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Urban River Water Level Increase Through Plastic Waste Accumulation at a Rack Structure

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Plastic debris in water systems is a major challenge for our ecosystem, because it is extremely persistent in the environment. 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 flood risks. Plastic waste accumulation at trash racks leads to a rise in upstream water level and may increase urban flood risk. Until now, most studies of riverine debris accumulation predominantly focused on organic accumulations at trash racks and bridge piers. In this study, flume experiments were used to study the behavior of plastic and mixed debris accumulations. One of the key findings from this study is that plastic debris causes a faster blockage than organic matter, as the plastic blockage contains fewer voids and therefore has a higher blockage density. In addition to the flume experiments, field measurements were performed in the Cikapundung River (Indonesia). This river is one of the tributaries of the Citarum River, which is considered one of the world's most heavily polluted rivers. Combining the results of the flume experiments and field measurements demonstrated that a backwater rise of 1 m/h is plausible for a blocked trash rack in the Cikapundung River, illustrating the additional flood risk caused by plastic pollution. Our results emphasize the need for further quantifying riverine (plastic) debris and investigating its relation to changes in the water system behavior, including its influence on urban flood risk.

Keywords: macroplastic, urban hydrology, plastic, flood risk, Indonesia

INTRODUCTION

Plastic pollution in aquatic environments is an emerging hazard because of its direct and indirect negative effects on ecosystem health and human livelihood (van Emmerik and Schwarz, 2020). Direct effects include the entanglement or ingestion by animals (Gall Sarah and Thompson, 2015) or damage to vessels (McIlgorm et al., 2011). Longer-term effects include break down into microplastics (Weinstein et al., 2016) and negative impacts on mangrove forests (Ivar do Sul et al., 2014). Land-based plastic waste may enter rivers and urban drainage systems through natural drivers, such as wind and surface runoff (Bruge et al., 2018), or direct dumping (Mihai, 2018). Once in the water system, plastic pollution accumulates at hydraulic infrastructures (such as rack structures), leading to clogging of the urban drainage system. In turn, this may lead to increased flood risk in urban areas (Njeru, 2006; Windsor et al., 2019). Unfortunately, plastic waste accumulation at hydraulic infrastructures remains understudied. In this paper, we aim to shed additional light on the relation between the abundance of plastic debris in rivers and increased flood risk, by estimating the water level increase in response of plastic waste accumulation in the Cikapundung River, Indonesia.

Indonesia is estimated to be one of the largest plastic emitting countries in the world (Lebreton et al., 2017), mainly through the densely populated areas with high amounts of mismanaged plastic waste (Lebreton and Andrady, 2019). Recent work estimated the annual riverine plastic emission of the Jakarta rivers and waterways into the ocean to be 2,100 tonnes per year (van Emmerik et al., 2019a). Besides negative effects on the marine environment (Syakti et al., 2017), plastic debris has also been suggested to be one of the main causes for increased flood risk in cities such as Jakarta and Bandung (Marshall, 2005; Peters et al., 2015). As observational evidence to support this is lacking, our study assesses the effects of plastic debris in the Cikapundung River on increased flood risk in Bandung.

We used a combination of flume experiments and field observations to quantify the effect of plastic debris accumulation on water levels in the Cikapundung River. Flume experiments were done to determine the accumulation rate of debris at a trash rack as a function of flow velocity, plastic type, and the plastic/organic content of total debris. Field observations were done to obtain typical values for plastic mass transport and debris composition in a densely populated urban area with poor waste management infrastructure.

