic, landbouwplastic)	
3	Kleine plastic tasjes	
117.1	Ondefinieerbare plastic stukjes 0 - 2,5 cm (hard plastic)	
46.1	Ondefinieerbare plastic stukjes 2,5 - 50 cm (hard plastic)	
47.2	Plastic stukken > 50cm (hard plastic)	
1172	Ondefinieerbare stukjes piepschuim 0 - 2,5 cm (schatting)	
462	Ondefinieerbare stukjes piepschuim 2,5 cm - 50 cm	
472	Piepschuim > 50 cm	
6.1	Piepschuim voedselverpakkingen (o.a. take-away hamburger)	
212	Piepschuim bekers of delen daarvan	
21	Plastic bekers of delen daarvan	
117.2	Plastic folies of stukken daarvan 0 - 2,5 cm (zacht plastic)	
46.2	Plastic folies of stukken daarvan 2,5 - 50cm (zacht plastic)	

47.1	Plastic folies of stukken daarvan > 50cm (zacht plastic)	
22.1	Rietjes	
22.2	Roerstaafjes	
19	Snoep, snack en chips verpakkingen	
6	Voedselverpakkingen (o.a. yoghurt, ketchup, boter, frietbakjes etc.)	
4.3	Wikkels van drankflessen	
64	Sigarettenfilters	
63	Sigarettenverpakking of delen daarvan (papieren verpakking hier ook turven)	
5	Schoonmaakmiddelen (o.a. afwasmiddel, allesreiniger etc.)	
1	6-pack ringen	
16	Aanstekers	
14	Auto onderdelen	
22	Bestek	
22.1	Borden	
481	Biofilm/waterfiltertjes	
36	Breekstaafjes	
38	Emmers of stukken daarvan	
38.1	Bloem/plant potten, plantentrays of stukken daarvan	
43	Geweerpatronen en hulzen	
25	Handschoenen huishoudelijk (zacht plastic)	
113	Handschoenen professioneel (dikker plastic)	
42	Helmen	
10	Jerry cans	
11	Kitspuiten	
13	Kratten of stukken daarvan	
39	Plastic band en tie-wrap	
39.1	Plakband/ schilders- ducttape of stukken daarvan	
19.1	Lolly stokjes (let op: met gaatje aan de bovenkant)	
8	Motorolie verpakkingen < 50 cm	
9	Motorolie verpakkingen > 50 cm	
24	Netzakken (o.a. voor uien/fruit)	
2.1.	Vuilniszakken of stukken daarvan	
17	Schrijfwaren (o.a. pennen)	
20	Speelgoed	
35	Sportvisspullen (o.a. dobbers, aasbakjes, verpakkingen van sportvisproducten, visdraad)	
2	Tassen	
31	Touw diameter > 1 cm	
32	Touw en koord diameter < 1 cm	
35.1	Vispluis (plastic draden van nylon)	
43.1	Vuurwerk of resten daarvan (alleen plastic of gecombineerd met karton)	
48	Overige plastics (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	

Ospar ID	Rubber	Aantal
49	Ballonnen of resten van ballonnen (incl. sierlinten)	
52	Banden (o.a. auto/fiets)	
53	Overig rubber (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	

Ospar ID	Textiel	Aantal
54	Kleding	
57/44	Schoenen, laarzen en slippers	
55	Vloerbedekking	
59	Overig textiel (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld). Geotextiel / worteldoek ook hier turven.	

Ospar ID	Papier	Aantal
62.1	Drankkartons (o.a. sap, melk, yoghurtdrink)	
67.1	Ondefinieerbare stukjes papier 0 > 50cm	
61	Karton (o.a. delen van verpakking)	
65	Kartonnen bekers	
66	Kranten/ tijdschriften	
60	Tassen/zakken	
67	Overig papier (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	

Ospar ID	Hout	Aantal
72	IJsstokjes	
68	Kurken	
73	Kwasten	
69	Pallets	
74	Overig hout < 50 cm (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	
75	Overig hout > 50 cm (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	

Ospar ID	Metaal	Aantal
81	Aluminium folies en verpakkingen	
81.1	Capsules (o.a. koffie/ chocomel)	
78	Drankblikjes	
79	Elektriciteitsdraden	
83	Industrieel oud ijzer (o.a. kabels, pijp etc.)	
77	Kroonkurken & metalen doppen (o.a. bier doppen)	
84	Oliedrums	
88	Omheingsdraad, prikkeldraad	
76	Spuitbussen	
86	Verfblikken	
80	Vislood	

82	Voedselblikken	
120	Wegwerp BBQs	
89	Overig metaal < 50 cm (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	
90	Overig metaal > 50 cm (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	

Ospar ID	**Glas**	**Aantal**
91	Flessen, potten of stukken daarvan	
92	Lampen en TL lampen	
93	Overig glas (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	

Ospar ID	**Sanitair**	**Aantal**
7	Cosmetica verpakkingen (o.a. shampoo, deodorant, zonnebrand)	
98	Plastic wattenstaafjes (let op: ribbels aan beide zijden)	
982	Kartonnen wattenstaafjes	
102.2	Sanitaire/vochtige doekjes	
97	Condooms	
99	Maandverbanden, inlegkruisjes of verpakkingen ervan	
18	Plastic kam of borstel	
100	Tampons, tampon applicator of verpakkingen ervan	
102.3	Toiletpapier of stukken daarvan	
101	Toiletverfrisser	
102	Overig sanitair (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld)	

Ospar ID	**Medisch**	**Aantal**
103	Verpakkingen (van o.a. pillen, lenzen- en vloeistof)	
104	Injectiespuiten	
105	Overig medisch (indien herkenbaar, noteer omschrijving per gevonden item in opmerkingen veld) Mondkapjes ook hier turven.	

Ospar ID	**Granulaat**	**Aantal granulaatkorrels**
	Detailmeting 50x50 cm x strooisellaag	