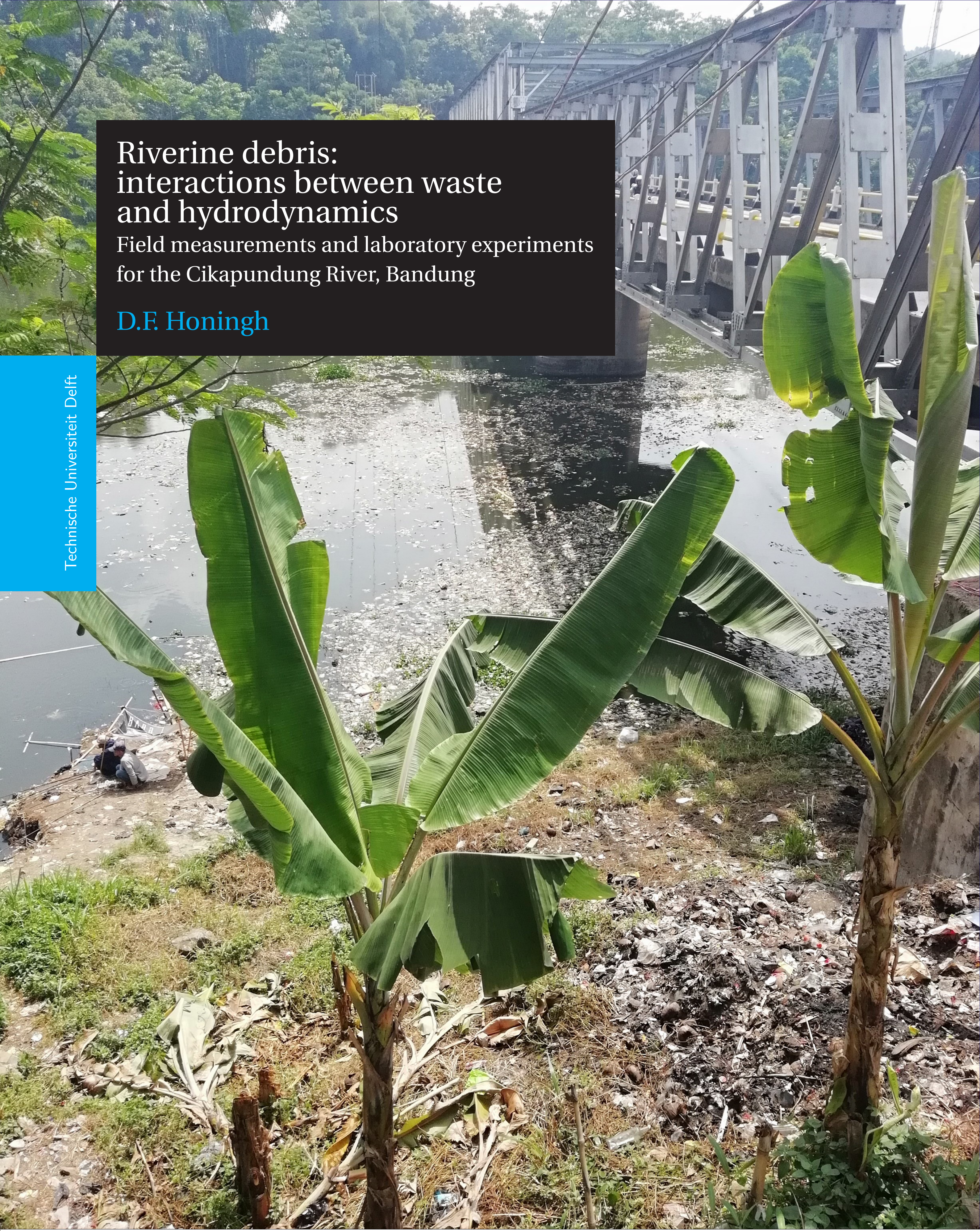

Riverine debris: interactions between waste and hydrodynamics

Field measurements and laboratory experiments for the Cikapundung River, Bandung

D.F. Honingh

Technische Universiteit Delft

Delft University of Technology

Challenge the future

RIVERINE DEBRIS:

INTERACTIONS BETWEEN WASTE AND HYDRODYNAMICS

FIELD MEASUREMENTS AND LABORATORY EXPERIMENTS FOR THE CIKAPUNDUNG RIVER, BANDUNG

by

D.F. Honingh

in partial fulfillment of the requirements for the degree of

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PREFACE

This master thesis is the final product of my master Water Resources Management at the Delft University of Technology. The subject of this graduation work is riverine debris in Indonesia, for which both field measurements and flume experiments were conducted in Bandung. The study was done in collaboration with the Bandung Institute of Technology (ITB) and was financially supported by the Lamminga Fund.

First, I would like to thank my thesis committee for their advice and guidance. Many thanks to Nick van de Giesen and Olivier Hoes, who provided me with this interesting subject, helped me with local contacts and a scholarship. Without their help, it wouldn't have been possible to do fieldwork on this important and socially relevant problem. Many thanks to Wim Uijttewaal who not only inspired me with the possibilities of debris accumulation related flume experiments, but also guided me in the data analysis process.

Second, thanks to the people from the ITB, who helped me during my time in Indonesia. My sincerest gratitude goes out to Hadi Kardhana, who not only helped me in the preparation process of both field and lab measurements, but really took the time to personally assist me in times of need. Furthermore, I would like to thank the master students Siti Ardian and Fikih Iqrammullah for their involvement in the field measurement campaign of this thesis. In addition, I would like to thank the lab employees Sopandi and Sukadi for their help during the flume experiments. Their willingness to help, despite the language barrier was great and I really enjoyed the cooperation and learning some more Indonesian words and habits.

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Fourth, many thanks to Michelle Loozen, Tim van Emmerik and Kees van Oeveren of The Ocean Cleanup River Team. Assisting with your measurement campaign was a valuable experience for me and our measurement campaign benefited greatly from the material we could borrow. Furthermore, I'm grateful for the discussions, critical reviews and helpful remarks I got from the three of you.

Fifth, many thanks to the moral support of my family and friends. I especially want to thank Joreen Merks, Nura Jaafar, Steven Janssens, my parents in law and my sister, Anita, for reading and giving a critical review of this thesis. I owe much to my boyfriend, Cas van Bemmelen, who supported me unconditionally. Thank you for listening, visiting me in Bandung, giving me feedback and suggestions, I really appreciated it and you really motivated me throughout this thesis! Last, I would like to thank my parents for helping me where possible throughout my whole study in Delft.

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Delft, October 2018

ABSTRACT

Plastic debris in water systems form a major problem for our ecosystem because it is extremely persistent in the environment and the global plastic production is still increasing without adequate measures to prevent pollution. Apart from the importance of reducing the amount of plastic entering the ocean, clearing the rivers from debris is important for societal concerns, such as health related issues and flood risks. The interaction between riverine debris and the hydrodynamics of water systems plays an important role in the construction of trash racks that can block water flow in the river. These clogged trash racks lead to an increase in upstream water level and can cause regional flood risks. This study was set up to investigate the amount and accumulation of riverine debris in the Cikapundung River in Indonesia, one of the tributaries of the Citarum River.

The Citarum River is one of the world's most heavily polluted rivers, predominantly caused by industries and households dumping their waste directly in the river. With a length of 270 kilometres, this is the longest river of West-Java and it is the main source of water for 27 million people. The river flows through three reservoirs and the area upstream of these reservoirs is called the Upper Citarum River Basin. The main contribution of pollution comes from this area, as the city of Bandung is located in this area. The Cikapundung River flows through the city of Bandung and is one of the tributaries of the Citarum River. This river was selected for the field measurements in this study as it allowed measurements to be performed in river parts with rural and urban areas neighbouring the river. Up until now, many studies of riverine debris accumulation are predominantly focused on organic debris accumulations at bridges and gates. This study also investigated plastic debris accumulations, as it forms a significant part of the debris in the Cikapundung River and other Asian rivers.

Field measurements in the Cikapundung River were performed with a single and double trawl, to determine the riverine debris composition and flux. Scaled laboratory tests were carried out, to (1) monitor the blockage growth process for different debris compositions, (2) investigate the influence of different parameters on the upstream water level and (3) determine the impact of a blocked trash rack on regional flood risks.

From the field measurements, an increase in downstream direction was found for the debris flux, but the debris composition varied in both time and space. The plastic debris mass varied between 11% and 78% of the total debris mass. Based on the laboratory tests, the behaviour of riverine debris is studied during normal flow conditions and in front of a trash rack. One of the key findings from this study is that plastic debris causes a faster blockage than organic debris, as the plastic blockage contains fewer voids and therefore has a higher blockage density. In the formation of a blockage in front of a trash rack, a mix of organic and plastic debris behaved more similar to plastic debris. The shape of the blockage was also found to be different for plastic and organic debris: a high amount of plastic in the debris lead to an angular blockage shape, whereas mainly organic debris produced a curved blockage shape. The most important indicators for flood risks related to debris accumulations were found to be the debris load, loss coefficient, initial flow velocity and initial flow depth. By rescaling the results to the case study location in Bandung, it was found that a backwater rise within the hour of $O(1\text{ m})$ is plausible for a blocked trash rack.

This study forms the stepping stone to further quantifying riverine (plastic) debris and investigating its relation to changes in the water system behaviour, including its influence on regional flood risks.

CONTENTS

NOMENCLATURE

Acronyms

BMA	Bandung Metropolian Area
BOD	Biological oxygen demand
CL	Chile
FR	France
HDPE	High-density polyethylene
ITB	Bandung Institute of Technology
LDPE	Low-density polyethylene
MMPW	Mismanged plastic waste
MPL	Macroplastic load
MY	Malaysia
NL	Netherlands
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Poly-styrene
PVC	Polyvinyl chloride
RMSE	Root mean squared error
Rp	Indonesian Rupiah
TSP	Total suspended particles
UK	United Kingdom
VN	Vietnam
ZA	South Africa

Symbols

α	Reduction factor to include inequality in vertical debris distribution	[-]
Δh	Water level difference between up and downstream ($\Delta h = h_1 - h_3$)	[m]
ρ	Density	[g/cm^3]
ρ_{pop}	Population density	[#/km^2]
ξ	Loss coefficient	[-]
A	Area	[m^2]
c	Debris concentration	[kg/m^3]

D	Diameter	[m]
F	Froude number	[-]
F_0	Approach Froude number	[-]
F_{river}	Debris load	[kg/d]
F_{trawl}	Debris load	[kg/m^2/s]
g	Gravitational acceleration	[m/s^2]
H	Hydraulic head	[m]
h	Height	[m]
h_0	Approach water depth	[m]
h_1	Upstream water level	[m]
h_3	Downstream water level	[m]
h_η	Relative water level difference with respect to the initial water level ($h_\eta = \Delta h + h_0$)	[m]
h_B	Dimensionless backwater rise	[m]
h_t	Height trawl	[m]
h_t	Transition flow depth	[m]
h_{avg}	Average water depth	[m]
k_{str}	Strickler coefficient	[m$^{1/3}$/s]
L	Length	[m]
L_c	Length carpet	[m]
M	Mass	[kg]
$MMPL$	Mismanaged plastic waste	[kg/d/pp]
MPL	Macroplastic load	[t/y]
n	Manning's roughness coefficient	[s/m$^{1/3}$]
Q	Discharge	[m^3/s]
R	Hydraulic radius	[m]
Re	Reynolds number	[-]
t	Time	[s]
V	Volume	[m^3]
v	Flow velocity	[m/s]
v_0	Approach flow velocity	[m/s]
V_d	Debris volume	[m^3]
w	Width	[m]
w_t	Width trawl	[m]

1

INTRODUCTION

1.1. PROBLEM DEFINITION

ECOLOGICAL, SOCIETAL AND ECONOMIC RELEVANCE

Plastic debris in the ocean is a major problem for our marine ecosystem because it is extremely persistent in the environment. This is worrisome, especially since the global plastic production is increasing, and therefore also the chances that it ends up as plastic debris in the worlds oceans. According to Lebreton (2017), about two-thirds of the global plastic pollution that ends up in the world's oceans originates from the 20 most polluting rivers, which are mainly located in Asia (Figure 1.1). Four of these rivers (Brantas, Solo, Serayu and Progo) are located at the Indonesian island Java, which makes Indonesia world's second biggest plastic polluter after China (Lebreton et al., 2017).

It is yet unknown how much plastic exactly enters the marine environment, but since most plastics are non-biodegradable the quantities are increasing over time. This leads to a variety of negative effects for marine life, such as entanglement and ingestion of plastic by fish, turtles, marine mammals and birds. Furthermore, plastic pollution can cause partial or total mortality of coral reefs, as the presence of plastic debris has a negative impact on the benthic assemblage within these sensitive systems (Gall and Thompson, 2015). An example of such a sensitive system is the Coral Triangle Reef (encompassing Indonesia) which has one of the world's highest marine biodiversities, so the presence and associated consequences of plastic debris can be a

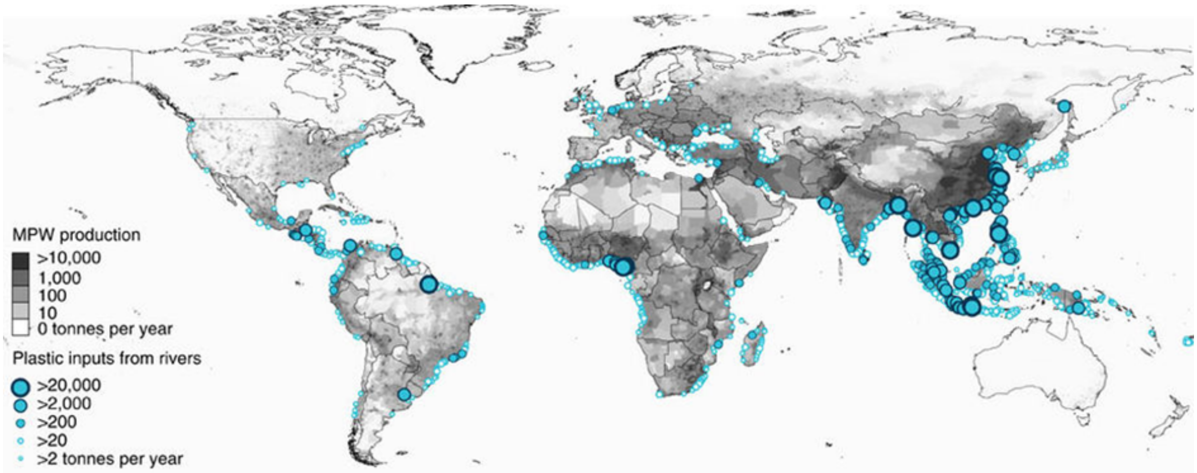


Figure 1.1: Annual amount of tonnes of river plastic flowing into the ocean and mismanaged plastic waste production (Lebreton et al., 2017).

disaster for the future of this coral reef ecosystem (Langenhiem, 2017).

Apart from the importance of reducing the amount of plastic entering the ocean, clearing the rivers from debris is important for societal concerns, such as health related issues and flood risk. Lack of solid waste management has been a persistent problem in Indonesia and was already brought to attention during the 1978 Solid Waste Management Seminar in Bangkok. Back then, it was already known that river blockage in combination with bad sanitation could lead to health hazards such as typhus, dentary and cholera (Duisberg, 1978). Next to the direct effect of poor waste management on health hazards, stagnant water serves as a breeding ground for mosquitoes which can cause people to suffer from malaria and dengue haemorrhagic fever (Peters et al., 2015).

Over the last decades, flood risks in Indonesia have increased in urbanised cities such as Jakarta and Bandung. Both cities have highly polluted rivers, which is paired with large debris accumulations. These accumulations are often mentioned as being one of the causes of increased flood risks (e.g. Cochrane, 2016; Peters et al., 2015; Marshall, 2005). The Ciliwung River is Jakarta's most contaminated river (Ubud, 2017) and the Citarum River, which passes the city of Bandung, is often called the world's most polluted river (Rianawati and Sagala, 2014). The poor water condition in both rivers is a result of unprocessed dumping of both industrial and household waste. In addition to the described problems related with high amounts of riverine debris, both cities suffer from land inundation because of ground water extractions and reduced water infiltration due to the urbanisation, forest and agricultural areas have been replaced by paved areas. Furthermore, deforestation has led to siltation of rivers and moreover, the rivers of Jakarta and Bandung have not been properly maintained for decades. (Rianawati and Sagala, 2014)

Floods also have a major impact on the economy of Indonesia. The economic damages caused by flood events have been estimated to be around 383 thousand USD/year for the region of Bandung (Rianawati and Sagala, 2014). The economic losses associated with floods in Jakarta are several orders of magnitude larger; the damage of the large flood in Jakarta 2007 was estimated to be 695 million USD (HCC, 2017). Furthermore, the economy can be impacted indirectly, since frequent floods can impact the decision of companies to settle in this area. In addition, the mismanaged waste and debris form a threat to the international tourist status, which could have an additional negative influence on the Indonesian economy (Wright, 2016).

SCIENTIFIC RELEVANCE

Many studies have focussed on plastic particles in oceans, while fewer studies have investigated the presence of plastic in rivers (Gasperi et al., 2014; Morritt et al., 2014; Tweehyusen, 2015). Most of the studies concerning

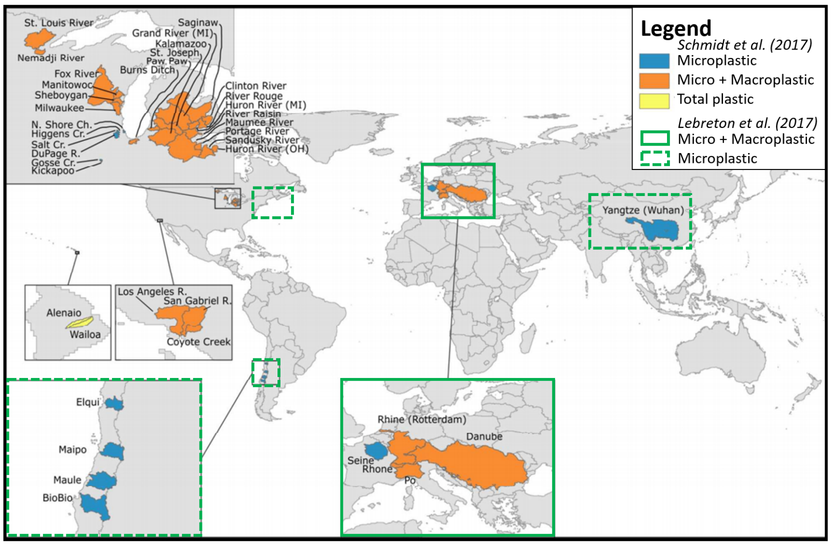


Figure 1.2: The coloured catchments show the locations of the studies used for validating the models of both Lebreton et al. (2017) and Schmidt et al. (2017). Adapted from Schmidt et al. (2017).

Figure 1.3: (A) Debris bridge blockage in Cikapundung River in January 2010 (Ministry of Public Works and Housing, 2010), compared to (B) the regular flow condition at the same bridge in May 2018.

riverine plastics were conducted in industrialized countries of Europe and North America (Dris et al., 2015), with a focus on microplastics (particles < 0.5 cm). Apart from the limited amount of plastic field measurements in rivers, three global models have been developed to estimate the plastic input from rivers into the ocean (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017). All model predictions are based on the assumed positive relation between mismanaged plastic waste (MMPW) and plastic debris flux. The prediction by Jambeck et al. (2015) is based on the annual MMPW of the populations living within 50 km of a coast, whereas the other models take a larger region for MMPW into account. The models by Lebreton et al. (2017) and Schmidt et al. (2017) both used the MMPW, population density and the seasonal varying hydrological conditions as input for their models. The main difference between these two models is that they used different validation data, population density data and hydrological parameters. Lebreton et al. (2017) used the rainfall data, whereas Schmidt et al. (2017) used discharge data. Figure 1.2 shows the study locations used for model validation of both models.

Lebreton et al. (2017) estimated a yearly global plastic debris input from rivers into the sea between 1.15 and 2.41 million tonnes, whereas Schmidt et al. (2017) provided a range between 0.41 and 4 million tonnes of plastic each year. Schmidt et al. (2017) and Lebreton et al. (2017) both mentioned that due to the limited amount of data, their models include major uncertainties. For improvement, more riverine studies should be performed, covering more continents and including different regions. Nevertheless, the models provide an overview of the biggest polluters. For Indonesia, which is the second largest plastic polluter, the model of Lebreton et al. (2017) predicted a peak plastic discharge into the ocean in February, with on average 1,150 tonnes plastic/day. The lowest plastic amounts (average of 59 tonnes/day) are expected during the dry season in the month of August (Lebreton et al., 2017).

Apart from the environmental impact, debris accumulations in rivers also result in increased flood risks. Up until now, riverine debris studies predominantly focused on vegetation accumulation at bridges and gates. These studies found the maximum debris length and the pier shape to be the most important parameters (De Cicco et al., 2015). Figure 1.3A shows a bridge blockage in the Cikapundung River, which is not only composed of vegetation but also contains other types of debris (e.g. macroplastics, diapers, cardboard). The effect of these non-organic materials on the water system (and flood risk) is poorly understood. Filling in this knowledge gap is required to assess the impact of (plastic) pollution on flood risk.

1.2. SCOPE OF THIS RESEARCH

As debris causes various problems in rivers, the objective of this thesis is to obtain a better understanding of the riverine debris problems. This thesis focusses on the following two issues:

1. The amount of plastic within rivers (and drains) and thus the amount of plastic reaching the ocean is currently unknown.

2. Debris has the potential to cause river blockage, which can influence the flood risks. However, knowledge regarding dynamics of debris blockage related flood risks is lacking.

Since global plastic models indicate Indonesia as the second largest contributor of plastic debris to the ocean (Jambeck et al., 2015; Lebreton et al., 2017), it is an interesting country of study. This thesis focusses on West-Java, and more specifically on the city of Bandung. Bandung was selected since it is slightly smaller compared to Jakarta, which makes it possible to do measurements in rural and urban areas.