MATERIALS AND METHODS

Study Site and General Framework

This study focuses on the Cikapundung River that runs through the city of Bandung, Indonesia (**Figure 1**). Upstream from the city of Bandung, the river predominantly flows through farmlands and the mountainous city Lembang, which is a tourist hotspot. The Cikapundung River is 28 km long and merges with the Cigede River just before it reaches the Citarum River. Due to a lack of waste collection, the Citarum River Basin, of which the Cikapundung River is an upstream tributary, is highly polluted with plastics and other types of waste (Soeriaatmadja, 2018). In this study, reference is made to organic debris, which is often called large wood or instream wood as it forms a relevant part of the river ecosystem. Trash racks, covering the total river width, were installed at the downstream end of the Cikapundung River and several other tributaries, to lower the amount of debris reaching the Citarum River. Such structures in confined areas near bridges can result in clogging of the water system, leading to increased risks of flooding. In order to obtain a better understanding of debris accumulations upstream of a trash rack and particularly the effect of the presence of plastic, flume experiments were performed in the hydraulic laboratory of Bandung Institute of Technology. Additional field experiments were performed at both upstream and downstream locations in the Cikapundung River (indicated in **Figure 1** and specifications in **Supplementary Material S1**) during the end of the rainy season in May, 2018. The field measurements were performed to explore (1) both the mass load and debris composition through the river and (2) to investigate the differences in riverine plastic debris composition and transport flux between rural and densely urbanized area. The ultimate goal was to combine the riverine plastic flux with the results of the flume experiments to determine the initial water level rise if the trash rack in the Cikapundung River gets blocked by (plastic) debris.

Flume Experiments

In total, 39 tests were performed in order to test the reproducibility, flow velocity, debris mass and test duration (overview can be found in the **Supplementary Materials S2, S4**). To combine these experiments to observations in the field, a translation of the flume scale to the field scale is essential. In this study, the geometric, kinematic and dynamic similarity was considered (Froude scaling, Heller, 2017). An overview of these scaling properties can be found in the **Supplementary Material S3**. Cauchy scaling, which takes the Young's modulus of the materials into account, and Richardson 4/3-law, for scaling turbulent diffusion, were both not performed. Schalko et al., 2018 mentioned that the Young's moduli was estimated to be negligible, since they used a predefined accumulation compactness. Furthermore, Schalko et al., 2018 studied several scaling factors, but no scaling effects were found. Schmocker and Hager, 2013 also performed an additional test to study scale effects, but did not find scaling effects.

Different materials were used as debris, i.e., rigid wooden sticks (ρ = 0.3–0.5 g/cm^3) as organic materials and pieces of straws (Polystyrene, PS) and flexible bags (High Density Polyethylene, HDPE) representing plastics (ρ = 0.9–1.6 g/cm^3). Prior to each test, 15 bags were prepared with dried debris mixtures of 0.8 kg to ensure a constant debris deployment. 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 blocking debris and passed debris weight. Debris that accumulated in front of the trash rack was distributed in either vertical or horizontal direction. A vertical spread of the debris in front of the trash rack is referred to as "gate formation." The horizontal spread of debris is referred to as "carpet formation."

To assess the backwater rise (Δh) for each of the experiments, the relative water level increase compared with the starting level (h_0), ($\frac{\Delta h+h_0}{h_0} = \frac{h_\eta}{h_0}$) was related to the added volume percentage (V_d). The added volume percentage was defined with respect

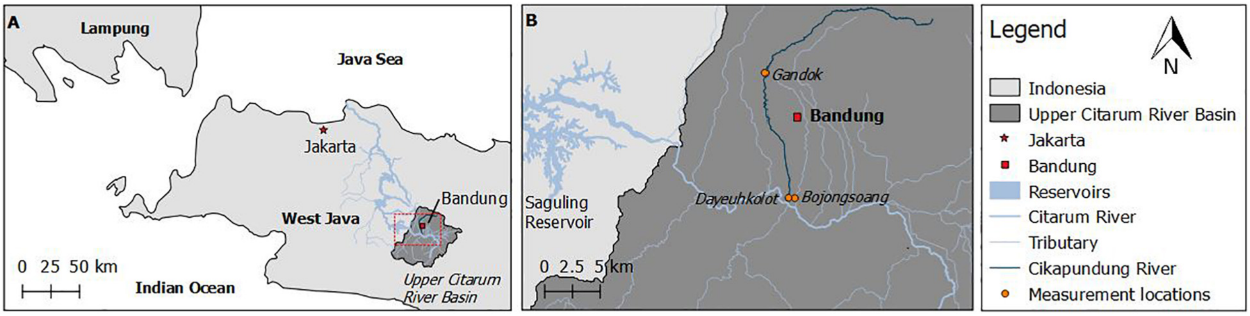

FIGURE 1 | (A) The Citarum River Basin, located in West Java (Indonesia). **(B)** Indication of the measurement locations in the Cikapundung River in Bandung, West Java (Map: DIVA-GIS, Country boundaries Indonesia, 2018; HydroSHEDS, river network and basin outlines, 2018).

to the total added mass for each experiment. In addition, the friction parameters (the loss coefficient and the Manning roughness coefficient) of both the gate and floating debris carpet were based on an energy balance between the up- and downstream hydraulic head.

