ISBN 978-83-927084-8-3
ISSN 0867-7964

SOME ASPECTS OF THE TRANSPORT OF PLASTIC PARTICLES IN RIVERS

Maarten van der Wal*, Mirjam van der Mheen and Gijsbert Tweehuijsen*****

**Deltares, Boussinesqweg 1, Delft, Netherlands, maarten.vanderwal@deltares. nl or wal2000@xs4all.nl*
***Deltares, Boussinesqweg 1, Delft, Netherlands, mirjam.vandermheen@deltares.nl*
**** Foundation Waste Free Waters, Voerendaal, Luiperbeekstraat 23 (6343 PT), g.tweehuysen@hotmail.com.*

The presence of (plastic) litter in the catchment areas of rivers is of high environmental and societal concern. Plastic litter particles transported by rivers vary widely in shape, density and size. These parameters are relevant for the transport mode of plastic litter: floating at the water surface, in suspension in the water column and as part of the bed load transport processes. Individual monitoring campaigns in the field are expensive and time consuming and therefore they need to be combined with mathematical modelling of the transport process for a better understanding of the contributions by different sources and the storage of plastic litter in rivers. The first experiences with this type of modelling concerns the transport of plastic litter in seas. It is recommended to standardize procedures and equipment for monitoring plastic litter in rivers, to set up a European (international) database on monitoring data of plastic litter and to develop standard mathematical models to simulate the transport of plastic litter in rivers.

KEY WORDS: rivers, plastic litter, monitoring, transport plastic particles

1. INTRODUCTION

The presence of (plastic) litter in the catchment areas of the Rhine, Meuse and Scheldt rivers is of high environmental and societal concern and is perceived as such by the general public. Regular clean-ups by volunteers have raised awareness about the pollution of the environment in the floodplains of these rivers. The large yearly effort to remove debris with plastic litter from the dykes and the floodplain by river management organizations requires considerable budgets. For effective policies to reduce the amount of plastic litter transported by rivers a better understanding is required of the transport processes of plastic particles in rivers. Especially a better identification of the sources of plastic litter is prerequisite to implement effective measures to reduce the riverine input of plastic litter to the marine environment.

The amount of available quantitative data for plastic litter in Dutch rivers is limited and can mainly be found from clean-ups and first reconnaissance field measurements of plastic litter transport. These measurements had been carried out in the Meuse River and the Rhine River near Rotterdam recently. This means that research in this area depends strongly on estimations based on expert judgment and a few available data sources.

The monitoring of plastic litter transported by rivers is always confined in space and time. At this moment no regular monitoring programs exist to quantify the transport of plastic litter in rivers including the riverine contribution to the plastic litter in seas. For a complete interpretation of the monitoring data mathematical models are required to simulate the transport of plastic particles. As a first step a conceptual model is presented showing the main phenomena to be simulated in a mathematical model.

The transport of plastic particles via a river system shows interesting conceptual similarities with the transport of sediment particles in rivers. Existing models for the transport of sediments will be helpful to develop models to simulate the transport of plastic litter.

2. TRANSPORT PROCESSES OF PLASTIC LITTER IN RIVERS

2.1. MAIN PROPERTIES OF PLASTIC LITTER

Plastics are polymer chains that are formed either by joining monomers or by creating a free radical monomer which produces a long chain polymer, Leslie et al. (2011). Plastic litter particles transported by rivers vary widely in shape, density and size. These parameters are relevant for the transport mode of plastic litter: floating at the water surface, in suspension in the water column and as part of the bed load transport. These parameters are also relevant for the storage of plastic litter in rivers and floodplains.

Size

Plastic particles smaller than 5 mm (meaning that a particle can pass a gauze with openings of 5 mm size) are called microplastics and very small particles are called nanoplastics. Particles larger than 5 mm are called macroplastics. However, also other classification criteria can be found in the literature. Microplastics can be divided into primary and secondary microplastics. Primary microplastics are intentionally produced either for direct use, or as precursors to other products. They originate from pre-production plastic pellets, industrial abrasives, cosmetics, plastics used in rotomilling, and other consumer products. Secondary microplastics are created by the fragmentation of macro plastics as it degrades.