1.3. RESEARCH QUESTIONS

To cover the described objectives, the main research question has been defined as follows:

- *What is the influence of riverine debris on the hydrodynamics within a water system, based on experiments in Bandung (Indonesia)?*

In order to answer this main question, sub-questions are formulated for which a survey, field measurements and flume experiments are conducted.

Survey

- *What are the bottleneck locations of the Bandung water system?*

Field measurements

- *What is the ratio of riverine debris, distinguishing the categories plastic, organic and other debris?*
- *What is the composition of the present plastic debris in the Cikapundung River?*
- *What is the relation between discharge and debris flow?*

Flume experiments

- *How does debris blockage evolve over time and how is this process related to debris composition?*
- *How does the debris flux, debris load, debris composition and flow condition influence upstream water levels?*
- *What is the impact of a blocked trash rack at the downstream case study location in the Cikapundung River on the regional flood risks?*

1.4. REPORT STRUCTURE

This study is separated into two sections; (1) research and knowledge gathering and (2) experiments (Figure 1.4). The aim of the first section is to determine the state of art regarding debris studies and obtaining an overview of the bottleneck locations within the Bandung water system. The goal of the second section is to determine the debris generation, the debris composition and the debris flux in the rivers. In addition, this section focusses on obtaining knowledge regarding the horizontal and vertical debris growth, the impact on the water level and the associated debris friction. Flume experiments are performed in order to obtain this knowledge. Various flow velocities, debris compositions and debris quantities are used during those flume experiments, which are based on the results of the first section.

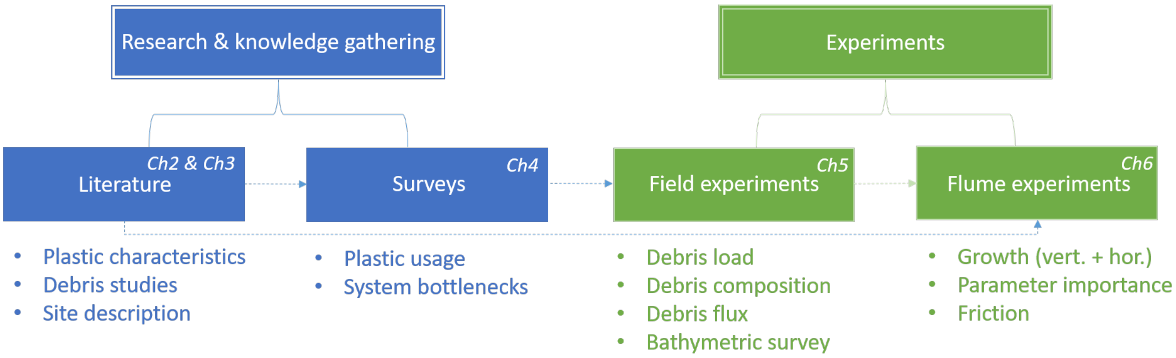


Figure 1.4: Overview of the study phases and interactions between the different phases.

The report is structured as follows;

Research & knowledge gathering The current state of art regarding debris accumulations in front of thrash racks is explained in chapter 2. This chapter also elaborates on the plastic debris measurement techniques. In chapter 3, several components of the study area are presented (e.g. the most important water quality polluters in the Citarum River Basin, the population density near the rivers and the topography of the Upper Citarum River Basin and the study locations in the Cikapundung River). In chapter 4, the approach, results and discussion of the questionnaire are discussed. The questionnaire focused on the Bandung citizens lifestyle with regards to waste and bottleneck locations in the Bandung waterways.

Experiments The approach, results and discussion of the field experiments and flume experiments are discussed in chapter 5 and 6. Chapter 6 also includes the analysis of the friction caused by the different debris mixtures. Chapter 7 is concerned with translating the findings of the flume experiments to prototype scale, which provide insights into the flow conditions at which floods can occur from debris accumulations and the mixture dependency. Furthermore, possible prevention measures that can be taken are mentioned based on the overall findings from the questionnaire, field experiments and flume tests. Chapter 8 contains the conclusions of this thesis and recommendations for further research.

2

THEORETICAL BACKGROUND

2.1. PLASTIC

The first 50 years of the twentieth century were the most important for the development of the modern types of plastics (Andrady and Neal, 2009). Plastics have become a successful material since they are inexpensive, strong, durable, lightweight, easy to manufacture and can be used at a wide temperature range. Hundreds of plastic materials are commercially available, but approximately 90 % of the total demand is covered by the six categories presented in Table 2.1.

Table 2.1: The plastic categories covering approximately 90 % of the total plastic demand, with their corresponding abbreviations and densities (RSC, 2014).

Number	Plastic category	Abbreviation	ρ [g/cm^3]	Example
1	Low-density polyethylene	LDPE	0.91-0.93	Plastic bags
2	High-density polyethylene	HDPE	0.94-0.96	Cups
3	Polypropylene	PP	0.98-0.91	Straws
4	Polyvinyl chloride	PVC	1.20-1.55	Containers
5	Poly-styrene	PS	1.04-1.11	Cutlery
6	Polyethylene terephthalate	PET	1.38-1.40	Bottles

The usage of plastic as a material can have many advantages, for example using PET instead of glass or metal for packaging beverages reduces the energy consumption by 52 % (Andrady and Neal, 2009). Furthermore, the usage of light plastic components allows for more efficiency in various industries (e.g. 20 % fuel cost reduction of the Boeing 787 (Andrady and Neal, 2009)). However, there is also a downside to the use of plastic. The majority of plastic products are used for disposable packaging or other products that are permanently discarded within the same year of manufacture (Hopewell et al., 2009). As a result, plastic particles cover a major part of urban litter and can persist for a long time. The exact life time of plastic particles depends on the chemical nature of the material and the environment, but also how the term degradation is defined.

In general, it is expected that the fragmentation into microplastic particles takes centuries, which happens though photo-, physical, and biological degradation processes. In recent decades the so-called 'biodegradable' plastics have been developed in order to decrease the residence time of plastic particles in the environment. Complete biodegradation of plastic occurs when only methane, water and carbon dioxide remain and no oligomers or monomers are present anymore. Considered truly biodegradable plastics are polylactic acid, polycaprolactone and polybutyrate adipate terephthalate. There are also other types of plastics commonly promoted as biodegradable, such as oxo-degradable plastics (Kubowicz and Booth, 2017). Oxo-degradable plastics are conventional plastics like PE, PP or PET, but contain additives that accelerate the oxidation process. Despite the faster start of the degradation process in which macroplastics become microplastics, the produced microplastic is no different to any other type of produced microplastic (Kubowicz and Booth, 2017). In addition, some of the claimed biodegradable plastics require temperatures of above 50 °C for complete break-down, but those required conditions are rarely, if ever, met in the natural environment (Kershaw, 2006).

2.2. PLASTIC BEHAVIOUR IN WATER

Two forces play a major role in the prediction of the movement of plastic particles in water, namely turbulence and buoyancy. In water without turbulence (laminar flow, which means that the flow is dominated by viscous forces), all items with a positive buoyancy will be at the surface and items with a negative buoyancy will be at the bottom. However, this is rarely the case in a river, since river bed roughness and other physical disturbances introduce internal river turbulences (González et al., 2016). As a general rule of thumb, open channel flow is turbulent (dominated by inertial forces) if the Reynolds number > 500, which can be determined by Equation 2.1 (Nguyen, 2012).

$$Re = \frac{\upsilon \cdot R}{\nu} \tag{2.1}$$

In which;

Re	Reynolds number	[-]
υ	Fluid velocity	[m/s]
R	Hydraulic radius	[m]
ν	Kinematic viscosity of the fluid	[m^2/s]

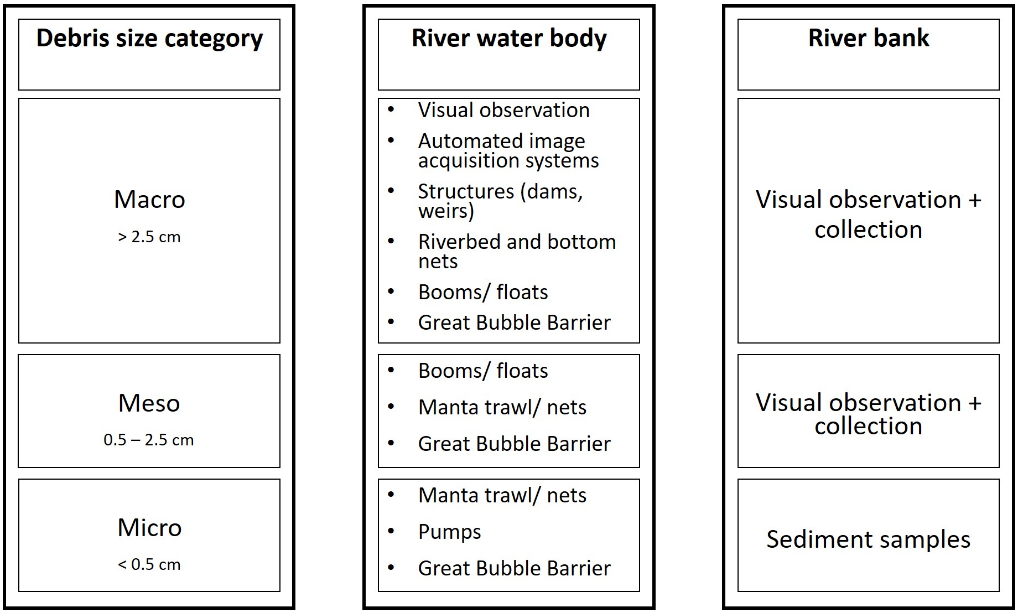
The buoyant force is affected by (1) the fluid density, (2) the volume of the displaced fluid and (3) the local gravity acceleration (Elert, 1998). The buoyancy in combination with the ratio between particle surface area and particle volume (s/v ratio) determines then the terminal velocity in up or downward direction. Long and flat particles with a low terminal velocity (e.g. microplastics) are most likely to be found in suspension, while compact particles are most likely to be found at the river surface or bottom (González et al., 2016). Based on this principle, a three-way distinction can be made between:

1. Persistent buoyant ($\rho_{particle} < \rho_{fluid}$)
2. Short-term buoyant
3. Non-buoyant items ($\rho_{particle} > \rho_{fluid}$)

As in most cases, a mix of the three buoyant types of litter is present, it is important to sample both at the surface and below the surface of the river. Furthermore, differences in the horizontal spread of plastic particles are often observed because of differences in flow velocities across the river width. This mechanism also causes river litter to accumulate in the outer bend (González et al., 2016). The persistent buoyant litter can be transported over long distances and therefore has the potential to eventually reach the ocean. About half of the plastics belong to the persistent buoyant category (Wabnitz and Nichols, 2010).

2.3. PLASTIC DEBRIS MEASUREMENTS

Carpenter and Smith (1972) were the first to report the widespread of plastic particles in oceans. On average they found 3500 particles (with a combined weight of 290 gram) per square kilometre in the western Sargasso Sea, located in the North Atlantic Ocean. After this first study, many more investigated the rising concern regarding (floating) plastic debris in oceans (e.g. Day et al., 1990; Morét-Ferguson et al., 2010; Wabnitz and Nichols, 2010; Law, 2010; Cozar et al., 2014; Jambeck et al., 2015). Apart from the many plastic debris studies



Debris size category	River water body	River bank
Macro > 2.5 cm	• Visual observation • Automated image acquisition systems • Structures (dams, weirs) • Riverbed and bottom nets • Booms/ floats • Great Bubble Barrier	Visual observation + collection
Meso 0.5 – 2.5 cm	• Booms/ floats • Manta trawl/ nets • Great Bubble Barrier	Visual observation + collection
Micro < 0.5 cm	• Manta trawl/ nets • Pumps • Great Bubble Barrier	Sediment samples

Figure 2.1: Distinction in plastic size and appropriate observation technique. Adapted from (González et al., 2016).

performed in oceans, several studies have looked at plastic debris within rivers (e.g. Moore et al., 2011; Gasperi et al., 2014; Morritt et al., 2014; Tweehyusen, 2015).

These studies categorize the plastic by size and material. Apart from the categorization based on material, a distinction can be made between;

1. Micro (particles < 0.5 cm)
2. Meso (particles between 0.5 and 2.5 cm)
3. Macro (particles > 2.5 cm)

Most studies only make a distinction between micro and macro plastic particles, which often means that the category mesoplastics is added to the category microplastics. This distinction also influences the choice for measurement technique and net mesh-size. An overview of appropriate measurement techniques per size class is given in Figure 2.1.

Most of the studies conducted on riverine plastics took place in industrialized countries of Europe and North America, with a focus on microplastics. High variations of microplastic concentrations have been recorded, which are partly caused by the different measurement techniques used throughout the studies. The most common measurement techniques involve sampling using Manta trawls (333 μm mesh size), hand nets (< 1 mm mesh size) or stationary driftnets (500 μm mesh size). Choosing between these techniques is often based on the water column sampling location. As most studies use different methods and techniques, comparing the results of each measurement campaign can be rather challenging (Dris et al., 2015).

Fewer studies have focused on mesoplastic and macroplastic debris (Tweehyusen, 2015). An overview of the different macroplastic studies and the associated measurement techniques is given in Table 2.2. Similar to the different techniques used throughout microplastic studies, the macroplastic studies also show a large variance in the applied measurement methods. In most of these macroplastic studies, PP, PE and PET are the most abundant types of plastic.

Sampling plastic in rivers has shown that the amount of litter present within a river system can be highly time dependent (Moore et al., 2011). Short-term variations can be the result of sudden dumping of debris or the opening of upstream weirs. On longer time-scales, seasonal variations in plastic litter amounts can be caused by accumulation on land during dry periods and subsequent litter wash into the river during rainy

Table 2.2: Overview of the macroplastic river studies and associated measurement techniques.

River	City, Country	Measuring method	Results	Source
Tyume	Alice town, ZA	Manual collection	2250 kg in 1 day for a 1800 m river section	Wiseman and Vurayayi (2012)
Seine	Paris, FR	10 booms, from which samples were analysed	0.8-5.1 % of total 1937 tons debris/year (monitoring campaign of 6 years)	Gasperi et al. (2014)
Elqui, Maipo, Maule & BioBio	CL	Sampling at river sides and coastal beaches	13.3-42.9 % of total debris (river side sampling)	Rech et al. (2014)
Thames	UK	Four fyke nets, to measure the bottom reach	8490 plastic items captured in the months Sep - Dec 2012	Morritt et al. (2014)
Meuse	Maastricht, NL	Trawling sampler, 3.2 mm mesh size	116,455 per day (13.25 kg/d) 9 % macro plastics (measurement campaign of 2 weeks in Dec 2013)	Tweehyusen (2015)
Sungai Batu	Kuala Lumpur, MY	Log boom in combination with bucket collector	63 ± 15 kg/d, 39 % of total debris weight (14 days of measurements in Mar & Apr 2017)	Malik and Manaf (2017)
Saigon	VN	Surface nets (h: 70 cm, mesh size: 2 cm)	Five samples with a total sample weight of 21 kg, 26 % plastic (Apr 5, 2016)	Lahens et al. (2018)

seasons (González et al., 2016). It is therefore important to monitor regularly during different seasons to better understand the underlying principles and causes of litter.

2.4. DEBRIS ACCUMULATION STUDIES

Larger organic debris, such as tree branches enter the river and are transported during floods. The risk of debris accumulations is particularly high in front of bridge pillars and other hydraulic structures in the river. A number of authors reported an increased flow resistance as a result of debris accumulations (Shields and Smith, 1992; Marriott, 1996; Dudley et al., 1998). Dudley et al. (1998) performed water level measurements prior to and after removal of accumulated tree branches at bridge piers, which on average resulted in an increased Manning roughness value of 39 %. The friction caused by debris, increased as the flow depth decreased. The increased roughness results in an increase of the upstream water levels (Schmocker et al., 2013). The resulting forces from these accumulations, in combination with the intensifying pier scour can lead to structure failure (Diehl, 1997; Zevenbergen et al., 2006). Diehl (1997) estimated that about 30 % of the bridge failures in the United States were related to organic debris accumulations.

It is challenging to examine the consequences and parameter importance in situ due to the many variables and uncertainties within a river, which makes it challenging to draw well-founded conclusions. For this reason, there are limited studies that conducted field measurements regarding debris accumulations in rivers. Scaled flume experiments provide a good alternative to obtain further knowledge and insights in debris accumulations.

DEBRIS LABORATORY STUDIES

In recent years, a number of laboratory studies have reported on debris transportation, the formation of debris accumulations and the backwater effects caused by debris accumulations.

Braudrick and Grant (2001) examined the transportation and deposition of tree branches. They reported that floating pieces tend to orient parallel to the flow and are predominantly located in the centre of the channel. Pieces were deposited when the channel depth met the buoyant depth, typically at the outside of bends, at wider shallow river sections or at the head of mid-channel bars. The presence of these parameters is therefore important for the travel distance, but also the debris roughness, length and diameter in relation to the channel width, depth and degree of meandering were found to be important parameters.

Schmocker et al. (2013) performed small scale (1:35) tests with a trash rack set-up to evaluate the importance of various parameters, including test duration, watering time of the debris, debris volume, debris dimension, debris mixture, approach flow Froude number and diameter of the trash rack pillars. Even though a certain randomness in the formation and ordering of a debris accumulation has to be accepted, the reproducibility of the tests was found to be acceptable to draw well-founded conclusions. The Froude number and debris volumes were found to be the most important parameters for both the accumulation process and the backwater effects. The final backwater level was not influenced by the pole diameter or test duration. Furthermore, two phases of debris accumulation (gate forming and carpet formation) can be distinguished (Figure 2.2).

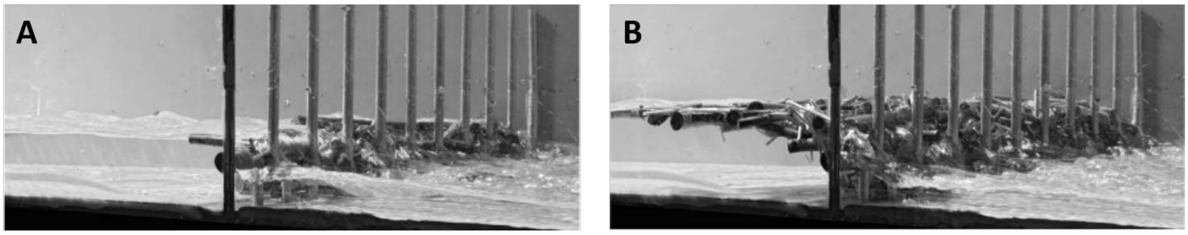


Figure 2.2: (A) Initial debris accumulation at trash rack and (B) formation of debris carpet. Adapted from Schmocker et al. (2013).

Panici et al. (2017) investigated the stability of debris accumulations in front of single piers. The jam behaviour can be described by three phases:

1. Unstable; rapid debris accumulation growth at a bridge pier, but debris can easily be separated again.
2. Stable; lower growth rate, but captured debris is also less likely to be disengaged.
3. Critical; the debris accumulation shifts slightly, until it ultimately drifts away.

The maximum achieved width before failure was 1.5 times the length of the longest particle in the experiment with a non-uniform mixture and 3 times the length of the particles in the experiment with an uniform mixture. The maximum width was achieved during the experiment with the lowest Froude number while for higher Froude numbers, the growth predominantly increased in the vertical direction.

Hartlieb (2017) performed large scale (1:20) tests in a rectangular canal on an open laboratory area. The test focussed on debris accumulations in front of both spillways and retention racks. Similar to Schmocker et al. (2013), the approach flow Froude number was found to be one of the main parameters regarding the impact on the backwater effect. In addition, the density of the debris was found to be an important parameter as well. In contrast with Schmocker et al. (2013) different tests with identical test conditions, resulted in significant different backwater effects due to the randomness of debris accumulation ordering. No quantification of the dependence of the backwater effect on the approach flow Froude number and the density of the debris was performed.

3

Site description

3.1. Introduction

First, the general pollution problem of the whole Citarum River Basin will be explained in section 3.2. Second, the upstream conditions of the Upper Citarum River Basin are described, as well as a more detailed explanation of the impact of the pollution (section 3.3). Third, section 3.4 contains the specific properties of the Cikapundung River, because both the field measurement locations and case study location are based in this tributary of the Citarum River.

3.2. Citarum River Basin

The Citarum River flows from Bandung to the Java Sea and with a length of 270 kilometres it is the longest river of West-Java (Figure 3.1). The Citarum River is one of worlds most polluted rivers because industries and households dump their waste directly in it. Surprisingly enough, 27 million people depend on the water from the Citarum River, since it is used for crops and piped household water in both Bandung and Jakarta. (Soeriaatmadja, 2018)

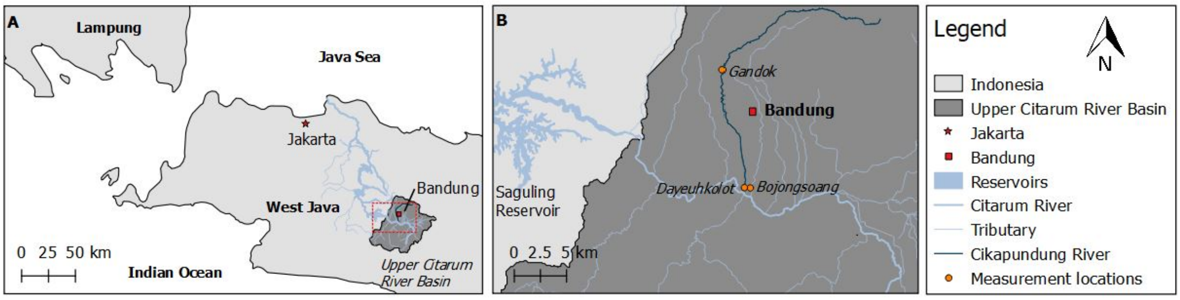


Figure 3.1: (A) The Citarum River Basin, located in West-Java (Indonesia). (B) Indication of the measurement locations in the Cikapundung River in Bandung, West-Java.

Figure 3.2: Field observation of the floating debris at June 12, 2018 in the Citarum River (6°56′00.8″S, 107°30′20.5″E). Photos facing North-East direction.