Furthermore, the friction parameters (n, ξ) were determined based on the water level difference for 100% added debris (**Supplementary Material S2**), for which the following equations were used:

$$\Delta H = H_1 - H_3 = h_1 + \frac{v_1^2}{2g} - h_3 - \frac{v_3^2}{2g} = \Delta H_{\text{gate}} + \Delta H_{\text{carpet}} \quad (1)$$

$$\Delta H_{\text{gate}} = h_1 - h_3 + \frac{v_1^2}{2g} - \frac{v_3^2}{2g} = \xi\frac{v_3^2}{2g} + \frac{v_1^2}{2g} - \frac{v_3^2}{2g} \quad (2)$$

$$\Delta H_{\text{carpet}} = \frac{n^2 v^2 L_c}{R^{4/3}} \quad (3)$$

In which $H_1[m]$ is the upstream hydraulic head, $H_3[m]$ the downstream hydraulic head, ΔH_{gate} $[m]$ the head loss due to the gate formation, ΔH_{carpet} $[m]$ the head loss due to the carpet formation, $h_1[m]$ is the upstream flow depth, $h_3[m]$ the downstream flow depth, ξ $[-]$ the loss coefficient, v $[m/s]$ the flow velocity, g [m/s^2] the gravitational acceleration of 9.81 m/s^2, n the manning roughness coefficient, $L_c[m]$ the floating carpet length and $R\,[m]$ the hydraulic radius. Equation 2 is only applicable before carpet growth takes place.

Figure 2 shows the set-up for the tests and includes a graphical representation of the parameters used in this study. The rectangular flume had a length of 7 m, a width of 0.5 m and a height of 0.7 m (no slope), equipped with a 0.2 m high trash rack with a 1 cm^2 mesh. Similar to the Cikapundung River, the trash rack did not reach the bottom of the flume (installed at 0.05 m above the flume bottom) and trash could still pass underneath the trash rack.

Two water 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 $\pm$ 1 mm. Each test was recorded using action cameras (Nikkei X6S Actioncam, Elmarc B.V., Ridderkerk, Netherlands), both from above and on the side of the flume to capture the horizontal and vertical blockage growth.

Field Measurements

Floating debris samples were taken at three locations in the Cikapundung River (**Figure 1**) during a 10-day measurement campaign, during which measurements were performed from 8 AM to 6 PM with a normal sampling time of 10 min. After every sampling event, the debris was separated in (1) plastics, (2) organics, (3) other debris and the semi-wet mass was determined. For plastic, a secondary separation was performed, distinguishing the five categories (1) Polyethylene terephthalate (PET), (2) Polypropylene (PP)+ Poly-styrene (PS), (3) High-density polyethylene (HDPE), (4) Low-density polyethylene (LDPE), and (5) Multilayer plastics.

Measurements were performed using a single-layered trawl (height: 0.5 m, width: 0.7 m, mesh size: 4 cm; see van Emmerik et al., 2018) to focus on the debris surface load. Additional measurements with a double-layered trawl (height: 0.5 m (2×), width: 0.7 m, mesh size: 2 cm) were performed to also measure the surface and subsurface debris amounts. The α factor was calculated which represents the weight ratio between surface and subsurface captured debris. This factor was used in combination with the horizontal observed variations in flow velocity (measured with a current meter Flowatch FL-03) and the river bathymetry (measured with a Deeper Smart Pro Fish Finder), in order to calculate the riverine plastic mass transport T_p [kg/s] (Equation 4).

$$T_p = \frac{\alpha \cdot M_p \cdot Q}{A_{\text{net}} \cdot u \cdot t} \quad (4)$$

With a reduction factor α [−] for the vertical distribution, plastic mass M_p [kg] river discharge Q [m^3/s], net surface area A_{net} [m^2], flow velocity u [m/s] and sampling time t [s].