Forms and shapes

The shape of plastic particles varies widely form micro particles such as pellets to large plastic containers and from rigid particles to flexible particles, for example foils. The overall shape of a particle is fixed by the length along three axis perpendicular to each other: compact if all axes of a particle have almost the same size, a foil if the length of one of these axes is much less that the length of the other two axes. Bottles and boxes have a large volume, but the volume of the plastic material a bottle or box is made of, is much less. The volume of collected plastic litter by volunteers is always expressed in the volume including air contained in a particle. The size of a rigid plastic litter particle is determined by sieving (similar to the sieving of sand). Foils are measured individually piece by piece. Each particle from a sample can be photographed under the microscope.

The size of micro plastics fragments can be measured automatically from the pictures with picture analysis software.

The main categories of micro litter are fragments, pellets, foams, fibres and others. These 5 categories are derived from the TSG Marine Litter Master List, see UNEP (2009). The main categories for macro litter are fragments of shopping bags, food containers, foils, covers, packaging and other plastic/polystyrene items as found in the Rhine near Rotterdam, (Wal et al, 2015).

Density or specific gravity

Plastic polymers as polyurethane, acrylic and nylon have a density of about 1.2 gram/cm^3 and 1.11 to 1.18 gram/cm^3 respectively. Polytetrafluoroethylene has a relatively high density of 2.2 gram/cm^3. These type of fragments sink to the bottom of rivers discharging fresh water. In winter time these type of plastic litter can freeze in an ice sheet and sink to the bottom after melting of an ice sheet. Plastic polymers polyethylene and polypropylene have a density varying from 0.86 to 0.98 gram/cm^3 and from 0.60 to 0.70 gram/cm^3 respectively. Fragments of these materials will float. The density of a plastic litter fragment can change in time, for example by the formation of a biofilm on its surface, by gas bubbles trapped in a fragment or several particles may merge and behave like a single particle. Also floating particles can be transported as part of an ice sheet in a river.

The intensity of the turbulent fluctuations in a river depends on the roughness of the river bed and the discharge. On an alluvial river bed the most important fluctuations originate from the crest of river dunes. During floods the height of these river dunes and the turbulent fluctuations increase and therefore it is possible to measure at the water surface plastic litter with a higher density than 1 gram/cm^3 during and after floods. This was found by monitoring plastic litter in the Meuse by Tweehuijsen (2013) and in the Seine by Gasperi et al (2014).

2.2. TRANSPORT MODES OF PLASTIC LITTER

The transport of plastic litter in rivers occurs through different transport modes: a fraction floats on the water surface, a fraction is transported in suspension in the water column and a fraction is transported as part of the bed load transport over the bottom of a river. The most visible fraction is the coarse fraction (≥25 mm) of floating debris during floods, see figure 1. The transport of plastic litter with a density close to 1 and foil formed particles are the so-called suspended load, which stay in the water column for extensive periods of time because the upward forces (the natural turbulent fluctuations in flowing water) balance the underwater weight of the litter particles. The transport of a plastic bottle partly filled with air floats, but after the air escapes, it might sink to the bottom. A small part of the plastic litter, that with a higher density than water, sinks to the river bed and eventually becomes part of the bed load transport process. Those particles are stored temporarily in the active bed forms on a river bottom (ripples, local scour holes with varying sizes in time and river dunes). The propagating velocity of the bed load is much smaller than the velocity of the main flow in a river. In extreme cases the river bed is covered almost completely by plastic particles, as is described for the Thames (Morritt et al 2013).

The plastic fraction of the total volume of floating debris during normal flow appears to be smaller than 10 %, since debris at the water surface mainly consists of organic material such as branches, roots and leaves. In the Seine the percentage of plastic litter varied between 1 and 5 % (Gasperi et al, 2014). Since floating plastic litter is the most visible fraction, it receives the most attention from the general public and researchers alike, however it is not representative of the total amount of plastics present in the considered river systems, where plastic litter occurs mainly in the water column and river bed.

Figure 1: Illuminated island full plastic litter in the Meuse River near Borgharen during night, 28 March 2011, (an art project by artist Toon Eerdekens to draw attention of the general public to the transport of plastic litter in rivers).