The Citarum River flows through three reservoirs, which were primary constructed for hydro-power and irrigation purposes (Sembiring, 1995). The reservoirs from Bandung to the Java Sea are:

1. The Saguling Reservoir ($V = 1.0 \times 10^9 m^3$, $A = 5.3 \times 10^7 m^2$, completed in 1985)
2. The Cirata Reservoir ($V = 2.2 \times 10^9 m^3$, $A = 6.2 \times 10^7 m^2$, build in 1988)
3. The Jatiluhur Reservoir ($V = 3.0 \times 10^9 m^3$, $A = 8.3 \times 10^7 m^2$, construction finished in 1967)

Within the Citarum River Basin there are thousands of factories serving various industries. As mentioned before, these industries have a significant effect on the water quality. The textile and paper industries are the main polluters, but also pharmaceutical and food processing industries have a large effect on the water quality. The industries all together are responsible for a significant amount of Biological Oxygen Demand (BOD), nitrogen, phosphorus, heavy metals (such as zinc, mercury and selenium), cyanide and phenol pollution. The domestic sewage pollution is responsible for BOD, nitrogen and phosphorus, these chemicals stimulate plant growth and algal blooms. In addition, an excessive inflow of nitrogen and phosphorus comes from agricultural waste, since the use of fertilizers (e.g. Triple Super Phosphate and urea) is relatively high. Furthermore, the waste of both livestock and fish farming are equivalent to the effect of domestic sewage. These fish farming practices take place in all three of the aforementioned reservoirs and have a negative influence on the water quality of these reservoirs. (Sembiring, 1995)

The Upper Citarum River Basin ($A = 1.8 \times 10^8 m^2$) is the most industrialized area within the basin and is located upstream of the Saguling Reservoir (Sembiring, 1995). This area includes the city of Bandung, which is a major source of pollution. Figure 3.2 shows the floating debris where the Citarum River enters the Saguling Reservoir at June 12, 2018.

3.3. UPPER CITARUM RIVER BASIN

In 2017, a large-scale clean-up operation started at the origin of the Citarum River, after which the operation continued in downstream direction. Military troops were deployed to curb the river pollution and prevent

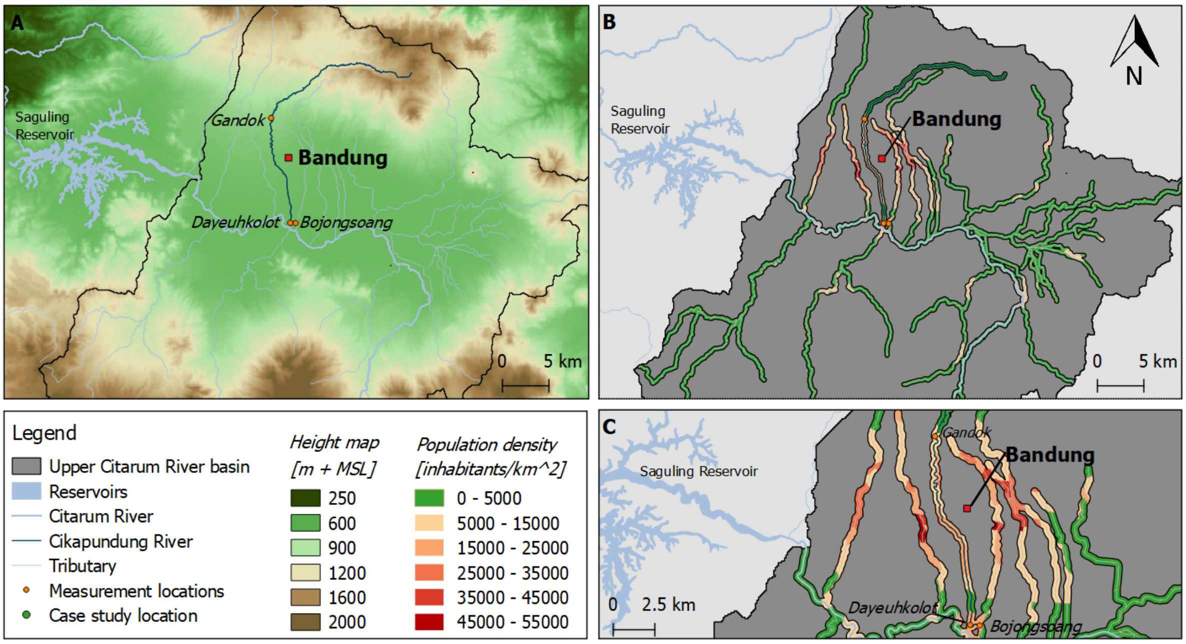


Figure 3.3: (A) The height map of the Upper Citarum River Basin, (B) a map showing the population density for a 200 m buffer zone from the river banks and (C) a close-up for the population density for the city of Bandung. The Cikapundung River is indicated by a dark blue line in all sub-figures.

public littering and factories dumping their waste (Soeriaatmadja, 2018).

The Bandung Metropolian Area (BMA) is crossed by 15 rivers, that are part of the Upper Citarum River Basin and most of those rivers are highly polluted due to the lack of community awareness, waste disposal and direct disposal of waste water (OECD, 2016). There are three main issues affecting the solid waste management in the BMA:

1. Limited waste collection; according to estimations, about 35 % of the within BMA produced solid waste is not collected or disposed at a landfill. This portion is either burned or dumped in open spaces, drains or rivers.
2. Lack of recycling; only 5 % of the non-organic waste is recycled.
3. Lack of disposal sites; Sirimukti landfill site is the only disposal site for solid waste.

Figure 3.3A shows the elevation map for the Upper Citarum River Basin, combined with the origin of the 15 rivers. Figure 3.3B shows the population density for a 200 m buffer zone from the river banks, since this part of the population is most likely to dispose their waste directly into the river. A close-up of the population density for the city of Bandung in Figure 3.3C. This study will focus on the Cikapundung River, which is one of the 15 tributaries of the Citarum River.

3.4. STUDY AREA: CIKAPUNDUNG RIVER

The 28 km long Cikapundung River intersects with the city of Bandung and is depicted dark blue in Figure 3.1 and Figure 3.3. Upstream from Bandung, the river predominantly flows through rural area and the mountainous city Lembang, which is a popular tourist destination. The river merges with the Cigede River in the Southern part of Bandung, after which it finally reaches the Citarum River.

The regional military already started cleaning actions in the Cikapundung River in June 2016 (DCI, 2016). Apart from the cleaning actions, the military also installed a temporary trash rack construction in the down-

Figure 3.4: (A) Temporary trash rack construction installed by the military in the Cikapundung River in Bandung compared to commonly used trash racks, (B) such as the Mangarai Gate in Jakarta (Pagano, 2011)

stream part of the Cikapundung River (Figure 3.4A). Similar temporary trash rack constructions have also been installed at the river mouth of other tributaries, to lower the pollution reaching the Citarum River and the Saguling Reservoir.

There are no working permanent trash rack constructions in Bandung, such as the Mangarai Gate in Jakarta (Figure 3.4B). However, both types of debris racks must be cleaned manually, since integrated trash cleaners are missing. In Jakarta, excavators are permanently present at the trash rack to remove the collected debris. In Bandung the trash rack constructions (as well as debris accumulations at bridges) are manually cleaned by the military. The temporary trash rack constructions in Bandung are often destroyed during heavy floods, after which a similar construction is installed again. A similar temporary trash rack construction of Figure 3.4A will be used as a barrier for flume experiments (chapter 6). Furthermore, measurements to determine the debris flow are performed at three different locations in the Cikapundung River (chapter 5).

3.5. SEASONAL VARIATIONS

The monthly rainfall and daily discharge variations are presented in Figure 3.5. On average, the highest amounts of rainfall occur during the month November, while the peak discharge follows in the month February. Figure 3.5B indirectly shows an increase in the flow depth. The increase in discharge starts in October and keeps increasing until it reaches its maximum value in February ($Q = 3.9\ m^3/s$), after which the discharge decreases again until the minimum flow is reached in September ($Q = 0.9\ m^3/s$).

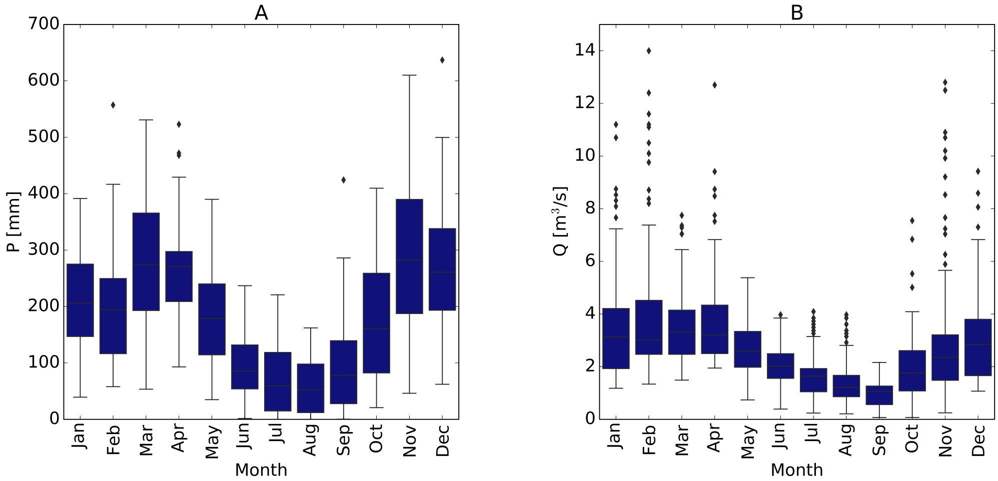


Figure 3.5: (A) The monthly precipitation variation, based on daily precipitation data of the Geofiska station in Bandung for the 1978-2018. (B) The spread for each month in average daily discharge values, measured at upstream discharge station Gandok in the period 1999 - 2005. *One outlier of the raw discharge data has been removed, since this value was a factor 10 higher compared to the average daily discharge of that month, while no extreme rainfall amounts were measured at the same period.

3.6. FLOOD AREAS IN UPPER CITARUM RIVER BASIN

Yearly floods in the Upper Citarum River Basin are a common problem. In the last 30 years, major floods took place in 1986, 2005, 2009 and 2010 (Maulana, 2001). A total area of 7,450 ha was flooded in March 1986 and 4,700 ha was covered by water from February till March 2005. The flooded areas are depicted in Figure 3.6. As of May 2005, channel improvements started in the Citarum River as well as in several tributaries of the Citarum River (Natasaputra, 2010). At some places river normalisation took place, but the most common approach was dredging. One of the researchers of the Centre for Water Resources Research (PUSAIR) mentioned that the focus should be on the long-term solution, such as reforestation to overcome the erosion and raising awareness to no longer throw waste in the river (Maulana, 2001).

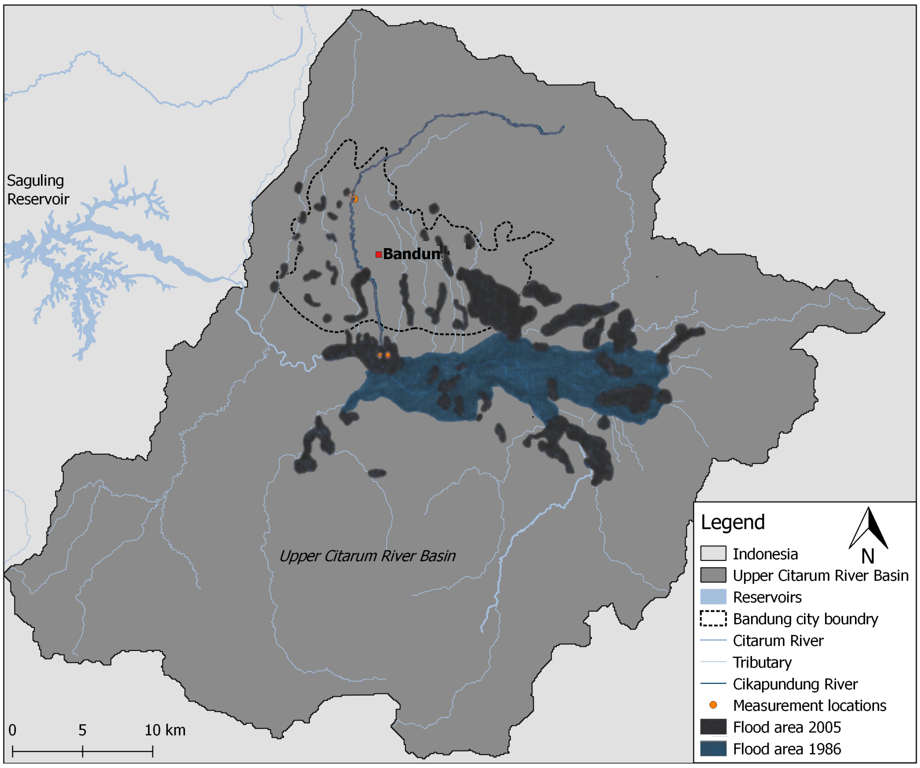


Figure 3.6: The areas covered by water during the major flood events of 1986 and 2005 in the Upper Citarum River Basin (Natasaputra, 2010).

4

QUESTIONNAIRE

4.1. PURPOSE OF THE QUESTIONNAIRE

As mentioned before, flood events are common problems in the Upper Citarum River Basin. In this chapter, the debris bottleneck locations of the Bandung Regency are assessed using questionnaires. Based on these findings, several locations were visited to determine which locations were suitable for measurements. Accessibility to the water and a decent flow velocity were the most important parameters for deciding whether a location was suitable. Furthermore, the questionnaire was aimed at obtaining insights into the local waste management.

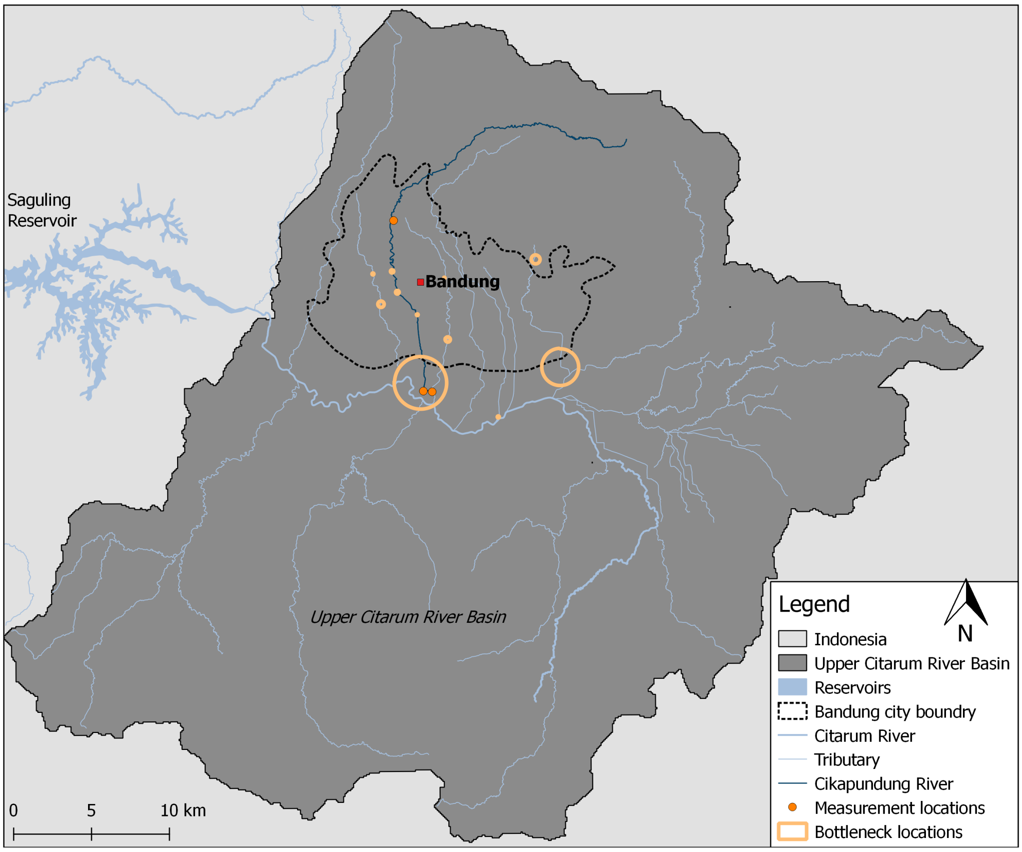


Figure 4.1: Overview of the bottleneck locations in the Bandung Regency mentioned during the questionnaire of May 2018.

4.2. MATERIALS AND METHOD

After determining the measurement locations, 15 people per location were asked about their knowledge of and experience with floods, debris accumulation and river cleaning activities. Furthermore, residents were asked some questions related to their household size, waste production, waste disposal, income and willingness to pay waste collection tax. The questionnaire is shown in Appendix B. In total 55 participants contributed; 15 per measurement location, one local contact, one employee of Waste4Change and 8 students and employees of the ITB.

4.3. RESULTS

The mentioned bottleneck locations are presented in Figure 4.1. The other most relevant results of the questionnaire (Appendix B) are summarized in Table 4.1 and a more complete overview can be found in Table B.1. Remarkably, no obvious relation was found between the household size and the amount of produced waste. Furthermore, only four of the questioned people mentioned willingness to pay money about 1 % of their monthly income for waste collection. Only two of the interviewed people mentioned to occasionally throw (organic) waste in the river. Floods and debris accumulations only occur frequently at two downstream locations, whereas most of the people have experienced damage from floods. Figure 4.2A shows the elevation of the water during a major flood event in the neighbourhood of measurement location 3 and Figure 4.2B shows the flood damage in a garage near measurement location 3.

Table 4.1: The most relevant results of the 55 questionnaires. One local contact, one employee of Waste for Change, 8 students and employees of the ITB and 15 persons per measurement location contributed to this survey.

Variable	General response	Remarks
Waste disposal	Burning (41 %) Burning/ collection (36 %) Brings to collection point (17 %) River (4 %) Collection + fermenting organic waste (2 %)	One person mentions to throw all the waste in the river and one person only throws organic waste in the river.
Collection by the government	Yes (56 %)	Mostly once per week
Willingness to pay money for waste collection	Yes (8 %) Rp. 20,000-60,000*	About 1 % of monthly income
Floods	Only downstream at loc. 2 & 3	Floods multiple times per year Major floods about 1/3 years
Flood damage	Loc.2 (100 %), Loc. 3 (70 %) Rp. 100,000-25,000,000*	Extreme floods → damage costs up to 1/2 year salary
River cleaning frequency	Weekly check (52 %) Several times/year (18 %) In case of blockage problems (15 %) No knowledge of (11 %) Before public events (4 %)	Cleaning performed by military
Cleaning responsibility	Both residents and government (60 %) Government (22 %) Residents (18 %)	
General comments	- Debris is expected to partly come from the rubbish place (upstream). - Two persons mention to already pay Rp. 25,000*/ month tax for waste collection. - Pastor told location 2 was cleaned 10 times by the military in January-May, 2018.	

*Rp 100.000 equals 6 Euro

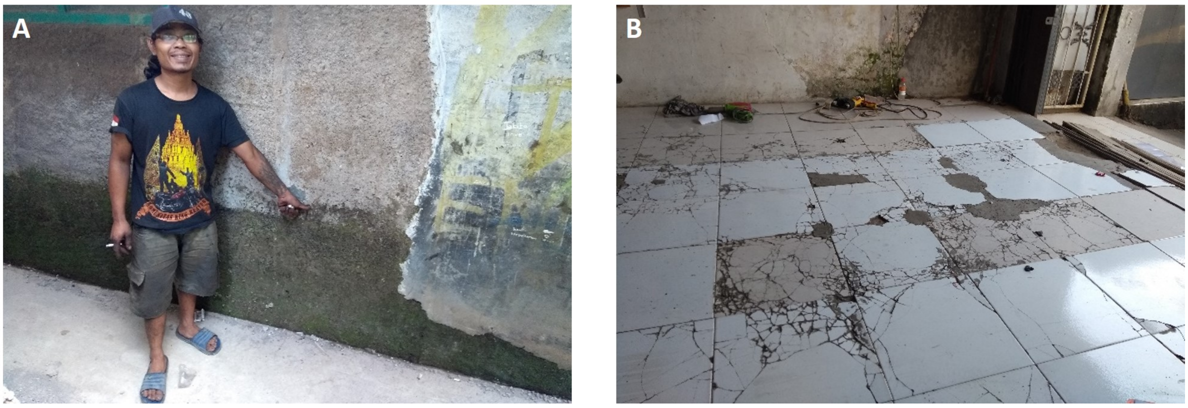


Figure 4.2: (A) One of the residents near measurement location 3 indicating how high the flood water reaches at houses in this area and (B) the flood damage in a garage near measurement location 3.

4.4. DISCUSSION

WASTE DISPOSAL IN THE CIKAPUNDUNG RIVER

The questionnaire result showed that just a few people throw waste in the water or are willing to admit that they throw waste in the water. This is quite different from the questionnaire results of 2008 in the Kelurahan Tamansari neighbourhood. In this study 132 inhabitants were interviewed of which 61 % mentioned to throw their waste in the Cikapundung River (Ghassani and Yusuf, 2015). The most important reasons mentioned for throwing were; (1) fastest method, (2) space and (3) garbage smell.

The significant differences can be the result of a different way of questioning. Furthermore, the population density in the Kelurahan Tamansari neighbourhood is much higher compared to the population density at the measurement locations of this research. The higher population density is related to the lack of space and might still be one of the important reasons that people from the Kelurahan Tamansari neighbourhood throw waste in the river, while burning is more common at the measurement locations. Another possibility is that the attitude of residents has changed in the meantime.

WILLINGNESS TO PAY TAX FOR WASTE COLLECTION

Currently, most people are not paying tax for garbage collection in the Bandung region. It is therefore not surprising that the willingness to start paying for this is rather low. In addition, the benefits of proper waste collection might not be very clear, since the people upstream the Cikapundung River had no knowledge of the downstream problems regarding debris accumulations and floods.