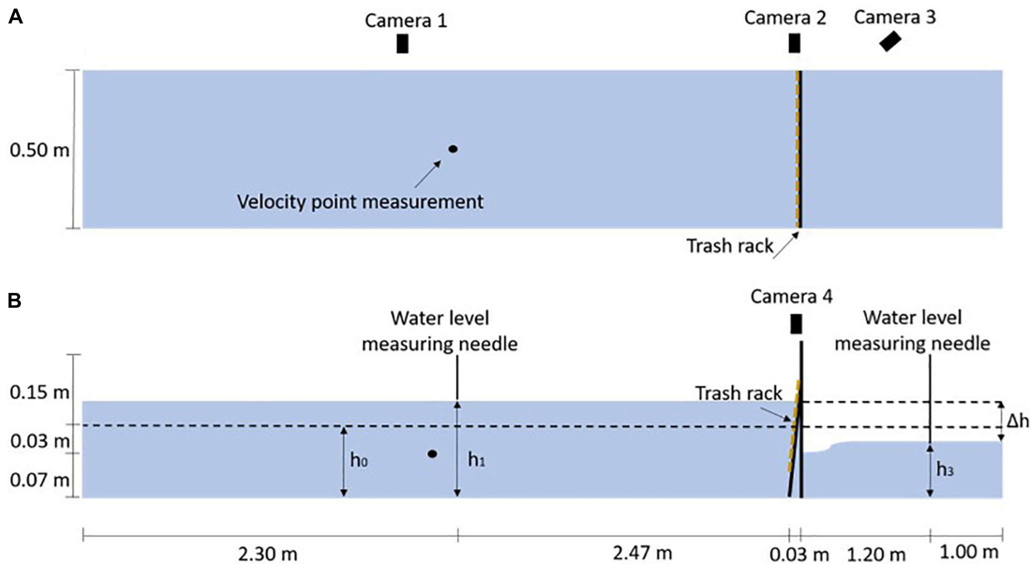

FIGURE 2 | (A) Plan view of flume set-up and camera arrangement and **(B)** side view of trash rack. In which h_0 represents the approach water depth, h_1 the upstream water level, and h_3 the downstream water level.

RESULTS AND DISCUSSION

Flume Experiments

The way in which debris accumulates in front of a trash rack was found to be different for plastic, organic and mixed debris. First of all, differences were observed in the shape of the blockage (**Supplementary Material S7**). Organic debris resulted in a curved shape blockage, whereas plastic debris formed an angular blockage. Furthermore, plastic debris blocks the trash rack faster compared to organic debris (**Figure 3**), which results in a faster water level rise behind the trash rack (five times as fast for a comparable backwater rise, with a similar debris load). The mixed debris shows comparable results to plastic debris at the start of the test, since a fast blockage was observed combined with fast-initial water level increase. Schalko et al., 2019 introduced the characteristic wood volume, which depends on the Froude number. They also found that the backwater rise depends on the Froude number, log characteristics and fine material percentage. In this study it was found that relation between the characteristic and total debris volume for mixed materials equals about 20% for a Froude number of 0.4. In this study, the impact of changing Froude numbers and plastic content was not studied. The passing percentage below the trash rack was found to be highly dependent on the debris type as well as the flow velocity. For the lower flow velocities (model flow velocity of 0.1 and 0.2 m/s), the trash rack was not fully blocked, since the debris primarily contributed to the carpet formation and the passing percentage stayed always below 18%. For the higher flow velocities (model flow velocity of 0.3 and 0.4 m/s) the trash rack was blocked first after which the debris contributed to the carpet growth or passes underneath the trash rack. For 0.4 m/s the passing percentage was 38–49% for plastic, 26–45% for mixed debris and 13–19% for organic debris.

Schmocker and Hager (2013) mentioned two phases of organic debris accumulations at trash racks: (A) the initial debris accumulation at the trash rack and (B) the formation of a debris carpet. Schmocker and Hager (2013) noticed that the first phase causes a major backwater rise (the increase before the inflection point of **Figure 3A**), while the second phase only causes a minor backwater rise (the rise after the inflection point of **Figure 4A**). Similar phases were observed for plastic and mixed debris in the experiments performed in this study (**Figures 3**, **4**), with a major versus minor backwater rise of 75% and 25%, respectively. **Figure 4A** also shows that the test reproducibility is not flawless, for this experimental set-up. A spread in the backwater rise can be observed for the same test conditions, because the trash rack doesn't reach the bottom of the flume and debris can occasionally pass underneath the trash rack.

Additionally, a friction parameter (loss coefficient, equation 2) was calculated for the formed gate (initial trash rack blockage phase) and a friction parameter (Manning roughness coefficient, equation 3) for the second phase in which a carpet was formed. The loss coefficient of plastic due to the denser trash rack blockage was comparable to, or even higher than, a half closed gate, while the organic blockage had much more voids and therefore resulted in a smaller loss coefficient. The results for the Manning roughness coefficient were the other way around, since the organic carpet resulted in a higher friction compared to the plastic carpet (**Figure 3B**).

Field Measurements

A total of about 100 kg debris was collected over 12 h during 10 measurement days. The average weight distribution for plastic, organic and rest debris was, respectively, 34%, 43%, and 23%. This weight composition varied considerably between the measurements, for example the plastic percentage ranged from 11

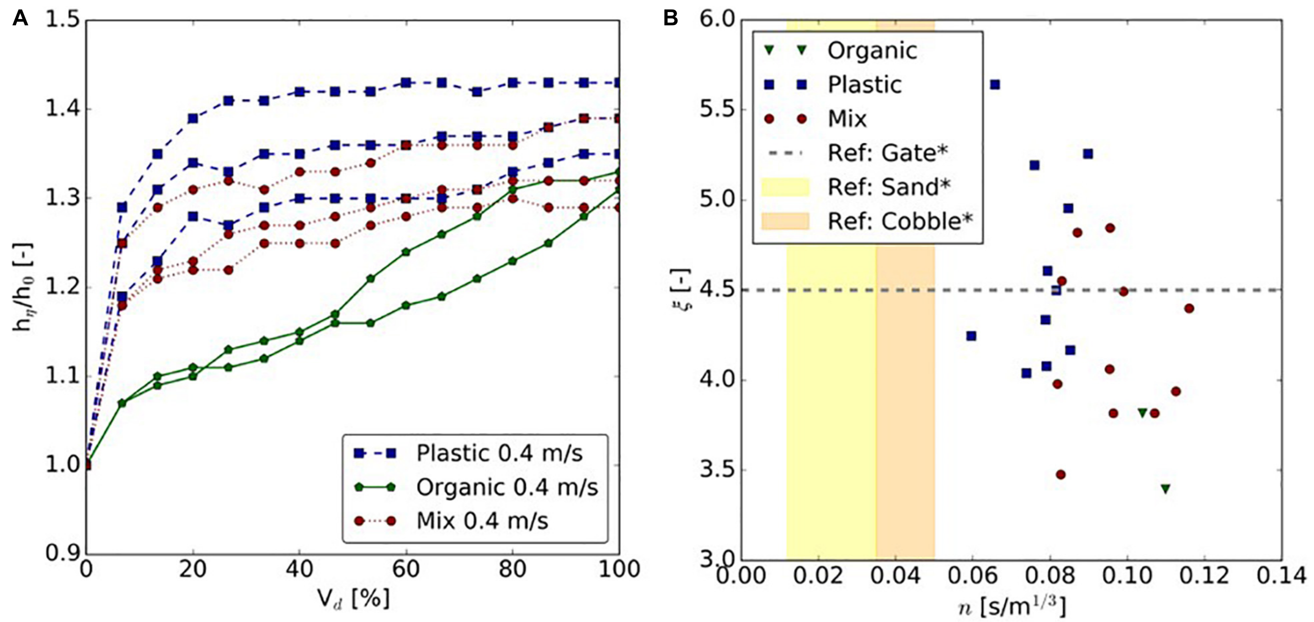

FIGURE 3 | (A) Initial debris accumulation at trash rack and **(B)** carpet formation for experiment 4 with M = 0.8 kg and v_0 = 0.4 m/s.

to 78%. Plastic bags (LDPE, 57%) were the most abundant type of plastic, followed by food packaging (multilayer plastics, 21%) and plastic cups (HDPE, 16%). This abundance of plastic bags was also found in a global riverine plastic debris study by van Calcar and van Emmerik (2019).