5

FIELD MEASUREMENTS

5.1. INTRODUCTION

This chapter will elaborate on the performed field measurements. The locations are discussed first. Second, the approach and method are explained. Then the results are presented as third. As fourth and final part, there is a discussion section of the results.

5.2. MEASUREMENT LOCATIONS

The measurement locations are presented in Figure 3.1 and the corresponding coordinates are given in Table 5.1. At location 1, which is the most upstream location, the debris is measured in the Northern part of the city of Bandung. Upstream from Bandung, the river predominantly flows through rural area and the mountainous city Lembang, which is a popular tourist destination. Location 2 and 3 are located close to each other in the Southern part of Bandung, which is also the downstream area of the Cikapundung River. At location 3 the Cikapundung merges with the Cigede after which it reaches the Citarum River. Location 3 was selected to compare the debris composition between location 2 and 3, since this could provide valuable information of the differences between the Cikapundung River and the Cigede River.

Table 5.1: Specification of the in Figure 3.1B displayed study locations in the Cikapundung River in Bandung, Indonesia. The population density is based on Bandung inhabitants statistics of 2015 (BCG, 2015).

Location	Neighbourhood	Latitude	Longitude	Sub-district	ρ_{pop} [#/km^2]
1	Gandok	$6°52'56.79"S$	$107°36'22.62"E$	Cidadap	34368
2	Dayeuhkolot	$6°59'2.02"S$	$107°37'29.66"E$	Dayeuhkolot	56264
3	Bojongsoang	$6°59'3.35"S$	$107°37'48.19"E$	Bojongsoang	14346

Figure 5.1: (A) Upstream measurement location 1, Gandok and (B) downstream measurement location 2, Dayeuhkolot. (C) Merging point of Cikapundung River and Cigade River upstream of measurement location three and (D) downstream measurement location 3, Bojongsoang. Note the colour difference between the Cikapundung and Cigade River in sub-figure C. All pictures date from May 2018. The corresponding geographical locations are presented in Figure 3.1.

5.3. MATERIALS AND METHOD

Field measurements were performed at three locations in the Cikapundung River, of which the coordinates are mentioned in Table 5.1. Floating debris samples were taken during a 10-day measurement campaign. During the first three days, measurements were performed using a trawl (h_t = 0.5 m by w_t = 0.7 m, mesh size = 4 cm, Figure 5.3A) and a net (h_t = 2 m by w_t = 7 m, mesh size = 2.5 cm, Figure 5.2). The combination of acting water forces, the weight of all the accumulated debris and the weight of the anchor line became too heavy for the manpower of five people to extract the net out of the water. After 10 minutes, there was a water level difference in front of and behind the net of several centimetres, caused by the accumulated debris indicated in Figure 5.2. Since the heavy net could not be extracted from the river, it was decided to focus on trawl measurements. The trawl measurements focus on the surface debris load, but also measure the debris ratio between the surface and subsurface using a double trawl (h_t = 2×0.5 m by w_t = 0.7 m, mesh size = 2 cm, Figure 5.3B).

At the selected survey locations, three days of single trawl measurements were performed. Only at location 2, additional double trawl measurements were performed during two measurement days. Details are explained in Table 5.2. The standard time of a trawl session was set to 10 minutes, aiming to capture between 1 to 4 kg of waste per trawl session. Since the waste was significantly less at measurement location 1, the measurement time for this location was set to 30 minutes. The standard measurement time at measurement location 1 was altered when both the water level, flow velocity and debris load increased after heavy rainfall.

Table 5.2: Overview of the field measurements performed in Bandung. Presenting the number of measurements per location and for both the single and the double trawl of the number of measurements days, the number of trawl sessions and the total measurement time.

		Location 1	Location 2	Location 3
Single trawl	# days	3	3	3
	# trawl sessions	17	14	15
	# minutes	390	125	147
Double trawl	# days	0	2	0
	# trawl sessions	0	10	0
	# minutes	0	80	0

After every trawl session, the debris was separated in (1) plastics, (2) organics, (3) other debris. The weight was determined for all measurement days and an additional volume measurement was done for 20 kg debris. After this, a secondary separation of the plastics was based on the following 5 categories (described in Table 2.1); (1) PET, (2) PP + PS, (3) HDPE, (4) LDPE and (5) Multilayer plastics.

Apart form the debris composition measurements, the flow velocity and the river bathymetry were measured. The flow velocity was measured with a current meter Flowatch FL-03 (Figure 5.4B) and the river bathymetry

Figure 5.2: Water level difference between up and downstream of the big net filled with 5 minutes of accumulated debris at measurement location 2 on 16/05/2018.

Figure 5.3: (A) Trawl measurement set-up at measurement location 2 and (B) emptying the double trawl measurement before sorting.

was determined with a deeper Smart Pro Fish Finder (Figure 5.4C). The flow velocity and river bathymetry were then used to calculate the discharge Q [m^3/s], the debris concentration c [kg/m^3] and the debris load F [$kg/m^2/s$].

$$Q = \Sigma A_i \times v_i \tag{5.1}$$

$$c = \frac{M_d}{A_{trawl} \times v_{trawl} \times t} \tag{5.2}$$

$$F_{trawl} = c \times v_{trawl} \tag{5.3}$$

$$F_{river} = c \times \alpha \times \frac{Q_{river}}{A_{river}} \tag{5.4}$$

$$\alpha = \frac{M_{surf} + M_{subsurf}}{2 \times M_{surf}} \tag{5.5}$$

In which A_i [m^2] represents the river subsection area, v_i [m/s] the river subsection flow velocity, M_{debris} [kg] the debris mass, A_{trawl} [m^2] the trawl measurement area, v_{trawl} [m/s] the flow velocity in front of the trawl, t [s] the trawl measurement time and α [-] the factor by which the measured surface debris mass has to be reduced, in order to get the average debris mass.

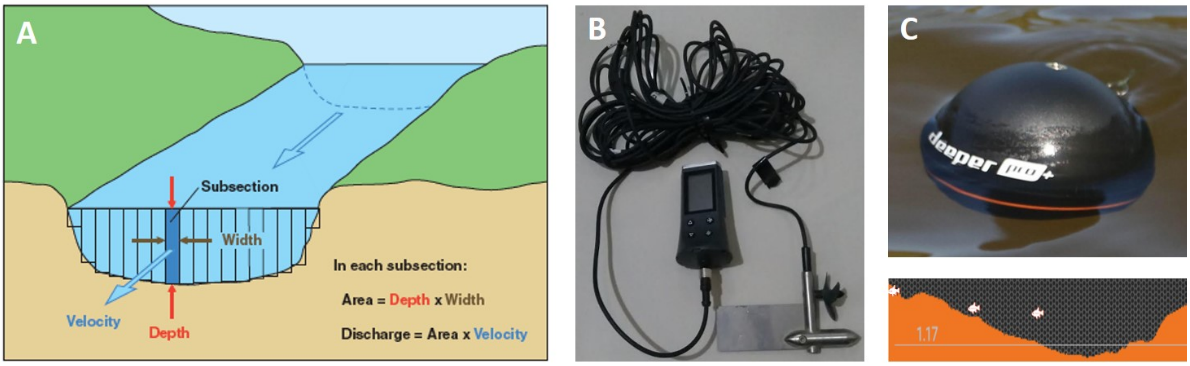


Figure 5.4: (A) River discharge determination based on (B) flow velocity measurements with the current meter Flowatch FL-03 and (C) bathymetry measurements with the Deeper Smart Pro Fish Finder.

5.4. RESULTS

PRIMARY SORTING

A total of ± 100 kg debris was caught over 12 hours during 10 measurement days (Table C.1). Figure 5.5A displays the debris caught during one of the trawl surveys at measurement location 3. Figure 5.5B shows the results of the primary sorting of debris.

The average weight distribution that was found for plastic, organic and rest debris was respectively 34 %, 43 % and 23 % (Table C.1). This composition varied considerably between the measurements, for example the plastic percentage ranged from 11 % to 78 % (Figure 5.6 and Table C.1). The highest average amount of plastic was captured at measurement location 2. In addition to the debris weight measurements, the volume of 20 kg debris was also determined (Figure C.1). The average deviation in percentages of organic, plastic and rest debris are comparable for the weight and volume (e.g. 48 % vs 46 % for organic).

Apart from the change in composition, also a high variation in debris was measured. As stated in the method, during some measurements the trawling time deviated from the standard ten minutes. The measurement results are converted to a debris weight per 10 minutes for equal comparison and shown in Table C.2. The lowest amount of debris was captured at measurement location 1 (0.1 kg/ 10 min) and the highest amount at measurement location 2 (8 kg/10 min). The average captured debris was 0.5 kg/10 min for measurement location 1, 2.6 kg/10 min for measurement location 2 and 2.5 kg/10 min for measurement location 3.

Figure 5.5: (A) Captured debris at location 3 during at one of the trawl measurement at 22 May 2018 and (B) primary sorting.

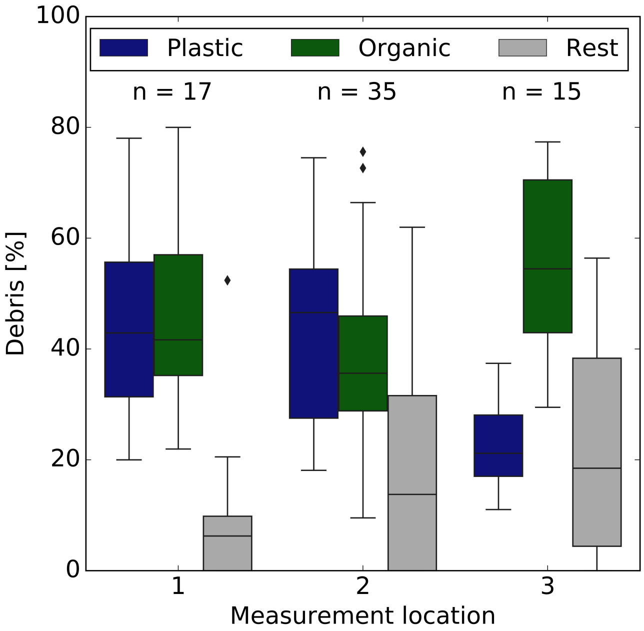


Figure 5.6: Range per measurement location for debris percentage distinguishing the categories plastic, organic and rest. The number of debris ranges, for each measurement location is given by the value n.

Table 5.3: Measurement results of debris distribution over the water column, based on double trawl measurements performed at measurement location 2 on May 23 and 26, 2018.

Specification	Unit	Surface	Bottom	Total
M	kg	8.6	8.3	16.9
A	m^2	0.23	0.35	-
M	kg/m^2	37.4	23.7	61.1
M	%	61	39	100

Table C.1 shows the difference between surface and subsurface floating debris, based on double trawl measurements performed at location 2 on May 23 and 26, 2018. Since the upper part of the trawl was for 2/3 underwater, a multiplication factor of 3/2 was used to determine the ratio between surface and subsurface flow. This resulted in 61 % surface and 39 % subsurface debris flow. Furthermore, a comparison was made between the weight percentages for plastics, organics and rest material in the surface and subsurface flow (Figure 14). The mass percentages for organics was significantly higher in the subsurface compared to the surface (32 % and 51 % respectively), whereas the mass percentages for both plastics and rest material are much lower in the subsurface than in the surface layer.

SECONDARY SORTING

Table C.3 shows the secondary sorting results of the total captured debris for the three measurement locations. The distributions in terms of percentages is quite similar for the different sites. Plastic bags are the most abundant type of plastic (57 %), followed by food packaging (21 %) and plastic cups (16 %).

In addition, a comparison was made of the weight percentage per type of plastic in the surface and subsurface (Figure 5.7). LDPE is the most abundant type of plastic in both surface and subsurface. However, the percentage of LDPE is lower in the subsurface than at the surface (67 % surface vs 56 % subsurface), whereas the percentage of multilayer plastic increases in the subsurface (23 % surface vs 37 % subsurface). During the double trawl measurements, there were no bottles (PET) captured and only a few straws and cutlery (PP/PS) items. The weight of those PP/PS particles was for every measurement lower than the sensitivity

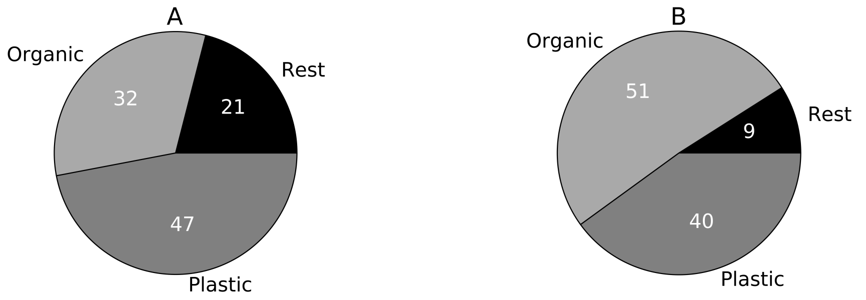


Figure 5.7: The debris in mass percentages for (A) surface and (B) subsurface flow, based on double trawl measurements performed at measurement location 2 on May 23 and 26, 2018.

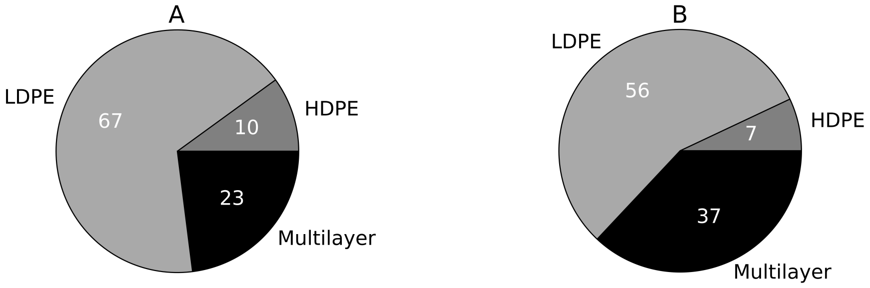


Figure 5.8: The weight percentage per type of plastic for both the (A) surface and (B) subsurface, data obtained with the double trawl at measurement location two on May 23 and 26, 2018.

of the weighing gauge (0.01 kg). PET bottles are collected by citizens, since recycling companies buy these bottles (S. Ardian, personal communication, May 26, 2018).

For each plastic category with the exception of PET, 20 samples (Figure 5.9) were taken back to the laboratory in order to compare the wet weight to the dry weight. The biggest differences between dry and wet weight occurs for plastic bags (LDPE), for which the wet weight was twice the dry weight (Table C.4).

DEBRIS LOAD

The results of the average flow velocity, bathymetry and discharge for each measurement location are presented in Appendix D. The heavy rainfall events on May 18 and 21 resulted in a doubling of the discharge at measurement location 1 (Table 5.4). The debris trawl flux even increased by a factor 30 (Table 5.4).

Figure 5.9: The 20 samples of the four plastic categories; PP/PS, PO Hard, PO Soft and multilayer, that were taken back into the laboratory to compare the dry and wet weight.

Table 5.4: Overview of the measured average flow conditions, the plastic particle flux and debris load for each measurement location. In this table the 6.5* minutes of measurements at location 1 were taken after heavy rainfall events, which significantly changed both the river bathymetry and flow conditions on May 18 and 21, 2018.

Loc.	Trawl	t min	v_{trawl} m/s	Q_{river} m^3/s	A_{river} m^2	M kg	c_{trawl} kg/m^3	α -	F_{trawl} $\#/m^2/s$	F_{trawl} $kg/m^2/s$	F_{river} kg/d
1	Single	390	0.3	1.9	6.5	9.8	0.005	0.83	0.1	0.001	$6.3 \cdot 10^2$
		6.5*	0.5	4.4	9.7	3.6	0.062	0.83	1.6	0.03	$1.9 \cdot 10^4$
2	Single	125	0.5	2.3	7.3	28.0	0.025	0.83	0.6	0.01	$4.1 \cdot 10^3$
	Double	80	0.5	2.3	7.3	16.9	0.023	1	0.3	0.01	$4.7 \cdot 10^3$
3	Single	147	0.3	2.8	7.1	39.1	0.049	0.83	0.4	0.02	$1.0 \cdot 10^4$

Figure 5.10: Comparison of the debris accumulation at the intersection of the Cikapundung and Cigede River between (A) May 15, 2018 and (B) June 26, 2018.

5.5. DISCUSSION

SEASONAL VARIATIONS

Field measurements were performed in May of 2018. Heavy rainfall showers frequently occurred in the afternoon even though it was the beginning of the dry season. The heavy rainfall events caused increased water levels and debris loads. However, this relation between discharge and debris flow is not expected to be constant over the year. The debris accumulation in the river banks will increase during the dry period and more debris is expected to flush away when water levels increase in the beginning of the rainy season (González et al., 2016). This assumption is supported by the observed growth of accumulated debris at the intersection point of the Cikapundung and Cigede River between May 15, 2018 and June 26, 2018 (Figure 5.10). This means that the measured debris flux is not representative for the entire year.

CROSS-SECTIONAL VARIATIONS

Less surface floating debris was noticed at measurement location 2, while the results indicate the highest debris load for this location. This could be explained by higher turbulence caused by the higher flow velocity and thus more debris scattered over the water column. The double trawl results indicating the spread over the water column have been used to determine the factor α, which is used to determine the total debris river load. Since the flow velocities at measurement location 1 and 3 are lower, the α factor for those measurement locations might be lower too, resulting in a lower debris load. Furthermore, the α factor might be influenced by the measurement method. Since the newly built double trawl was not heavy enough, the trawl had to be fixed at the river bottom to ensure the trawl was perpendicular to the water flow. This was done by two people standing in the water, next to the trawl. The people standing in the water are in fact obstacles causing increased turbulence, which on its turn results in a higher vertical distribution of the debris and might result in an overestimation of the actual α factor.

The measurements were performed at fixed locations to compare the different measurements. It was impossible to simultaneously study the horizontal variation of debris over the width of the river, because two identical trawls were unavailable. Performing trawl measurements over the river width on different moments in time makes a direct comparison between the locations troublesome. Another constraint was the limited debris size that could be captured with the available trawl for this study. This limitation especially influenced the measurements after the heavy rainfall showers, because the increased water levels and flow velocities brought an increased amount of larger debris.

SPATIAL VARIATIONS

The debris flux was found to be significantly larger at the downstream measurement locations, compared to the upstream measurement location. This might be the result of difference in land use, since agriculture is predominant for the upstream location and urban for the downstream locations. The measurements show a great variety in the ratio between plastic, organics and other debris for each location. However, compared to the other locations, the amount of plastic at measurement location 3 is significantly lower and the amount of organics is higher. This could be explained by the fact that this is the only measurement location where dead animals were regulary found in the trawls, which resulted in a much higher organic weight compared to the other sites. Measurement location 2 and 3 are close to each other, still we observe differences in the ratio organic to plastic debris. This could be attributed to the fact that the Cikapundung and Cigede River come together just before measurement location 3 (Figure 5.1).

SECONDARY SORTING

Although PP/PS was captured during the double trawl measurements, this plastic category is lacking in the secondary sorting weight results for both the surface and subsurface (Figure 5.8). The minimum weight observed by the scale was 0.1 kg, but the weight of the caught PP/PS for all double trawl measurements was less than 0.1 kg. The approach of performing a secondary sorting after each trawl session is not the most suitable method to provide an overview of the ratio of captured plastic types, at least not with the accuracy of the used scale. Even though this method could be improved, the main goal of determining the most abundant types of plastic in the river is met.

The results show that plastic bags are the most abundant type of plastic at all measurement locations in the Cikapundung River, followed by multilayer plastic particles and plastic cups (Figure 5.8). This is as expected because these types of plastics are mostly used for food packaging and grocery transportation. Another notable result was the absence of PET bottles. During the measurement campaign, only three PET bottles were caught. This absence might be explained by the collection of PET bottles by citizens, with the purpose of selling them to recycling operations (S. Ardian, personal communication, May 26, 2018).

MESH SIZE

The single and double trawls had mesh sizes of 4 cm and 2.5 cm respectively. As a result, some macroplastic particles (>2.5 cm) can pass through the single trawl, which might result in an underestimation of the macroplastic debris flux. It also influences the fair comparison of different macroplastic studies, for which an uniform measurement method would be preferable. The need for one uniform measurement method in plastic studies has also been mentioned by; Tyler (2011); González et al. (2016); González-Fernández, D., Hanke (2017).

COMPARISON WITH OTHER MEASUREMENT CAMPAIGNS

Several macroplastic studies (mentioned in Table 2.2) used a boom to collect surface floating debris. The boom will impact the flow conditions in a comparable way as a blocked trash rack, which means that for low flow velocities a debris carpet is formed and the passing percentage underneath the boom increases for increasing flow velocities. The trawl on the other hand has a limited impact on the flow conditions and it is not suitable to use the same alpha factor as found in this thesis for trawl measurements to determine the riverine plastic flux for studies conducted with a boom, at least not without additional tests. Despite the different measuring method, the measurement results were used to compare the average debris composition found in this research to the results of other macroplastic studies.

MODELLED VERSUS MEASURED PLASTIC RIVER LOAD

The models of Lebreton et al. (2017) and Schmidt et al. (2017) both ranked the Yangtze River as the number one polluter, but the models were less unanimous for the other top 10 most polluted rivers. For example, the Indonesian Solo River was positioned by Lebreton et al. (2017) at the 10^{th} place while Schmidt et al. (2017) rated it as number 45.

Lebreton et al. (2017) did not distinguish between macro and microplastic load, a distinction that was made by Schmidt et al. (2017). To compare the macro plastic results of Schmidt et al. (2017) to the field measurement of this thesis, the model results of several rivers as well as the Cikapundung River measurement results are presented in Table 5.5. The load for the Cikapundung River is based on the measurement results of location 2, by which the calculated flux of Table 5.4 is multiplied by 0.35 to only focus on plastic debris and deviated by 2 to convert it to dry plastic.

Table 5.5: Comparison of the measured dry plastic river load in relation to the by Schmidt et al. (2017) predicted plastic river load.

Rating	River	Receiving	Q_{avg} [m^3/s]	$A_{catchment}$ [km^2]	ρ_{pop} [$\#/km^2$]	MMPW [kg/d/pp]	MPL [t/y]
1	Yangtze	Yellow Sea	$1.6 \cdot 10^4$	$1.9 \cdot 10^6$	$2.6 \cdot 10^2$	0.092	$6.9 \cdot 10^4$
45	Solo	Java Sea	$7.5 \cdot 10^2$	$1.6 \cdot 10^4$	$7.9 \cdot 10^2$	0.047	$1.5 \cdot 10^2$
48	Citarum	Java Sea	$7.8 \cdot 10^1$	$6.7 \cdot 10^3$	$1.7 \cdot 10^3$	0.047	$1.4 \cdot 10^2$
53	Rhine	North Sea	$2.0 \cdot 10^3$	$1.6 \cdot 10^5$	$3.0 \cdot 10^2$	0.009	$1.1 \cdot 10^2$
-	Cikapundung	Citarum*	2.5	$1.4 \cdot 10^2$	$1.5 \cdot 10^4$ **	0.047	$2.6 \cdot 10^{2}$***

*The Citarum River receives the debris of the Cikapundung River, but most of this trash stays behind in the Saguling Reservoir.

**This is the population density of the city of Bandung instead of the whole Cikapundung River catchment.

***This value is based on the measured debris trawl flux.

The yearly plastic river load determined for the Cikapundung River is higher than the one for the Citarum River even though this value is based on a moderate debris flow conditions for the Cikapundung River. The predicted yearly macroplastic load for the Cikapundung River is 1 % of the yearly produced MMPW and this value is remarkably low (0.1 %) for the Citarum River.

The debris load from the Upper Citarum River Basin will predominantly remain in the Saguling Reservoir, which makes it difficult to compare the obtained values. Despite this, the value for both the Citarum River and Solo River seems to be low, which might indicate that the value of MMPW is quite low. The retrieved MMPW value is constant for the whole country, while there are major differences within Indonesia regarding waste collection and plastic recycling.

6

FLUME EXPERIMENTS

6.1. INTRODUCTION

In this chapter, the performed flume experiments and results are presented. These experiments were carried out to get a better understanding of (1) the debris accumulation growth process, (2) the most important parameters in relation to the backwater rise caused by debris accumulations and (3) the friction parameters of both debris blockage and carpet growth. Furthermore, the results are interpreted with respect to the case study location.

6.2. MATERIALS AND METHOD

The flume experiments were based on a case study location located 650 m downstream of measurement location 2 and 200 m upstream of measurement location 3 (Figure 3.1). A temporary trash rack construction was present at this case study location, which covered the full river width and was positioned at a height of 1 m from the river bottom. At this section, the river has a width of about 11 m and on May 22, 2018, an average water depth of 1 m was determined. The dimensions and composition of the debris mixtures were based on the compositions found during the field measurements. Two types of debris were investigated in the tests; vegetation and plastic. A model scale of 1:20 was used, resulting in the debris classes indicated in Figure 6.1 and the dimensions and mixtures presented in Table 6.1.

The tests were conducted in a flume of the Institute Technology Bandung (ITB). The rectangular flume had a length of 7 m, a width of 0.5 m and a height of 0.7 m. Figure 6.2 shows the set-up for the tests and includes a graphical representation of the parameters used in this chapter. The trash rack was placed 2.2 m upstream of the flume outlet. The rack consisted of four pillars made from steel and an aluminium trash rack with a mesh size of 0.01 m. The rack was constructed at a height of 0.05 - 0.2 m from the bottom of the flume. Two water

Figure 6.1: Examples of the five different types of debris; large vegetation, medium vegetation, small vegetation, straws and plastic bags.

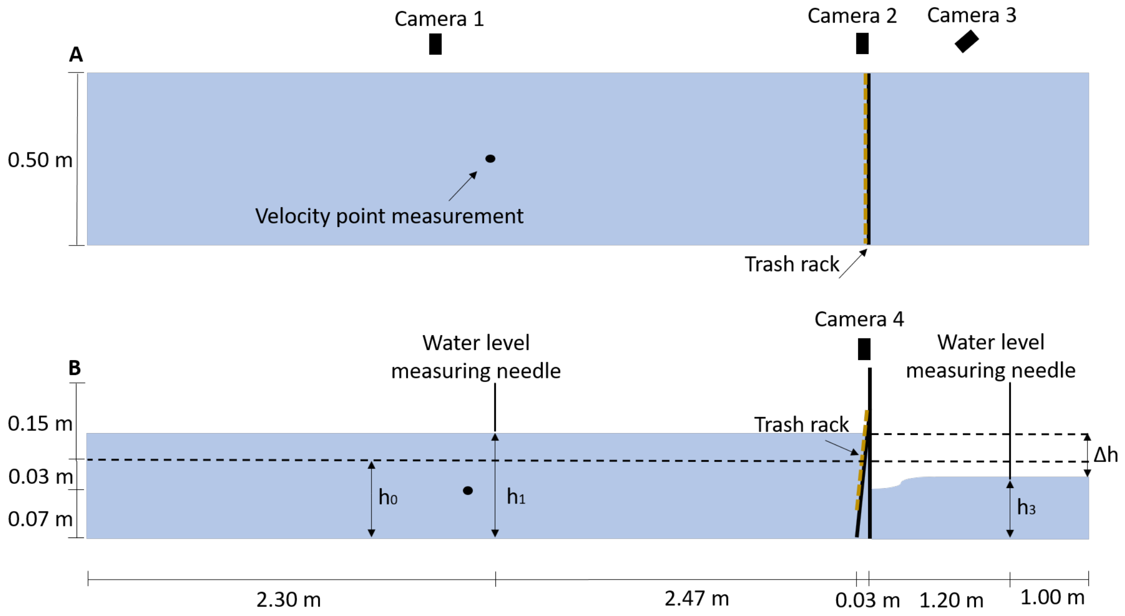


Figure 6.2: (A) Plan view of flume set-up and camera arrangement and (B) side view of trash rack.

level measuring needles were used, one needle was placed 2.5 m upstream of the trash rack and one needle was placed 1.5 m downstream of the rack. The water level was determined every minute and was read with an accuracy of ± 1 mm. Each test was recorded using action cameras, both from above and on the side of the flume to capture the horizontal and vertical blockage growth respectively.

Furthermore, the Froude number is used to obtain kinematic and dynamic similarity, since the gravity and inertial forces are dominant during these tests. The formula of the approach Froude number is given by:

$$F_0 = \frac{v_0}{\sqrt{(gh_0)}} \tag{6.1}$$

In which v_0 is the approach flow velocity, g the gravitational acceleration and h_0 the approach flow depth. The approach flow depth was kept constant at $h_0 = 0.10$ m, while the debris mixture, the debris weight, the approach flow velocity and the test duration were varied. Furthermore, some tests were performed to examine the reproducibility of the tests. A similar study concerned with organic debris accumulations already investigated the scale effects, by scaling up the trash rack, the debris and the flow conditions (Schmocker et al., 2013). Results from these scaling tests were found to be comparable and will not be further investigated in this research.

Schmocker et al. (2013) also investigated the impact of the watering time for organic debris particles. Their results showed that all particles were floating for watering times up to 8 h, particles only lost their floatability for a watering time of 1 week and were then transported lower in the water column. The watering time for organic material was therefore not further investigated, but tests were performed to investigate the impact of the wetness of plastic particles on the debris accumulation in front of the trash rack.

Prior to each test, 15 bags were prepared with the debris mixture to ensure a constant debris deployment. To ensure similar conditions for all tests, the debris mixtures were dried in the sun in-between the tests. At the end of each test, both the debris that passed the trash rack and the debris at the trash rack were separately collected and the wet weight (accuracy of 5 g) was determined to investigate the ratio between blocked debris and passed debris weight.

Table 6.1: Debris types (size specifications) and mixture compositions used for the flume tests.

Debris type	Dimensions/ specifications		Mixtures		
	Prototype	Flume	Organic	Plastic	Mix
Large vegetation	L: 4-6 m D: 0.2-0.8 m	L: 0.20 m D: 0.006 – 0.02 m	33 %	-	17 %
Medium vegetation	L: 1.2-4m D: 0.05-0.4 m	L: 0.10 m D: 0.006 – 0.01 m	33 %	-	17 %
Small vegetation	L: 0.1-1.2 m D: 0.005-0.05 m	L: 0.03 – 0.06 m D: 0.02 m	33 %	-	17 %
Plastic bags	h: 0.05-0.8 m w: 0.05-0.5	h: 0.01-0.03 m w: 0.01-0.02 m	-	67 %	33 %
Plastic cups	h: 0.15 m D: 0.10 m	h: 0.007 -0.015 m D: 0.007 m	-	33 %	17 %

Table 6.2: Test program for the flume tests performed in this study. The initial water level was set to h_0 = 0.10 m for all tests. The main variables are given in bold.

Parameter	Test	t_t [min]	M_d [kg]	F_0 [-]	v_0 [m/s]	Mixture
Reproducibility, Debris mixture	1-3	15	0.8	0.4	0.4	**Organic**
	4-6	15	0.8	0.4	0.4	**Plastic**
	7-9	15	0.8	0.4	0.4	**Mix**
	10,11	15	0.8	0.3	0.3	**Organic**
	12,13	15	2.4	0.3	0.3	**Organic**
	14-16	15	0.8	0.3	0.3	**Plastic**
	17,18	15	0.8	0.3	0.3	**Mix**
Flow condition F_0, v_0	19,20	15	0.8	**0.1**	**0.1**	Organic
	21	15	0.8	**0.1**	**0.1**	Plastic
	22,23	15	0.8	**0.2**	**0.2**	Organic
	24,25	15	0.8	**0.2**	**0.2**	Plastic
	10,11	15	0.8	**0.3**	**0.3**	Organic
	14-16	15	0.8	**0.3**	**0.3**	Plastic
	1,2	15	0.8	**0.4**	**0.4**	Organic
	4-6	15	0.8	**0.4**	**0.4**	Plastic
Debris mass M_d	17,18	15	**0.8**	0.3	0.3	Mix
	7-10	15	**0.8**	0.4	0.4	Mix
	26	15	**1.2**	0.3	0.3	Mix
	27	15	**1.2**	0.4	0.4	Mix
	28	15	**1.6**	0.3	0.3	Mix
	29	15	**1.6**	0.4	0.4	Mix
	30	15	**2.4**	0.3	0.3	Mix
	31	15	**2.4**	0.4	0.4	Mix
Test duration t	32	**7.5**	0.8	0.4	0.4	Organic
	33,34	**7.5**	0.8	0.4	0.4	Plastic
	1,2	**15**	0.8	0.4	0.4	Organic
	4-6	**15**	0.8	0.4	0.4	Plastic
	35	**30**	0.8	0.4	0.4	Organic
	36-39	**30**	0.8	0.4	0.4	Plastic

After completing the experiments, the water level differences between up and downstream were used to create plots showing the test reproducibility, the differences in the accumulation growth process for various approach Froude numbers, the influence of debris mass on the backwater rise and the variations as a result of changing time durations. The above mentioned parameters were plotted against the percentage added debris volume (V_d). Furthermore, the friction parameters (k$_{str}$, ξ) were determined based on the water level differences for 100 % added debris volume, for which the following equations were used:

$$n = \frac{1}{k_{str}} \tag{6.2}$$

$$H_1 = h_1 + \frac{{v_1}^2}{2g} \tag{6.3}$$

$$H_3 = h_3 + \frac{{v_3}^2}{2g} \tag{6.4}$$

$$\Delta H_{gate} = \xi \frac{v^2}{2g} \tag{6.5}$$

$$\Delta H_{carpet} = \frac{v^2 L_c}{{k_{str}}^2 R^{4/3}} \tag{6.6}$$

$$\Delta H = H_1 - H_3 = \Delta H_{gate} + \Delta H_{carpet} \tag{6.7}$$

$$h_\eta = \Delta h + h_0 \tag{6.8}$$

In which;

n	Manning's roughness coefficient	[s/m$^{1/3}$]
k_{str}	Strickler coefficient	[m$^{1/3}$/s]
ξ	Loss coefficient	[-]
h_1	Upstream water level	[m]
h_3	Downstream water level	[m]
v_1	Upstream flow velocity	[m/s]
v_3	Downstream flow velocity	[m/s]
H_1	Upstream hydraulic head	[m]
H_3	Downstream hydraulic head	[m]
R	Hydraulic radius	[m]
L_c	Carpet length	[m]
g	Gravitational acceleration = 9.81	[m/s^2]
h_0	Approach flow depth = 0.1	[m]

A generalization of the measurement results was obtained with a fit based on the dimensionless backwater rise results. The formula of the dimensionless backwater (h_B) rise is given by Equation 6.9. The transition flow depth (h_t) is the changing point between predominantly gate formation and carpet growth. The h_t value was determined based on a linear tail fit on the backwater rise results. This means that for every 15-nth step a linear line was fitted, for which the root mean squared error (RMSE) was determined. This RMSE value is almost constant in the beginning but this RMSE value increases significantly when the initial water level rise occurred, which is the transition point.

$$h_B = \frac{h - h_0}{h_t - h_0} \tag{6.9}$$

6.3. RESULTS

Figure 6.3 shows the comparison of the debris accumulation at the trash rack over time for tests 1, 4 and 7 (organic, plastic and mixed debris respectively, Table 6.2). At t = 0 s, the flow slightly affects the trash rack, resulting in a $\Delta h \approx 4$ mm. Debris is added from t = 0 s until t = 900 s and water levels were measured until t = 1200 s.

Figure 6.3: Comparison of the debris accumulation growth over time at trash rack for plastic debris (test 4), a mixture of organic and plastic debris (test 7) and organic debris (test 1), with a debris weight of 0.8 kg and an approach flow velocity of 0.4 m/s.

DEBRIS ACCUMULATION

The way in which debris accumulates in front of a trash rack is different for plastic, organic and mixed debris. Plastic debris blocks the trash rack faster compared to organic debris, which results in a faster water level rise behind the trash rack (Figure 6.3). After the blockage of the trash rack, the plastic debris contributes to the carpet growth or passes underneath the trash rack. The carpet growth for organic debris occurs on a slower pace since the organic debris first contributes to a curved shape whereas the plastic blockage growth is more angular. The mixed debris shows comparable results to plastic debris at the start of the test, which results in a fast-initial water level increase. However, over time the mixed debris also forms a curved shape accumulation, similar to the organic debris.

Table 6.3 provides an overview of the amount of debris that accumulates in front of the trash rack and the debris weight percentage of debris that passes underneath the trash rack. For all mixtures, the amount of debris that accumulates in front of the trash rack reduces for increasing flow velocities, but this is most significant for plastic and mixed debris.

Table 6.3: Overview of the weight percentage of debris blocked by the trash rack and the weight percentage that passed the trash rack for various flow velocities and various debris mixtures. In addition to the average value of blocked debris, the maximum variation for the different experiments are also given.

Flow velocity	Plastic debris		Mixed debris		Organic debris	
[m/s]	% Blocked	% Passed	% Blocked	% Passed	% Blocked	% Passed
0.1	84	16	-	-	99	1
0.2	82 ± 7	18 ± 7	-	-	90 ± 4	10 ± 4
0.3	73 ± 12	27 ± 12	77 ± 15	26 ± 15	87 ± 7	13 ± 7
0.4	51 ± 38	49 ± 38	55 ± 11	45 ± 11	85 ± 19	13 ± 19

TEST REPRODUCIBILITY

The reproducibility of the tests was assessed for all mixtures with the basic debris weight of 0.8 kg and approach flow velocities of 0.3 m/s and 0.4 m/s. For both flow velocities, it was found that all test results were reasonably consistent (differences for h_η/h_0 of about 0.1, Figure 6.4). The most significant differences occur for the organic debris, which will later be discussed in more detail in Figure 6.3.

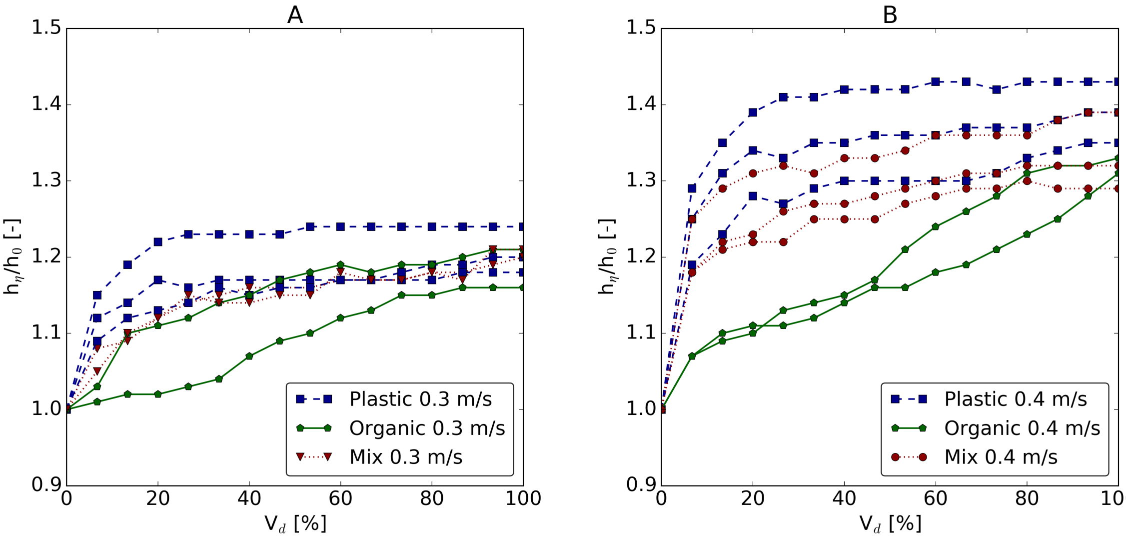


Figure 6.4: Reproducibility tests displaying the relative backwater rise (h_η/h_0) in relation to the added debris volume percentage (V_d). All tests conducted with a debris weight of 0.8 kg and flow velocities of (A) 0.3 m/s and (B) 0.4 m/s.

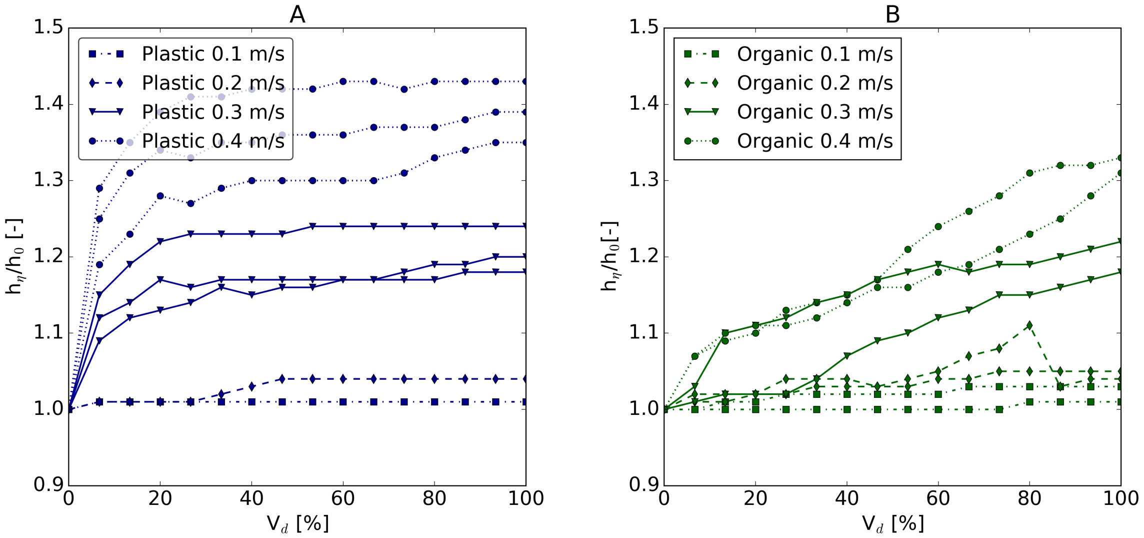


Figure 6.5: Relative backwater rise (h_η/h_0) in relation to the added debris volume percentage (V_d). Tests conducted with different flow velocities, for both (A) plastic and (B) organic debris with a constant weight of 0.8 kg.

FLOW CONDITION

During tests performed with flow velocities of 0.1 m/s, it was observed that some plastic particles managed to pass through the trash rack. This phenomenon only occurs with plastic particles and small vegetation fractions in the beginning of the tests, when particles arrive individually and the supply at that moment was too low to cause a debris accumulation. Most of the debris that passed the trash rack went underneath the construction. The amount of plastic debris that passed the trash rack increased significantly for increased flow velocities (Table 6.3).

The influence of the flow velocity on the backwater rise is presented in Figure 6.5, displaying results of both (A) plastic and (B) organic debris. Both figures show an increased backwater level for increased flow velocities. The results for the flow velocity of 0.2 m/s for organic debris (Figure 6.5B) are striking, because one of the tests shows a large drop in the measured water level. This drop is caused by a reduction of organic debris in front of the trash rack since part of the initial blocked debris passed underneath the trash rack. This phenomenon is checked and confirmed by video recordings.