In addition to variation in composition, a high variation in debris concentration was measured. The lowest debris transport rate was captured at measurement location 1 (0.01 kg/min) and the highest flux at measurement location 2 (0.8 kg/min). The average captured debris was 0.05 kg/min (σ = 0.08 kg/min) for measurement location 1, 0.26 kg/min (σ = 0.10 kg/min) for measurement location 2 and 0.25 kg/min (σ = 0.18 kg/min) for measurement location 3. Measurements were performed after a rain event at measurement location 1, for which the debris flow significantly increased from 0.01 to 0.55 kg/min. During this event, the plastic ratio stayed almost constant (∼38%). Furthermore, the two-layered net measurements yielded on average a ratio of 61% surface (0–50 cm depth) and 39% subsurface debris flow (50–100 cm depth), during a constant flow velocity of 0.5 m/s.

Estimating Plastic Waste Induced Water Level Rise

The flow velocities and Froude numbers of the flume experiments both range between 0.1 and 0.4 m/s. These velocities scale to 0.4 and 1.8 m/s in the field, respectively. These flow values correspond to the average and most common flow velocity measured during fieldwork conducted in May and June 2018 (0.4 m/s), and a typical flow velocity during heavy showers in the rainy season (1.8 m/s; H. Kardhana, personal communication, May 29, 2018).

During flume experiments with flow velocities between 0.1 and 0.2 m/s (respectively 0.4–0.9 m/s in the field), it was found that the debris flow predominantly contributed to carpet formation. As carpet formation only causes a minor water level increase and the water levels associated with 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 flow velocities between 0.3 and 0.4 m/s (respectively 1.3–1.8 m/s in the field), which causes a major water level increase. Combined with the higher water level during these conditions, a larger flood risk is expected than for carpet formation during low flow velocities.

The flume experiments performed with plastic debris and flow velocities of 0.4 m/s showed a water depth increase of 30–40% upstream of the blocked gate (backwater rise equation is presented in **Supplementary Material S5**). As these laboratory experiments were scaled with respect to the dimensions of the Cikapundung River, this would translate to a water level increase under these conditions (debris load and river flow) of about 1 m.

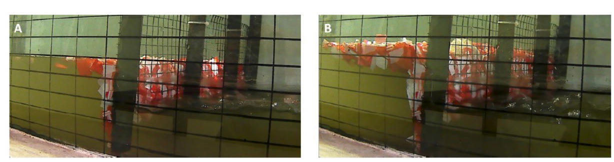

FIGURE 4 | (A) Reproducibility tests displaying the relative backwater rise ($\frac{h_\eta}{h_0}$) versus the added debris volume percentage (M_d). **(B)** The loss coefficient versus the Manning roughness. Manning values for sand and cobble (Phillips and Tadayon, 2006) and the reference value loss coefficient for a 1/2 open gate (Pope, 1997).

With the time dimension being scaled with a factor four and the duration of the flume experiments of 15 min, it would take about 1 h in the field for the water level increase to occur. It is therefore shown that a water level increase of 1 m in the first hour of a gate blockage by plastic debris can occur in the Cikapundung River. It should be noted that the debris load used for this translation is for typical flow velocities during the rainy season in combination with the average measured debris flux during the beginning of the dry season (see section "Field Measurements"). For example, 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.

In this study, no extreme conditions were used to assess the backwater rise as a result of gate blockage. The experiments performed have shown that the back water rise in front of a clogged gate is larger for higher flow velocities (**Supplementary Material S5**). For the Cikapundung River it was found that, when gate formation takes place, an increase of the flow velocity of 33% results in an increase of the backwater rise with by factor 1.8 (0.3 –0.4 m/s).

Additionally, these experiments with different flow velocities (0.3 and 0.4 m/s) have shown that the initial water level increase (gate formation) takes place within the time required to add 20% of the total debris (**Supplementary Material S6**). It is therefore expected that the duration of the initial water level increase is similar during extreme flow velocities ($>$0.4 m/s in the flume, 1.6 m/s in the field). The experiments showed that gate formation occurs rapidly during sufficient debris load and flow velocities above 0.2 m/s. Higher debris loads are therefore not expected to have a large influence on the time required for initial blockage and can be considered less important.

Synthesis

Provided the limitations of scaled laboratory experiments, we demonstrate that plastic debris tends to clog a trash rack faster than organic debris, and projected to the case of the Cikapundung River, can result in an increased water level of 1 m. At this specific location, the trash rack could be installed differently (e.g., rack not until street level or designed to open-up) to reduce flood risks. Our results emphasize that plastic pollution in urban water systems is an urgent problem and requires further research in order to optimize mitigation strategies. Despite the fact that plastic bags are amongst the most abundant debris items, future studies could shed light on more realistic debris compositions.