The previous results can be generalized by an equation in which the water level difference and the relative flow depth $\Delta h/h_0$ after finishing the test at t = 15 minutes depends on the approach flow conditions (F_0 and v_0). Figure 6.6 shows the results for test 2-6, 10, 11, 14-16 and 19-25. A power function (Equation 6.10) describes the relation between the F_0 and the water level difference, but even without added debris there is already a small water level difference between the up- and downstream measurement location as a result of the trash rack. Therefore, a second power function (Equation 6.11) describes the situation at t = 0 s for various F_0 values. Figure 6.6B displays the results for the relative flow depth h_η/h_0, in which both the fit of Schmocker et al. (2013) and the fit based on the results of this study are presented (Equation 6.12). Lebreton et al. 2017 focused on the spectrum $0.5 \le F_0 \le 1.5$, whereas this study investigated the range $0.1 \le F_0 \le 0.4$.

$$\Delta h = 3F_0^{2.3} \tag{6.10}$$

$$\Delta h = 0.2F_0^{1.3} \tag{6.11}$$

$$h_\eta/h_0 = \begin{cases} 1.9F_0 + 1.4 & \text{for } 0.5 \le F_0 \le 1.5 \\ 1 - 0.25F_0 + 3F_0^2 & \text{for } 0.1 \le F_0 \le 0.4 \end{cases} \tag{6.12}$$

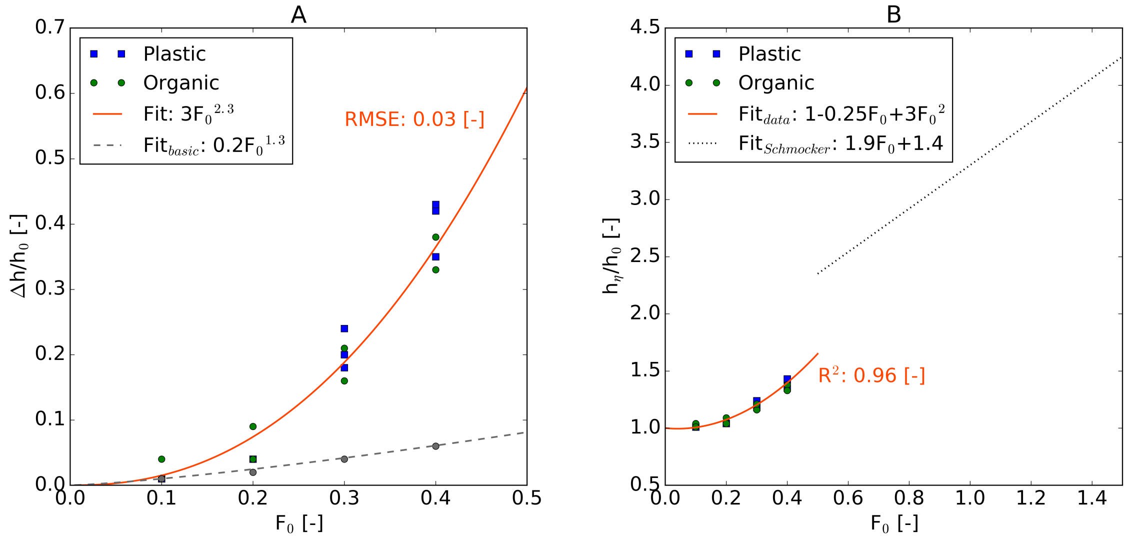


Figure 6.6: (A) Relative water level difference $\Delta h/h_0$ and (B) relative flow depth h_η/h_0 at test end for various F_0 (Test 2-6,10,11,14-16,19-25). The grey dashed line in figure A shows de basic conditions before debris is added and the water level difference is caused by the trash rack. The dotted black line of figure B displays the trend line of the backwater effect results for $0.5 \leq F_0 \leq 1.5$ found by Schmocker et al. (2013).

DEBRIS MASS

Figure 6.7 shows the impact of an increased debris mass on the backwater rise. In general, the backwater rise increases for an increasing debris mass. However, sudden drops are noticed for test 26 ($v_0 = 0.3$ m/s), 27 and 31 ($v_0 = 0.4$ m/s). These drops occur when a part of the blocked debris is pushed underneath the gate, which was confirmed by camera recordings. From these recordings it was found that larger vegetation particles passed underneath the trash rack first and smaller particles followed subsequently.

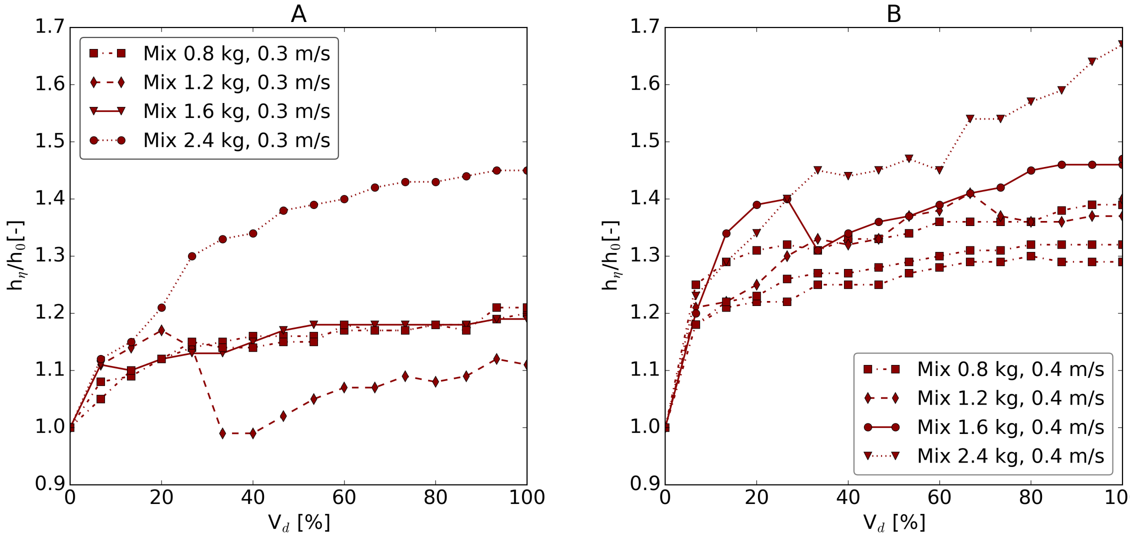


Figure 6.7: The impact of increased debris weight on the backwater rise (h_η/h_0) in relation to the added debris volume percentage (V_d) for a flow velocity of (A) 0.3 m/s and (B) 0.4 m/s.

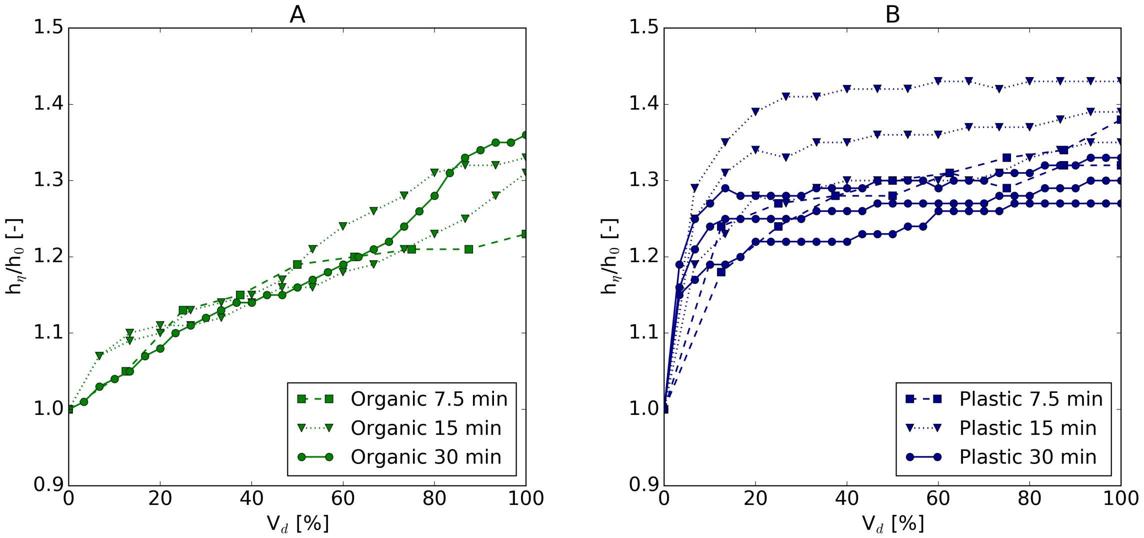


Figure 6.8: Test results of changed time duration of the added 0.8 kg debris on the backwater rise (h_η / h_0) in relation to the added debris volume percentage (V_d) for both the (A) organic and (B) plastic debris mixture

TEST DURATION

Figure 6.8 shows the results of changing the test duration from a default of 15 to 7.5 and 30 minutes. It can be observed that the highest backwater rise is obtained by adding organic debris over a longer test duration. For all tests, the pass rate was in the order of 5 %. However, the ordering of the organic debris was found to be different. A shorter time duration (adding the total debris weight of 0.8 kg in a shorter period), had a relatively high contribution to the carpet length. For test durations of 7.5, 15 and 30 minutes, the respective carpet lengths were about 30, 25 and 20 cm (Figure 6.9).

Figure 6.9B shows no obvious relation between the time span over which the debris is added and the final backwater rise for plastic debris. The major part of the water level increase takes place in the first three minutes, during this period the trash rack is blocked. After this period, most of the plastic particles contribute to the carpet growth or pass underneath the trash rack. In this second phase, the upward trend in water level flattens which is visible in Figure 6.12. The different tests for the same time duration showed varying carpet lengths and no relation was found between the time duration and the carpet length.

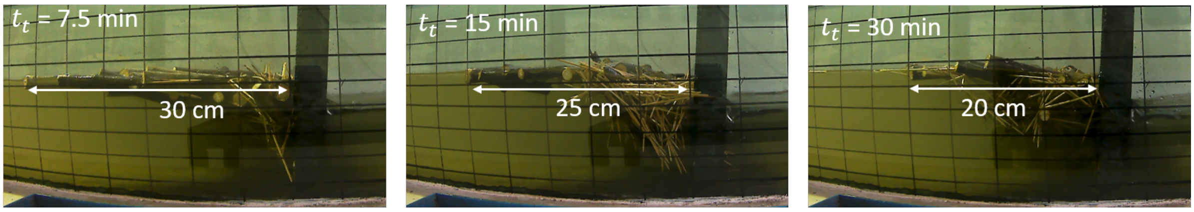


Figure 6.9: The influence of the test duration on the carpet length, while keeping the organic debris weight and the flow velocity constant at 0.8 kg and 0.4 m/s respectively.

NORMALIZED BACKWATER RISE

The previous results show an explicit difference between the accumulation growth for organic debris compared to plastic and mixed debris, including all tests with a debris mass of 0.8 kg. The curved shape back water rise of plastic and mixed debris does also occur for the two tests conducted with an increased organic debris mass of 2.4 kg. In order to determine the transition flow depth (h_t), water level measurements are required that have reached the second phase of the accumulation process (dominated by carpet growth).

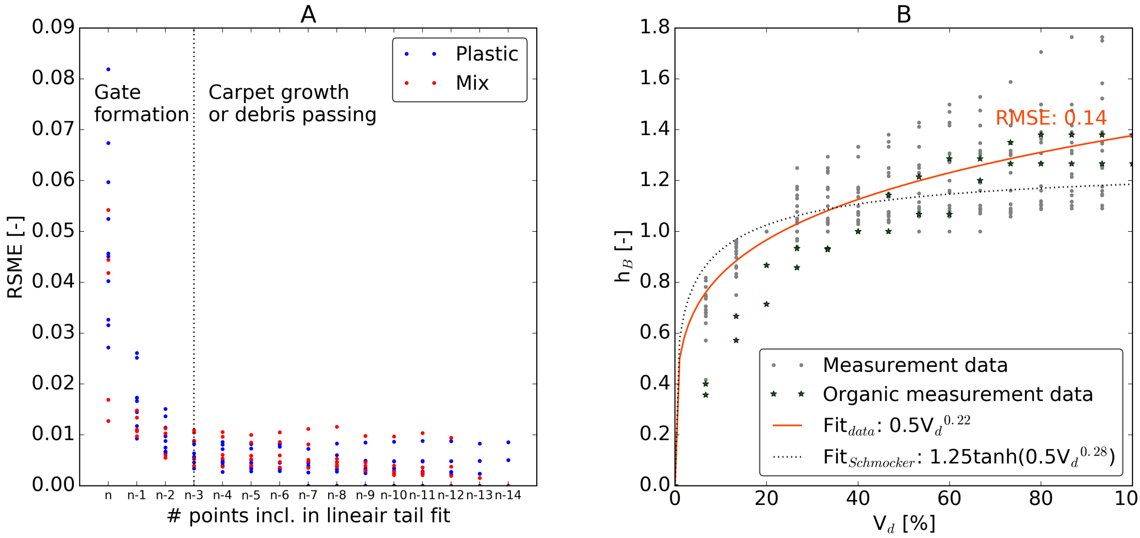


Figure 6.10: (A) The RMSE for linear tail fits conducted for n = 15 measurement steps and (B) the general backwater effect, based on the plastic and mixed debris measurement data.

This requirement was not met for organic debris tests with a mass of 0.8 kg, but the requirement was met for the organic debris tests with a mass of 2.4 kg. Therefore only organic debris tests with a mass of 2.4 kg are included in the following section.

The transition flow depth (h_t) had to be determined prior to the dimensionless backwater rise calculation (Equation 6.9). The results of the linear tail fit (explained in section 6.2) on the backwater rise are presented in Figure 6.10A. In general, the transition from gate forming to carpet growth occurs when 12 measurement points are included in the linear tail fit (n-3), which corresponds to 27 % of the debris volume is added to the flume. Figure 6.10B shows the results for the dimensionless backwater rise. For which the fit equation is given by:

$$H_{data} = 0.5V_d^{0.22} \tag{6.13}$$

$$H_{Schmocker} = 1.25tanh(0.5V_d^{0.28}) \tag{6.14}$$

Figure 6.10B furthermore indicates the comparison of the fit found in this study (Equation 6.13) to the fit equation (Equation 6.14) that was found by Schmocker et al. (2013) for organic debris. The test results of 2.4 kg organic debris of this study are displayed in green. The fit obtained by Schmocker et al. 2013 shows a faster backwater rise for the first 30 % of debris volume, but a lower final backwater rise at the test end.

FRICTION

The two friction parameters, the loss coefficient (ξ) and the manning roughness coefficient (n) are determined based on the differences in energy head (H) using Equation 6.8 and are presented in Figure 6.11. This figure also shows the rule of thumb ξ value for a 1/2 closed gate and the range for n values for both sand and cobble. The figure shows higher plastic debris ξ values with associated lower n values. Opposite results have been found for organic debris and the results for mixed debris are predominantly in between the results of plastic and organic debris.

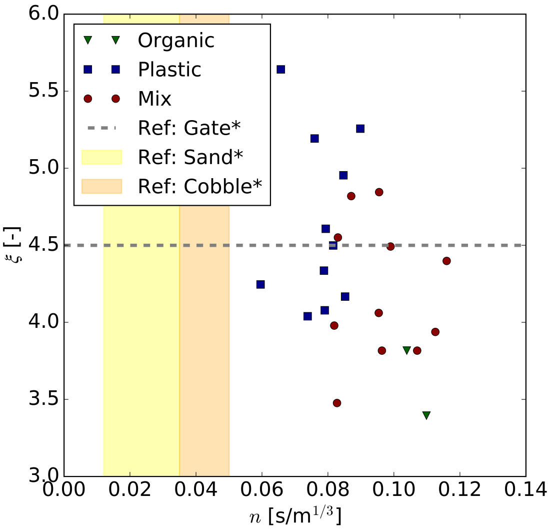


Figure 6.11: The two friction parameters, the loss coefficient (ξ) and the Manning roughness (n), plotted against each other. Note that the reference materials sand and cobble only display the range for Manning values (Phillips and Tadayon, 2006) and the reference value for the gate only shows the rule of thumb loss coefficient value for a 1/2 open gate (Pope, 1997).

6.4. DISCUSSION

DEBRIS ACCUMULATION

Schmocker et al. (2013) mentioned two phases of organic debris accumulations at the trash racks: (A) the initial debris accumulation at the trash rack and (B) the formation of a debris carpet. From the tests performed in this study, it was observed that the two phases also occur for plastic and mixed debris (Figure 6.3 and Figure 6.12). Schmocker et al. (2013) noticed that the first phase causes a major backwater rise, while the second phase only causes a minor back water rise. However, Schmocker et al. (2013) did not specify a ratio between the backwater caused by the two phases. Based on the general fit for plastic and mixed debris (Figure 6.10B), the ratio of major vs. minor backwater rise is $O(75\ \%/\ 25\ \%)$.

It was found that the initial accumulation phase was significantly shorter for plastic debris than for organic debris (M = 0.8 kg). This can be explained by the difference in blockage density. Plastic debris forms a very dense blockage in front of a trash rack, while there are more voids in organic debris accumulations. Therefore, the plastic blockage can fully block the flow, while there still is a flow through the gaps of organic debris particles. This is also the reason why the mass of organic debris has a big impact on the initial blockage of a trash rack, while the mass of plastic debris is less important for the trash rack blockage.

The results of the percentage debris passing underneath the trash rack related to the flow condition (Table 6.3) also showed significant variations for the different mixtures. For the plastic debris mixture (ρ = 0.9-1.6 g/cm^3), the amount of debris passing underneath was the highest (up to 49 %). For the organic mixture, especially the smaller fractions (toothpicks, ρ = 0.3-0.5 g/cm^3) went underneath the trash rack. The density of water is about 1 g/cm^3, which means that these materials will float in water without turbulence. The turbulence increases for increasing flow velocities, which explains the increase of debris passing underneath the trash rack. However, the higher increase of plastic debris passing underneath the trash rack compared to organic debris, can be explained by the differences in displaced volume. The volume of displaced water by organic debris is higher and thus the buoyant force is larger (see section 2.2, page 8).

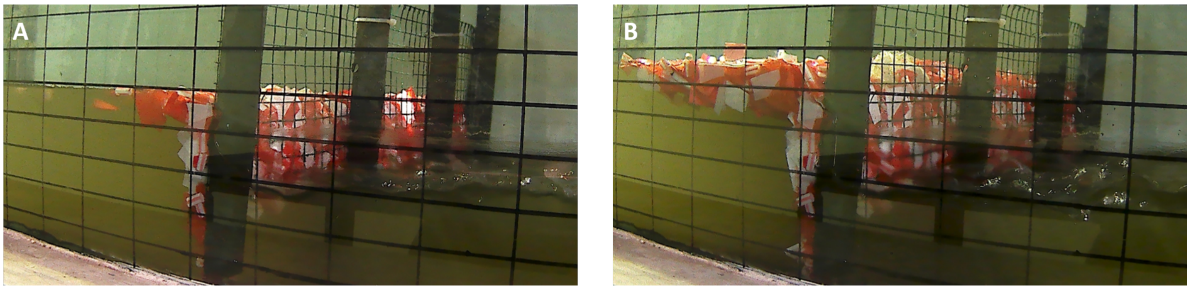


Figure 6.12: (A) Initial debris accumulation at trash rack and (B) carpet formation for experiment 4 with $M = 0.8$ kg and $v_0 = 0.4$ m/s.

TEST REPRODUCIBILITY AND SCALE EFFECTS

For all experiments, the test procedure was superseded by four minutes of basic flow without debris, in order to reach an equilibrium. During some of the plastic debris tests (0.1 m/s, 0.2 m/s), it was found that the downstream water level increased unexpectedly. The most likely cause for this effect were minor changes in discharge within the flume. Unfortunately, the discharge was not measured during these experiments. The changes in water level were therefore assessed using the relative water level increase between upstream and downstream. In this way, the minor changes in discharge were cancelled out.

The test results with comparable conditions depicted in Figure 6.4 yielded reasonably consistent results, which was also the case for the small scale flume experiments of Schmocker et al. (2013). However, this was not the case for the large scale flume experiments conducted by Hartlieb (2017). Hartlieb (2017) mentioned significant different backwater effects as a result of randomness in debris accumulation ordering. This phenomenon also occurred during the organic and mixed debris tests conducted in this research.

An example of this phenomenon are the test results for mixed debris with a flow velocity of 0.4 m/s (Figure 6.4B). Comparable growth was observed for the first 50 % added debris volume, but after this variations were noticed in the backwater effect. The variations can be explained by the with camera footage observed differences in horizontal ordering of the large vegetation fractions (Figure 6.13).

Figure 6.13A shows large vegetation fractions of the mixed debris that are almost perpendicular to the flow, whereas Figure 6.13B displays large vegetation fractions that are under a smaller angle to the flow. This horizontal ordering of the large fractions, results in a ‘dead-zone’ within the debris carpet. This causes the debris to be less compacted and increases the horizontal extent of the carpet. In contrast, the more compact the carpet the larger the vertical growth in front of the trash rack. As mentioned before, the vertical gate forming is responsible for a major backwater rise, whereas the horizontal carpet growth causes a minor backwater rise. This explains the differences in backwater rise for the tests displayed in Figure 6.13B and Figure 6.4B.

This randomness in ordering remained constant for increasing flume water depth. In reality the river width is

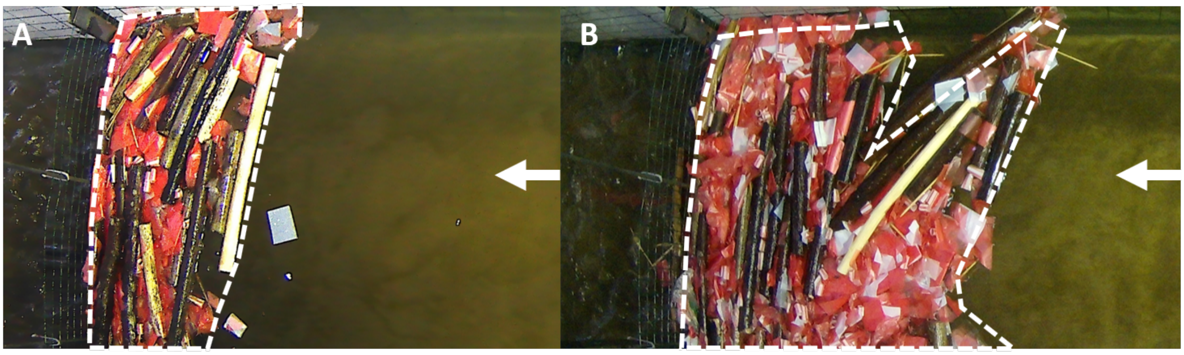


Figure 6.13: Differences in horizontal ordering of large vegetation fractions for the combined mixture ($M = 0.8$ kg and $v_0 = 0.4$ m/s. (A) Horizontal compaction of the debris, resulting in an increased vertical growth. (B) ‘Dead-zone’ formation caused by the horizontal ordering of the large vegetation, leading to an increased carpet growth.

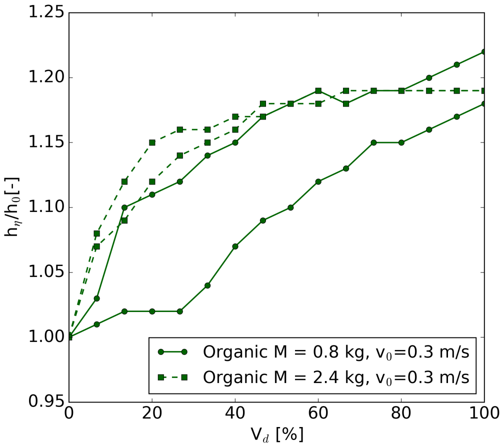


Figure 6.14: Backwater effect comparison for organic debris with M = 0.8 kg and M = 2.4 kg.

not constant and therefore changes in the water level might result in a reordering of the debris accumulation, which could reduce the occurrence of a 'dead-zone'. On the other hand, the randomness in ordering could be strengthened in the actual river, since the modelled organic debris particles had no branches and were thus relatively smooth compared to natural organic debris.

FLOW CONDITION

The results of the flow condition tests show a positive relation between the flow velocity and the final upstream water level rise for organic and plastics debris (Figure 6.5), which is in line with the findings for organic debris of Schmocker et al. (2013). However, the backwater rise patterns of organic debris (M = 0.8 kg) found in this study keeps increasing over time, whereas Schmocker et al. (2013) showed a flattening pattern over time for organic debris ($V_d = 50\ dm^3$). It is expected that the different patterns are the result of insufficient organic debris load used in this study. An increased organic debris load might be required to cause a full blockage at the trash rack. This theory is supported by the results of additional experiments presented in Figure 6.14. These experiments were conducted with a higher organic debris mass (M = 2.4 kg) and showed more similar backwater patterns to those presented in Schmocker et al. (2013).

The observed trend regarding the relative flow depth h_η/h_0 at test end for various F_0 differs from the trend found by Schmocker et al. (2013). The two studies focused on consecutive ranges for F_0 (0.1 - 0.4 and 0.5 - 1.5), but a significant large gap was observed between the two curves of Figure 6.6B. This gap can partly be explained by differences in flume set-up. The flow is less affected in this study, since the water can still flow underneath the blocked trash rack and the associated backwater effect is therefore smaller compared to the results found by Schmocker et al. (2013). The experiments of Schmocker et al. (2013) were conducted with a trash rack that started from the bottom of the flume and during their experiments, they noticed debris accumulations that indeed reached the bottom of the flume, which resulted in a greatly reduced flow and an increase of the upstream water depth.

DEBRIS WETNESS

Large differences were observed in the debris accumulation process for tests performed with similar plastic debris loads, but different material dryness. Completely dry plastic debris resulted in a much longer debris carpet (L_c of about 1.5 m instead of 0.4 m) and a lower debris passing percentage. In contrast to the low trash rack passage percentage of dry plastic, there was a significant increase in the amount of partly wet plastic particles that went underneath the trash rack. This resulted in a much smaller carpet length ($L_c \leq 0.4$ m).

Schmocker et al. (2013) found that all organic particles were floating for watering times up to 8 h and only lost their floatability for a watering time of 1 week and were then transported at the channel bottom. This study did not investigate this further, but surprisingly enough some toothpicks (representing small organic debris) lost their floatability during the tests. Schmocker et al. (2013) also used toothpicks as small organic debris, but the density of the toothpicks might be different.

DEBRIS MASS

In general, a positive trend was observed between debris mass and relative flow depth, which is in line with the results of Schmocker et al. (2013). However, all experiments with $M > 0.8$ kg were only conducted once and during some of these experiments a sudden drop (as a result of debris passing underneath the trash rack) was observed, making the positive correlation less obvious. This was especially the case for the experiments with a flow velocity of 0.3 m/s (Figure 6.7A). These drops were not observed by Schmocker et al. (2013) since their trash rack reached the bottom of the flume, which did not allow for debris to pass underneath. The number of performed experiments is not sufficient to quantify the relation between debris mass and the associated backwater effect, since (random) drops occur.

TEST DURATION

Changing the test duration, showed dissimilarities in the carpet length and the organic debris mass in front of the trash rack, while the passing percentages stayed constant (Figure 6.8A and Figure 6.9). This is assumed to be the result of the difference in time duration during which the water force presses on the accumulated debris. In the first scenario with an increased test duration (adding the 0.8 kg debris within 30 minutes) the water force acts longer on the accumulated debris, making the accumulation more compact. In the second scenario with a reduced test duration (adding the 0.8 kg debris within 7.5 minutes) the water force acts on the accumulated debris for a shorter period of time, explaining a longer carpet. No comparable results were found for plastic debris, which can be explained by the previously mentioned differences in the debris accumulation process for organic and plastic debris.

NORMALIZED BACKWATER RISE

A general description of the backwater rise results of this research is given by Equation 6.13, but deviates from Equation 6.14 which was found by Schmocker et al. (2013). The dissimilarity between the two equations can be explained by the flume set-up and associated contrast in debris accumulations. The main difference between the two studies is the position and type of trash rack. The trash rack from the experiments conducted by Schmocker et al. (2013) consisted of aluminium poles with a spacing of 0.05 m, whereas this study used four poles to position a trash rack screen with a mesh size of 0.01 m starting at a height of 0.05 m. It is expected that the initial increase of Schmocker et al. (2013) is higher, since the debris accumulation reaches the flume bottom and the final flow can only continue through the voids in-between the organic debris particles.

ORGANIC DEBRIS

As mentioned before, the modelled organic debris particles had no branches and leaves and were thus smoother than natural organic debris. The smoothness of the modelled organic debris might impact the manning roughness parameter negatively, since the presence of those branches increase the friction surface and could further disturb the flow. Interlocking caused by these branches will also reduce the percentage of (organic and plastic) debris passing underneath the rack.

Apart from the modelled organic debris in this study, individual leaves and water plants might result in a more dense debris accumulation near the gate. These organic materials could have a similar effect to the changes in water level as the modelled plastic debris.

7

SYNTHESIS

This chapter is concerned with translating the findings of the survey and field measurements into solutions regarding the large quantities of plastic debris in the Cikapundung and Citarum River. The laboratory experiments have shown the effect of debris composition, debris load, initial flow velocity and initial water depth on the debris accumulation. These results are translated to prototype scale in this chapter, which provide insights into the flow velocities at which floods can occur from debris accumulations and the mixture dependency. Furthermore, possible prevention measures that can be taken are discussed.

Survey The questionnaire results showed that only a few people mentioned to (occasionally) throw garbage in the river. The interviewed people often dump their waste on the river banks or at the intersection of rivers and bridges. Debris at these 'dumping sites' is rarely collected by the government. Therefore, the waste located on the river bank still end up in the river at times with high water levels, large amounts of rainfall and/or high wind speeds. Placing waste containers around bridges and improving the waste collecting frequency could prevent these large amounts of debris from entering the river. In addition, more public awareness should be given to the fact that disposing debris at the river banks can result in (downstream) flood risk problems.

Riverine plastic debris composition The field measurements showed an absence of PET, which indicates that a deposit on bottles ensures that bottles are less likely to ends up in the river. For this reason, it is plausible that an investment in the recycling of other plastics (and in particular LDPE), will lower the presence of plastic items in the river and the associated flood risks. However, polymers like PE cannot be recycled by simple chemical methods used for condensation polymers such as PET. Recycling of LDPE, HDPE and PP is possible by dissolution/reprecipitation as well as pyrolysis. The first recycling method allows for high polymer recovery, but with the disadvantage of using large amounts of organic solvents. The obtained gases and oils of the second recycling method have a great potential to be reused as feedstock for the production of new plastics or refined fuels. (Achilias et al., 2007)

Case study location The approach flow velocities of the flume experiments range between 0.1 and 0.4 m/s. These velocities correspond to 0.4 m/s, which is the typical flow velocities measured during fieldwork conducted in May and June 2018, and 1.8 m/s, which is a typical flow velocity during heavy showers in the rainy season (H. Kardhana, personal communication, May 29, 2018). An overview of the Froude scaled dimensions and the translation to prototype scale are presented in Table 7.1.

Table 7.1: Geometric (G), kinematic (K) and dynamic (D) similarity between model and prototype based on Froude scaling.

Parameter	Unit	Similarity	Scale ratio	Model	Prototype
v_0	m/s	K	$20^{1/2}$	0.1-0.4	0.4-1.8
h_0	m	G	20	0.1	2
h_{flood}	m	G	20	0.16*	3.1
t	min.	K	$20^{1/2}$	15	67
M_d	kg	D	20^3	0.8-2.4	6400-19200
$F_{trawl,max}$	kg/min/m^2	-	-	-	4.3
$F_{river,max}$	kg/d	-	-	-	$1.2 \cdot 10^5$ kg/d
F	-	D/K	$20^{2.5}$	0.8 kg/15 min.	$1.3 \cdot 10^5$ kg/d

*This water depth did not cause floods in flume.

During flow velocities between 0.1 m/s and 0.2 m/s (prototype 0.4 m/s and 0.9 m/s), the debris flow predominantly contributes to carpet formation. As carpet formation only causes minor water level increases and the water levels associated to these flow conditions are low, the resulting debris accumulation does not present a direct flood risk. Gate formation was observed in the flume experiments for 0.3 and 0.4 m/s (prototype 1.3 m/s and 1.8 m/s), which increases the flood risks. An average h_B factor of 1.4 was found for the backwater rise during experiments with a debris mass of 0.8 kg added in 15 minutes (Figure 6.10B). This translates into a riverine debris load of $1.3 \cdot 10^5$ kg/d and that a backwater rise at the case study location of $O(1$ m/h$)$ is plausible. This calculation is based on Froude scaling, whereas the results of Figure 7.1 are based on the difference in hydraulic head (Equation 6.8). Figure 7.1 shows the impact of changing debris accumulation (ξ, k_{str}, L) and hydrodynamic parameters (v_0, h_0) on the resulting backwater effect. The figure shows that the parameters v_0 and h_0 have the biggest impact on the flood risks for the case study location. The influence of the ξ parameter is smaller, but still has a more significant influence on the backwater effect compared to the parameters k_{str} and L. The relation between the backwater rise and the parameters ξ, v_0 and h_0 is linear, whereas this relation is non-linear for the parameters k_{str}, L.

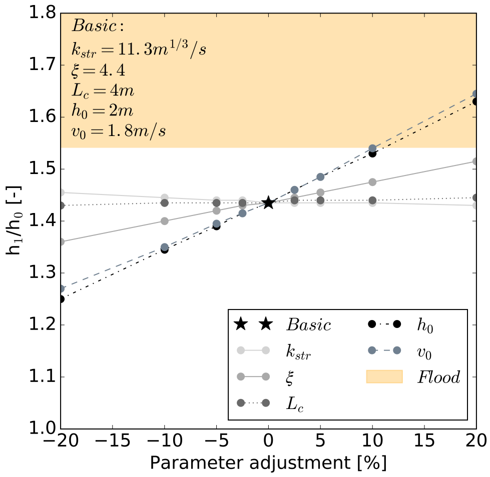


Figure 7.1: Parameter sensitivity regarding backwater effect. The basic (star) scenario is based on the average values obtained for k_{str}, ξ, L_{carpet} in combination with high water levels and flow velocities that are typical for the rainy season, but not extreme.

Table 7.2: Comparing the upstream water levels as a result of different mixtures blocking the temporary trash rack.

Parameter	Unit	Plastic				Mix				Organic			
ξ	-	4.6				4.2				3.5			
k_{str}	$m^{1/3}/s$	12.8				10.4				9.4			
L_c	m	4.0				4.0				4.0			
h_0	m	2.0				2.0				2.0			
v_0	m/s	0.4	0.9	1.3	1.8	0.4	0.9	1.3	1.8	0.4	0.9	1.3	1.8
h_1	m	2.0	2.2	2.5	2.9	2.0	2.2	2.5	2.8	2.0	2.2	2.3	2.7

The exact consequences for the case study location are hard to describe, since the backwater rise depends on the basic flow depth, the flow velocity, the debris load and the debris mixture. Plastic debris can be considered the most 'dangerous' mixture, since this type of debris has the highest value for the loss coefficient (ξ) and the loss coefficient has a larger influence than the carpet friction factor (k_{str}) on the backwater effect (Figure 6.11, Figure 7.1, Table 7.2). Floods only occur for two parameter sets of Figure 7.1, but this might be misleading. The basic scenario of Figure 7.1 is based on the average values obtained for k_{str}, ξ, L_{carpet} in combination with the high water levels and flow velocities that are typical for the rainy season. In case the basic scenario was based on the maximum determined values, more parameter sets would lead to additional flood scenario's.

The field measurements of this study were performed in the beginning of the dry season. González et al. (2016) mentioned seasonal variations in debris loads caused by accumulations on land during dry periods and subsequent debris wash away during the rainy season. Therefore, the debris load during the extreme flow conditions is expected to be higher as well as the associated flood risks, than presented in this thesis. The debris load measurements performed in this study are thus not sufficient to provide an accurate indication of the critical flood risk time span and could be improved by debris load results of the rainy season.

The main purpose of the trash rack in the Cikapungung River is reducing the amount of trash reaching the Citarum River. After the initial blockage of the trash rack, a lot of the moist plastic debris particles pass underneath the trash rack (especially during higher flow velocities), while the larger natural organic debris stays behind the trash rack. This means that the main aim of reducing the (plastic) debris quantity is not met or at least not completely, while the trash rack increases local flood risks. However, the trash rack often breaks during heavy flow conditions, which could be seen as a positive feedback regarding the local flood risks.

To reduce the flood risks and at the same time improve the trash rack functionality, it would be advisable to install the temporary trash rack lower in the water column. This way, the trash rack will be in the water during low flow conditions, for which debris accumulations do not result in direct flood risks. Furthermore, a lower crest level would ensure water flowing over the trash rack before flood risks occur during high discharge events. Other alternative solutions are presented in the conclusions and recommendations chapter.

8

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this thesis was to obtain a better understanding of the riverine debris problems in general, but more specifically in Bandung (Indonesia). This was studied by conducting field experiments in combination with lab tests, which were both aligned to the research questions defined in chapter 1. This chapter will provide concise answers to all the sub-questions (SQ), after which the answer will be given to the main research question (MQ). Finally, recommendations for future studies will be given together with a practical advice regarding the usage of trash racks.

CONCLUSIONS

SQ: What are the bottleneck locations of the Bandung water system?
The questionnaire results indicated that debris accumulations occur at obstructions in the river (e.g. bridge columns) and at merging rivers. The Dayeahkolot neighbourhood was marked as one of the most risk prone areas within Bandung. The district is located near the Citarum River, in a flood-sensitive area and has a high several bridges close together, where several blockage problems took place in the past.

SQ: What is the ratio of riverine debris, distinguishing the categories plastic, organic and other debris?
Field measurements showed that the average riverine debris ratio for plastic, organic and other debris was respectively 34 %, 43 % and 23 %. However, this ratio deviated a lot for individual measurements. For instance, the ratio plastic debris varies significantly over time at all measurement locations, with a lower boundary of 11 % plastic debris observed at measurement location 3 and an upper boundary of 78 % plastic debris retrieved at measurement location 1. In addition, there were obvious differences per measurement location, for instance hardly any other debris was measured at the upstream measurement location. Almost all the dead animals were found at the most downstream measurement location, which partially explains the big difference in debris ratio's between the two downstream measurement locations.

SQ: What is the composition of the present plastic debris in the Cikapundung River?
The most abundant types of plastics were LDPE, HDPE and multilayer. Especially a large number of plastic bags and food packaging items were captured. Only three PET bottles were collected during the performed trawl measurements, indicating that the recycling of these materials influences the presence of plastics in the river.

SQ: What is the relation between discharge and debris flow?
The trawl measurements showed a positive relation between the discharge and debris flow. Due to the limited variation in observed discharge, deriving a plausible equation was not possible. In addition, it is not expected that there is a linear relationship between discharge and debris flow as a result of seasonal dependencies. The peak discharge takes place in February while the peak debris flow is expected after the dry season in the months October and November. This peak is expected directly after the dry season, since a lot of waste accumulates in the river banks and washes into the river after the first rise of the water level.

SQ: How does debris blockage evolve over time and how is this process related to debris composition?
The time duration in which a trash rack gets blocked depends both on the debris load and the debris composition. A comparable debris load results in a faster blockage for plastic compared to organic debris, because the plastic debris blockage contains fewer voids and therefore has a higher blockage density. In addition, the shape of the blockage also depends on the debris composition. Namely, plastic debris causes an angular shaped blockage, whereas organic debris results in a curved shape blockage in front of a trash rack. The plastic debris was found to be the most 'dangerous' mixture, since the blockage of the trash rack had the largest impact on the flow patterns.

SQ: How does the debris flux, debris load, debris composition and flow condition influence upstream water levels?
Although changes in carpet length and blockage density were observed for different organic debris fluxes, the impact on the backwater effect was limited. Instead, the debris load was found to be the most important parameter. An increase of three times the initial debris mass resulted in an increase of the relative flow depth of ~1.7 instead of ~1.3 for $v_0 = 0.4$ m/s. The flow condition (v_0 and F_0) was found to have a significant effect on the backwater rise as well. An increase of three times the initial flow velocity resulted in an increase of the relative flow depth of ~1.2 instead of ~1.0. During low flow conditions (F_0 of 0.1 and 0.2), the backwater effect is minor since only carpet growth occurs. This leads to increased friction, reduced flow velocities and increased water levels both up- and downstream. During the higher tested flow conditions (F_0 of 0.1 and 0.2), the trash rack gets blocked first, after which the debris partly contributed to carpet formation and partly goes underneath the trash rack. The passing percentage and the blockage density both depend on the debris composition. The debris blockage density determines the ξ value, which is the highest for plastic debris, followed by mixed debris. The composition also determines the k_{str} value, but the influence of this parameter on the backwater effect is smaller compared to the other parameters. Based on the test results, a general dimensionless backwater rise function of $h_B = 0.5 \cdot V_d^{0.22}$ was obtained, with a RMSE of 0.14 [-].

SQ: What is the impact of a blocked trash rack at the downstream case study location in the Cikapundung River on the regional flood risks?
A blocked trash rack increases the regional flood risks in the Dayeukolot district significantly. A blocked trash rack can cause a backwater rise within an hour of $O(1\text{ m})$. This follows from both the general fit for the dimensionless backwater rise and the calculation based on the energy loss. The parameter sensitivity analysis showed that the initial flow conditions, the initial water depth and the loss coefficient have the most significant influence on the backwater effect. However, the debris load parameter was not considered in this sensitivity analysis.

MQ: What is the influence of debris on the hydrodynamics within a water system, based on experiments in Bandung (Indonesia)?
Throughout this research, riverine debris was found to vary over space, time and the water column. During normal flow conditions, the weight percentage of plastic debris was higher in the surface compared to the subsurface, which was opposite for organic debris. Debris accumulations were observed in the river, both at bridge pillars and a river section with low flow velocities and shallow water. An increase in the accumulated debris was observed in the beginning of the dry season in the Cikapundung River.

A temporary trash rack was present in the Cikapundung River, a blockage of this trash rack can greatly increase the regional flood risks. Based on lab experiments it was shown that an upstream water level increase as a result of the blocked trash rack of $O(1\text{ m})$ within an hour is plausible. Furthermore, it was found that the flood risks mainly depend on the initial water level, the initial flow velocity, the debris load and the loss coefficient of the formed gate. This loss coefficient depends on the debris composition and was found to be the lowest for organic debris, which contains voids that still allow water flow. A plastic blockage on the other hand resulted in a fast and dense blockage, causing a more complete flow obstruction. This type of blockage therefore has the largest impact on the regional flood risks. Unless an automatic trash rack cleaner is installed or the trash rack is taken out of the water in case the water depth is above 2 m, the Dayeuhkolot neighbourhood will remain at increased risk of flood.

RECOMMENDATIONS

As a result of the conducted research with regards to riverine debris, interesting results were found. However, there are still some areas of improvement in the academic field, for which follow up research is required. These recommendations are related to the riverine debris measurements, the flume experiments, the implementation of the findings into hydraulic models and investigating the possibilities for riverine solutions.

Riverine debris measurements Future research into riverine debris would benefit from a uniform measurement method. Furthermore, it would be wise to perform additional measurements of (1) seasonal and (2) cross-sectional variations within rivers. To gain a better understanding of seasonal variations, long term measurement campaigns can be set up that monitor the debris flux over time. The obtained data could be used to derive relationships between discharge, debris flux and the seasonal dependency. To optimize the alpha factor, which covers for cross-sectional variations in riverine debris flux, measurements with multiple double trawl devices could be performed simultaneously. Furthermore, double trawl measurements could be performed during different flow velocities to investigate whether there is an obvious correlation between the flow velocity and the vertical debris distribution.

Flume experiments Large drops in the backwater rise were noticed for test with organic and mixed debris. Those drops were the result of released initial blocked debris, passing underneath the trash rack. The drops made it impossible to quantify the relation between debris mass and backwater rise. Therefore, additional tests should be performed to be able to quantify this relationship and also to obtain an idea of how frequent those drops occur. Furthermore, additional tests are needed to determine the impact of smooth organic debris and preferably investigate the impact of a variable river width on the debris reordering. Additional large scale flume experiments are also required to further investigate scale effects, which was not done in this study because limited deviations for scale effects of small scale flume experiments were reported by Schmocker et al. (2013). However, Hartlieb (2017) noticed large deviations while conducting large scale flume experiments and additional experiments could investigate the impact of differences between the conducted small and large scale flume experiments.

Model implementation Using the findings presented in this study, hydraulic models (e.g. FLO-2D, Delft3D and SOBEK) could be extended to translate debris loads into changes in the water system. The newly added parameters for such a model would be the debris load and the friction parameters for both gate formation and carpet growth. The debris load can potentially be based on population density within the vicinity of the river, MMW and rainfall. Schmidt et al. (2017) used one value for the MMPW per country and multiplied this factor with the population density, while it is expected that this MMPW factor depends on the local conditions (e.g. waste collection services and land use).