Blocked trash racks have a major influence on flood risks (Schmocker and Hager, 2013), especially when blocked by plastic debris as a result of the blockage density. In the beginning of the rainy season, when trash from the river banks is flushed away ["first flush" concept, demonstrated by Moore et al. (2011)], a higher potential risk for floods near trash racks can therefore be expected. We demonstrate that plastic waste accumulation in a small urban river can result in a water level increase of 1 m. After this rapid initial water level increase, the water level is expected to slightly increase under the assumption that the flow conditions remain the same ($<$5% of the initial water level increase). From the world's ten most plastic waste producing urban centers, several have similar hydraulic infrastructure as the city of Bandung (Lebreton and Andrady, 2019). Our findings are also relevant for cities such as Jakarta (Indonesia), Kuala Lumpur (Malaysia), and Manilla (Philippines).

The method used to assess riverine debris transport in this study captured debris over the entire water column for a single measurement location (**Supplementary Material S1**). Based on these measurements with a flow velocity of 0.5 m/s, a constant reduction factor was determined to account for vertical variations. However, no information was gathered on the debris variations across the river width. Other studies demonstrated that plastic transport can vary considerably over the river width (e.g., van Emmerik et al., 2019a,b), and may therefore also affect the accumulation at specific hydraulic infrastructure. Additional measurements may also shed light on the effect of hydraulic infrastructure, plastic waste accumulation and carpet formation on the vertical distribution of riverine plastic. Additional studies into this distribution should also be performed at multiple locations along the river and preferably during different flow velocities.

Considerable variations in water level increase were observed for the flume experiments with plastic and organic debris. However, only smooth rigid sticks were used as organic debris, while the presence of fine organic materials (such as leaves) could lead additional friction losses, due to an increased blockage density (Schalko et al., 2018). Furthermore, it would be interesting to study the mixed debris accumulations at bridge piers. Plastic will already stick behind narrow trash racks, while for larger openings the larger organic debris gets more important.

CONCLUSION

A mean plastic debris mass transport for the Cikapundung River of 7.1×10^2 kg/d was found during the measurement period in May 2018, with 61% in the upper 0.5 m of the water column. Most plastics (67%) were identified as low density polyethylene (mainly plastic bags and foils). Furthermore, it was observed that the amount of debris transported through the river increased significantly after rain showers. An increase of the plastic debris flux with a factor 30 was observed after a rainfall event.

Flume experiments conducted for this study, with various debris compositions, showed that the presence of plastic leads to a faster and denser blockage in front of a trash rack. The rate at which the water level increased was five times higher for plastic debris than for organic debris, with a debris load of 0.053 kg/min and a flow velocity of 0.4 m/s for both experiments. This can be attributed to the rapid initial water level increase due to dense gate formation caused by the relatively flexible plastic debris. The experiments performed with plastic debris in this study have shown that the water level rise is caused by a major initial increase due to the gate formation and a minor increase due to the carpet formation of 75 and 25%, respectively.

Based on the flume experiments and field measurements, it was demonstrated that faster blockage occurs after showers due to the increased flow velocity in combination with the increased debris transport. The abundance of plastic debris leads to a faster and denser blockage and will therefore lead to a more sudden backwater increase. Through combining the measured water level increases in the flume and the measured typical debris flux of the Cikapundung River, a potential water level increase of 1 m within the first hour was estimated as a result of plastic debris accumulation in front of an hydraulic structure covering the entire river width.

Our paper demonstrates that plastic debris has a fundamentally different behavior compared to rigid wooden sticks, and poses an additional flood risk in urban areas. With increased urbanization rates and plastic production, additional local assessments are crucial to optimize prevention and mitigation strategies.

DATA AVAILABILITY STATEMENT

All data used for this study will be made available as **Supplementary Material** upon publication.

AUTHOR CONTRIBUTIONS

DH designed the study, collected the data, analyzed the data, and made the figures. WU, HK, and OH provided input for the design of the field and laboratory experiments. DH and TE prepared the first version of the manuscript. All authors contributed to the interpretation of the results and provided input for the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.00028/full#supplementary-material

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Conflict of Interest: DH is currently employed by HKV.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.