Possibilities for riverine solutions The current installation of temporary trash racks in Bandung does not work optimal. The trash rack is only under water for flow depths larger than 1 m, while the low flow depth is associated with low flow rates. The concept of reducing the amount of trash reaching the Citarum River by installing a trash rack works for these low flow velocities, since the accumulated debris predominantly contributes to carpet formation. When the debris flux increases for higher flow velocities, blocking of the rack occurs rather rapid, after which plastic particles passing underneath the trash rack increases. This debris passing percentage might be reduced by increasing the trash rack angle. However, this does not provide a solution to the increased backwater rise and thus increased flood risks associated to the high flow velocities. This is the case when the trash rack is not destroyed under the large loads during high discharge events. This feedback mechanism provides a balance between riverine debris and flood risk management and can potentially be used in the design of trash racks in the future.

The current installation can best be removed from the water as a precaution when flow depths exceed 2 m, to reduce the regional flood risks. Furthermore, alternative constructions could be used to lower the regional flood risks. Further research could investigate the possibilities of installing a boom or trash rack under an angle in the outer bend of the river which do not cover the entire river width. This way, it would be possible to catch a significant amount of debris, without the possibility of heavy backwater effects and the associated flood risks. Another alternative for further investigation would be a river bypass in the outer bend, where water conveying a high debris load will go during high water levels. A comparable construction was made in the Sihl River (Switzerland) and the water and tree branches could only flow in and out when a certain spillway height is reached (ETH, 2007). After the water depth in the bypass decreases again, the remaining water could infiltrate into the soil and the accumulated debris can be removed manually.

Other solutions are needed for permanent structures such as the Mangarai Gate in Jakarta. For such a location it would be useful to study the amount of debris taken out of the water by excavator and the seasonal differences, to determine the peak debris flow. This would help to design a proper automatic trash rack cleaner, so that debris can be removed regularly and accumulations can be prevented even during the night.

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A

PERSONAL COMMUNICATIONS

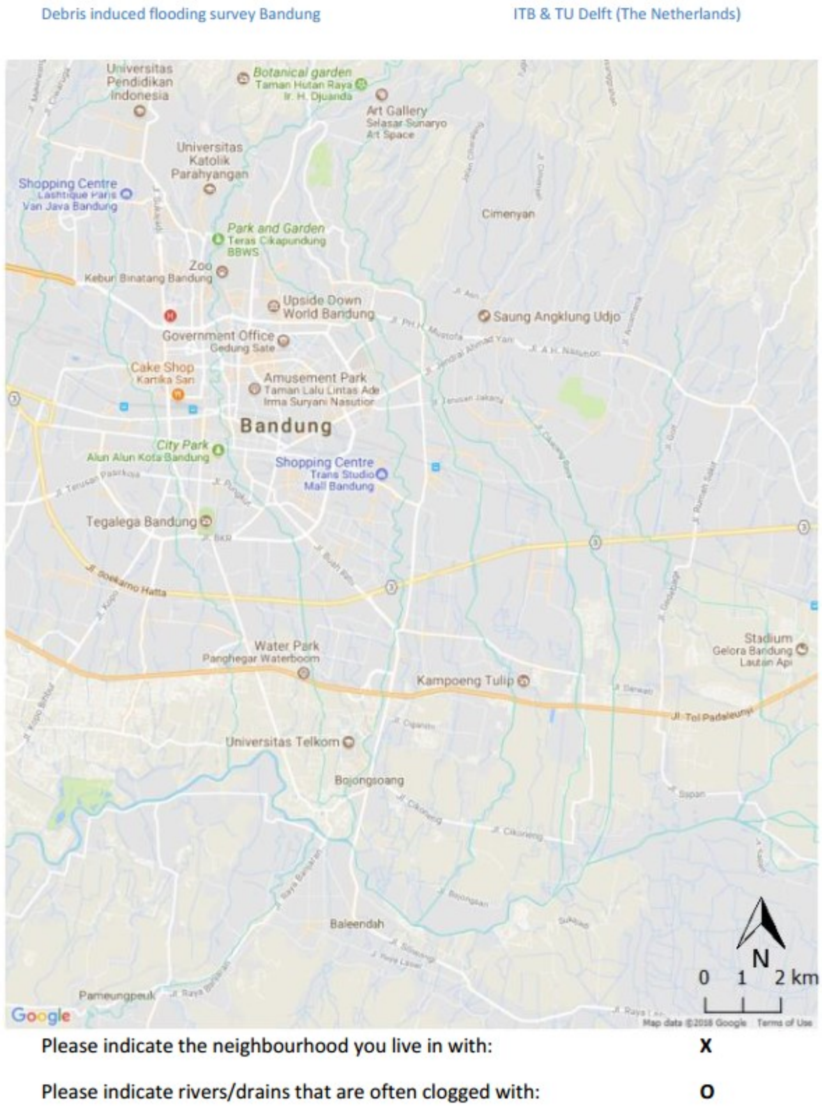
Apart from the interviews, several conversations are used as input for this thesis. This appendix concerns an explanation of the used personal conversations.

S. Ardian *Date: May 26, 2018* This contact person is an Indonesian Water Management student of the ITB, who was also working on her master thesis. She helped during the field measurements and was noticed how little bottles were caught. She shared her thoughts that this shortage might be explained by the PET bottles collection by inhabitants who sell the bottles to recycling companies.

H. Kardhana *Date: May 29, 2018* This contact person is also one of my supervisors during this thesis and a staff members of the Water Resources Engineering department of the ITB. During one of our talks, we discussed which flow velocities occur in the Cikapundung River, to determine a suitable range for the flume test flow velocities. Mr. Kardhana then mentioned 1.8 m/s to be a typical flow velocity during heavy showers in the rainy season.

B

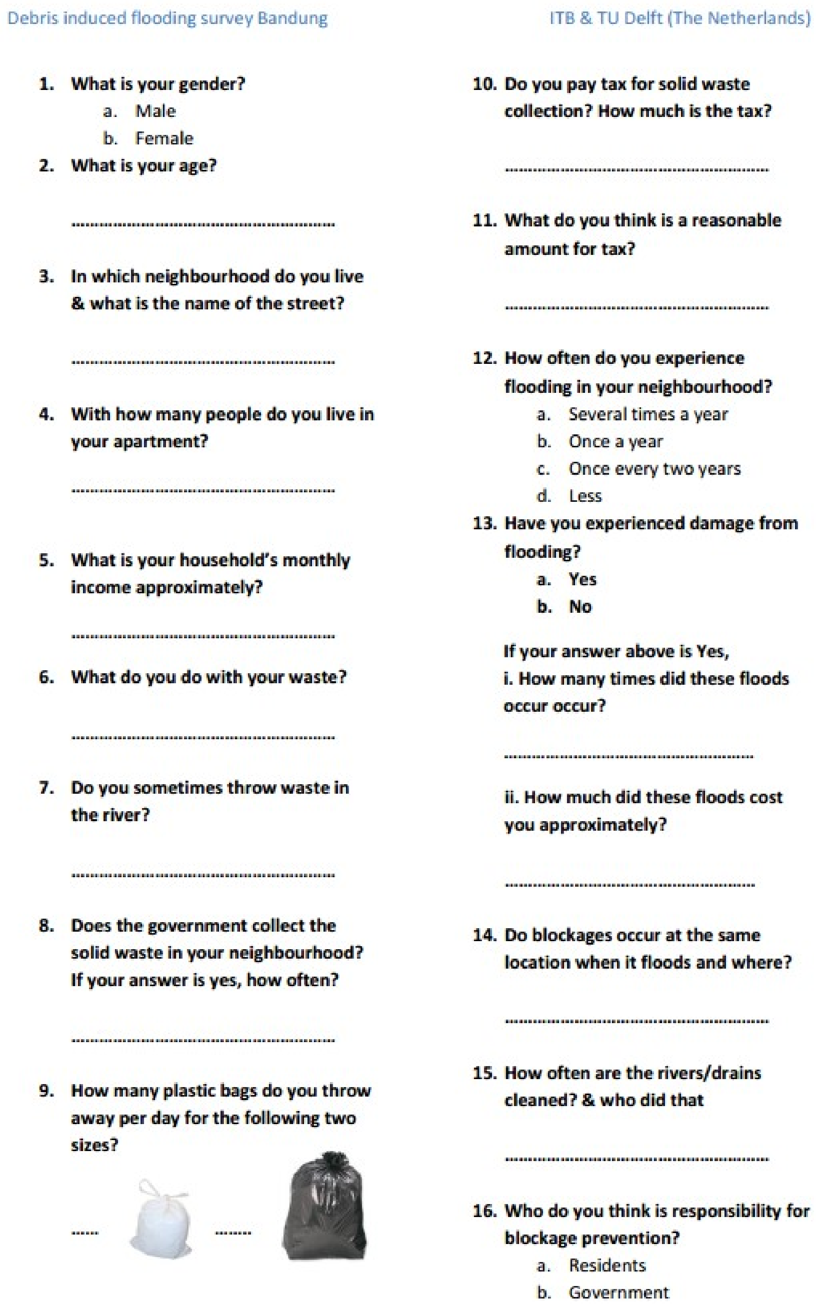
QUESTIONNAIRE



Debris induced flooding survey Bandung ITB & TU Delft (The Netherlands)

Please indicate the neighbourhood you live in with: **X**

Please indicate rivers/drains that are often clogged with: **O**



Debris induced flooding survey Bandung

ITB & TU Delft (The Netherlands)

1. **What is your gender?**
    a. Male
    b. Female
2. **What is your age?**

    ……………………………………………………

3. **In which neighbourhood do you live & what is the name of the street?**

    ……………………………………………………

4. **With how many people do you live in your apartment?**

    ……………………………………………………

5. **What is your household's monthly income approximately?**

    ……………………………………………………

6. **What do you do with your waste?**

    ……………………………………………………

7. **Do you sometimes throw waste in the river?**

    ……………………………………………………

8. **Does the government collect the solid waste in your neighbourhood? If your answer is yes, how often?**

    ……………………………………………………

9. **How many plastic bags do you throw away per day for the following two sizes?**

    …… ……

10. **Do you pay tax for solid waste collection? How much is the tax?**

    ……………………………………………………

11. **What do you think is a reasonable amount for tax?**

    ……………………………………………………

12. **How often do you experience flooding in your neighbourhood?**
    a. Several times a year
    b. Once a year
    c. Once every two years
    d. Less
13. **Have you experienced damage from flooding?**
    a. Yes
    b. No

    If your answer above is Yes,
    i. How many times did these floods occur occur?

    ……………………………………………………

    ii. How much did these floods cost you approximately?

    ……………………………………………………

14. **Do blockages occur at the same location when it floods and where?**

    ……………………………………………………

15. **How often are the rivers/drains cleaned? & who did that**

    ……………………………………………………

16. **Who do you think is responsibility for blockage prevention?**
    a. Residents
    b. Government

Table B.1: The most relevant results of the 55 questionnaires. One local contact, one employee of Waste for Change, 8 students and employees of the ITB and 15 persons per measurement location contributed to this survey.

Location	1	2	3	Other
Household size range	2-30	2-6	1-6	6-17
Monthly income	Rp. 1,500,000-2,700,000	Rp. 2,000,000-4,000,000	Rp. 2,000,000-45,000,000	Rp. 3,000,000-25,000,000
Waste disposal	Collected (13 %) burning (27 %) brings to garbage belt/ collection point (60 %)	Burning (67 %) burning/ collection (13 %) collected & occasionally river (7 %) brings to rubbish place (7 %) organic in river and rest burning (7 %)	Burning (33 %) collection & burning (67 %)	Collected (80 %) burning (10 %) fermenting organic waste and rest collected (10 %)
Collection by the government	Yes, daily (10 %)	Yes, 1/week (73 %)	Yes, 1/week(50 %)	Yes, 1-3/week (90 %)
Waste production	1 small - 3 big bags Mostly 3 small bags	1 small - 1 big bag Mostly 1 small bag	1 small - 3 big bags Mostly 1 big bag	1 - 3 small bags Mostly 2 small bags
Willingness to pay money for waste collection	Yes (13 %) Rp. 30,000-50,000/month	-	-	Yes (20 %) Rp. 20,000-60,000/month
Big floods	-	Multiple times per year (100 %)	1/year (30 %) 1/3 years (50 %) 1/10 years (20 %)	1/year (10 %)
Flood damage	-	Yes (100 %) Rp. 100,000-25,000,000	Yes (70 %) Rp. 500,000-10,000,000	Yes (10 %) Rp. 1,000,000
The frequency by which drains/ rivers are cleaned	No knowledge of (40 %) Weekly (30 %) Monthly (20 %) Before public events (10 %)	Weekly (73%) Daily at a different location (18%) Monthly (9 %)	Weekly (40 %) Several times/ year (40 %) Daily at different locations (20 %)	Only if there are blockage problems (75 %) Weekly (25 %)
Cleaning performed by	Military (100 %)	Military (81 %) Residents & military (18 %)	Military (100 %)	Military/ local government (80 %) Residents (20 %)
Blockage prevention responsibility	Residents (70 %) Government (30 %)	Both residents & government (100 %)	Both residents & government (100 %)	Government (67 %) Both residents & government (33 %)
Comments	Most of the debris is expected to come from the rubbish place in the North.	-	Military cleans the river since 2017. Pastor who lives next to the bridge said the military cleaned this location 10* times in 2018. *May, 2018	Two persons who pay tax for waste collection Rp. 20.000-30.000/month.

C

DEBRIS MEASUREMENT RESULTS

Table C.1: Overview of the total weight and percentage per debris category, captured during the trawl measurement in the period 14-26 May, 2018.

Loc.	Trawl type	Time [min]	M [kg] Total	$M_{plastic}$ [%]			$M_{organic}$ [%]			M_{rest} [%]		
				Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
1	Single	396.5	13.4	20	45	78	22	48	80	0	7	3
2	Singel	125	28.1	18	35	75	11	32	52	0	33	62
	Double	80	16.9	24	44	70	10	42	76	0	15	60
3	Single	147	39.1	11	25	37	29	49	77	0	26	56

Table C.2: Overview of the minimum, average, maximum and parameter range for the single trawl measurements, during the trawl measurement in the period 14-26 May, 2018. The captured debris weight of the measurements with deviating measurement times are converted to captured weight in 10 minutes, for equal comparison.

Loc	M	v [m/s]	M_{Total} [kg/ 10 min]	$M_{Plastic}$ [kg/ 10 min]	[%]	$M_{Organic}$ [kg/ 10 min]	[%]	M_{Rest} [kg/ 10 min]	[%]
1	Min.	0.3	0.1	0.02	20	0.08	80	0	0
	Avg.	0.4	0.47	0.21	44	0.23	47	0.02	9
	Max.	0.5	3.4	1.46	43	1.94	57	0	0
	Range	0.3-0.5	0.1-3.4	0.02-1.46	20-78	0.05-1.94	22-80	0-0.11	0-52
2	Min.	0.4	1.04	0.5	48	0.35	34	0.19	18
	Avg.	0.44	2.59	0.96	37	0.8	31	0.82	32
	Max.	0.5	7.84	2.1	27	2.84	36	2.9	37
	Range	0.4-0.5	1.04-7.84	0.41-2.10	18-75	0.29-2.84	11-52	0-3.00	0-62
3	Min.	0.2	1.07	0.26	24	0.81	76	0	0
	Avg.	0.27	2.52	0.59	24	1.41	56	0.51	20
	Max.	0.3	7.267	1.4	19	2.7	37	3.17	44
	Range	0.2-0.3	0.03-5.16	0.01-1.43	11-37	0.01-3.64	30-77	0-1.6	0-56

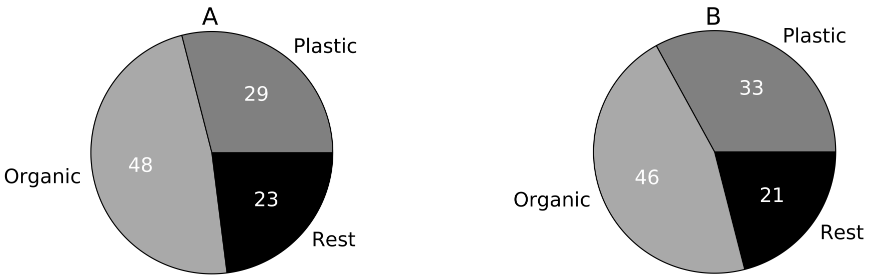


Figure C.1: The (A) weight vs (B) volume percentage for the deviation in organic, plastic and rest debris for 20 kg debris.

Table C.3: The secondary sorting results for the three measurement locations.

Loc.	PET			PP/PS			HDPE			LDPE			Multilayer		
	#	M [kg]	M [%]	#	M [kg]	M [%]	#	M [kg]	M [%]	#	M [kg]	M [%]	#	M [kg]	M [%]
1	1	0.02	0	39	0.1	2	96	1.1	189	443	3.6	60	295	1.2	19
2	1	0.02	0	161	1.4	9	218	2	13	1270	8.3	54	942	3.6	24
3	1	0.02	0	136	0.3	3	175	1.8	19	454	6	61	394	1.7	17
Total	3	0.06	0	336	1.8	6	489	5	16	2167	17.9	57	1631	6.5	21

Table C.4: The results of the comparison of the dry and wet weight of the 20 samples of the four plastic categories; PP/PS, HDPE, LDPE and multilayer, that were taken back into the lab.

Parameter	Unit	PP/ PS	HDPE	LDPE	Multilayer
Samples	#	20	20	20	20
V	cm^3	17.3	34.6	242	69.3
M_{wet}	g	50	250	220	120
M_{dry}	g	20	200	80	40
$M_{avg.particle,wet}$	g	2.5	12.5	11	6
$M_{avg.particle,dry}$	g	1	10	4	2

D

AVERAGED FLOW CONDITION

Table D.1: Average flow velocity and bathymetry for measurement location 1, based on measurements performed on May 18, 21 and 24, 2018. Heavy rainfall events took place at May 18 and 21, 2018.

		River section																
Parameter	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
ΔL	m	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
h_{avg}	m	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.5	0.4	-
h_{rain}	m	0.7	0.7	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.7	0.6	-
A_{avg}	m^2	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.5	0.4	6.5
A_{rain}	m^2	0.7	0.7	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.7	0.6	9.7
v	m/s	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	-
v_{rain}	m/s	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	-
Q	m^3/s	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0	0	0.1	0	1.9
Q_{rain}	m^3/s	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	4.4

Table D.2: Average flow velocity and bathymetry for measurement location 2, based on measurements performed on May 15, 16, 23 and 26, 2018.

		River section								
Parameter	Unit	1	2	3	4	5	6	7	8	9	Σ
ΔL	m	1	1	1	1	1	1	1	1	1	9
h_{avg}	m	0.4	0.5	0.7	0.8	0.9	1	1.2	1.1	0.7	-
A_{avg}	m^2	0.4	0.5	0.7	0.8	0.9	1	1.2	1.1	0.7	7.3
v	m/s	0.5	0.5	0.5	0.4	0.4	0.4	0.2	0.2	0	-
Q	m^3/s	0.2	0.3	0.4	0.3	0.4	0.4	0.2	0.2	0	2.3

Table D.3: Average flow velocity and bathymetry for measurement location 3, based on measurements performed on May 14, 22 and 25, 2018.

		River section											
Parameter	Unit	1	2	3	4	5	6	7	8	9	10	11	12	Σ
ΔL	m	1	1	1	1	1	1	1	1	1	1	1	1	12
h_{avg}	m	0.4	0.6	0.7	0.8	1.1	1.4	1.6	1.6	1.4	1	0.7	0.4	-
A_{avg}	m^2	0.4	0.6	0.7	0.8	1.1	1.4	1.6	1.6	1.4	1	0.7	0.4	7.1
v	m/s	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.1	-
Q	m^3/s	0	0.1	0.1	0.2	0.2	0.3	0.5	0.5	0.4	0.3	0.2	0	2.8

E

Backwater rise

Table E.1: Backwater rise study for the case study location in the Cikapundung River, based on the determined friction parameters. The study includes a sensitivity analysis for several parameters.

Variables	h_0	*[m]*	*2*				*2.5*			
	L	*[m]*	*4*		*8*		*4*		*8*	
	v	*[m/s]*	*1.3*	*1.8*	*1.3*	*1.8*	*1.3*	*1.8*	*1.3*	*1.8*
ΔH_{gate}	ξ_{min} *[-]*	*3.4*	0.3	0.6	0.3	0.6	0.3	0.6	0.3	0.6
	ξ_{max} *[-]*	*5.6*	0.5	0.9	0.5	0.9	0.5	0.9	0.5	0.9
	ξ_{avg} *[-]*	*4.4*	0.7	0.4	0.7	0.4	0.7	0.4	0.7	0.4
ΔH_{carpet}	$k_{Str,min}$ *[$m^{1/3}$/s]*	*16.8*	0.01	0.03	0.03	0.06	0.01	0.03	0.03	0.06
	$k_{Str,max}$ *[$m^{1/3}$/s]*	*8.6*	0.06	0.1	0.1	0.2	0.06	0.1	0.1	0.2
	$k_{Str,avg}$ *[$m^{1/3}$/s]*	*11.3*	0.03	0.06	0.07	0.1	0.03	0.06	0.07	0.1
ΔH	min	[m]	0.3	0.6	0.3	0.6	0.3	0.6	0.3	0.6
	max	[m]	0.5	1.0	0.6	1.1	0.5	1.0	0.6	1.1
	avg	[m]	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8
H_3	avg	[m]	2.1	2.2	2.1	2.2	2.6	2.7	2.6	2.7
H_1	min	[m]	2.4	2.8	2.4	2.8	2.9	3.3	2.9	3.3
	max	[m]	2.6	3.2	2.7	3.3	3.1	3.7	3.2	3.8
	avg	[m]	2.5	2.9	2.5	3.0	3.0	3.5	3.0	3.5
h_1	min	[m]	2.3	2.7	2.4	2.7	2.9	**3.2**	2.9	**3.2**
	max	[m]	2.6	**3.1**	2.6	**3.3**	**3.1**	**3.7**	**3.1**	**3.8**
	avg	[m]	2.4	2.9	2.5	2.9	3.0	**3.4**	**3.2**	**3.4**