The highest concentrations of plastic litter are observed during floods as floodplains become inundated. The light weight particles stored in a floodplain start to float after inundation of a floodplain. That is why high concentrations of floating plastic litter are observed during the rising limb of a flood wave. The dispersed plastic litter may be transported further downstream with a next flood. The pathway of floating plastic litter follows the direction of the resulting force of flow lines at the water surface (steered by secondary flow phenomena in meander bends) and the drag force exerted by wind on floating litter. A pathway ends temporarily at a bank, in vegetation topping above the water level, fences in a more downstream floodplain or at hydraulic structures (Figure 1). Floating plastic litter ends up in the North Sea either directly or indirectly after temporary storage in a floodplain after a flood. During each flood wave floating plastic litter travels a few meander lengths. Stored in a flood plain its size may decrease by ultra violet radiation (UV, photo degradation) and abrasion or mechanical action to microplastic particles transported in suspension. Additionally, the weight can increase by fouling with algae that attach to plastic particles where they might become part of the very slow bed load transport process during a following flood wave. The fouling of plastic particles means they get covered with a biofilm, leading to a change in their density. However, the rate at which this occurs is much slower than for organic materials.

Plastic litter on the river bed will transport small distances in a flood wave, because these particles are part of the bed load transport of river sediment. Particles will disintegrate by abrasion by moving sand or gravel particles. Some plastic particles will be buried under a river bed form (ripple, dunes) for a long period.

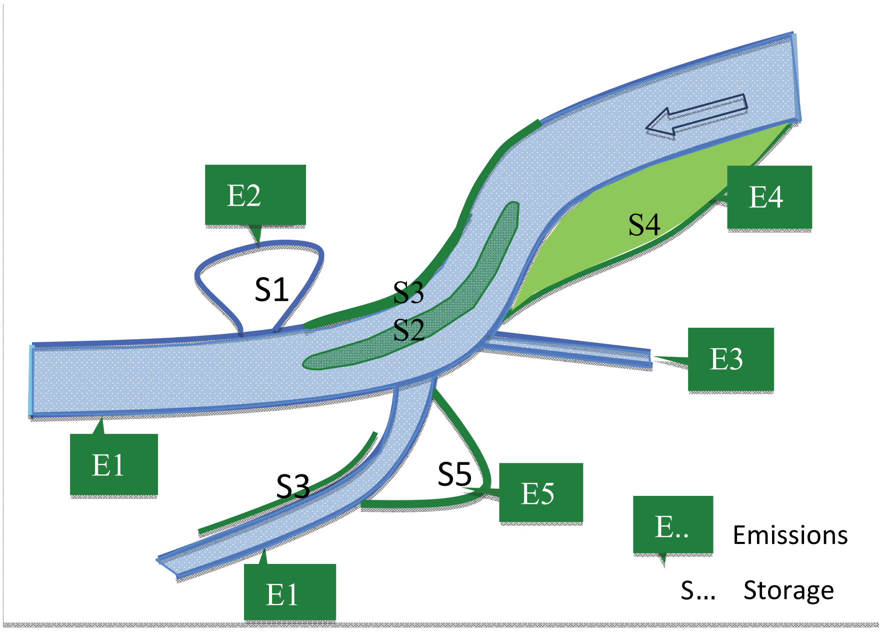

Figure 2: Conceptual illustration of emissions, transport and storage of riverine litter, prepared by Tweehuijsen (Wal et al, 2015)

The different emissions and storage locations of plastic litter in a river are indicated in Figure 2 as an illustration of the described processes:

- E1 is an emission directly into the river, like the emission from a waste water treatment plant (WWTP), a factory, a ship or a city;
- E2 is an emission in a water basin that is connected to a river. It can be a harbour basin or a connected lake;
- E3 is an emission into a tributary of the main river;
- E4 and E5 are emissions on a floodplain, waiting to be transported with a high water period (e.g. litter discarded by tourists, plastic used by farmers in a floodplain or plastic from illegal dumping);
- E6 is an emission outside the floodplain, but litter is transported by waterways, wind and sewage systems into the river;

- S1 is litter stored in basins that have a connection with the river and consists of litter input either from an emission or it has been pushed in the basin by wind or high water;
- S2 is litter with a relatively high density on the river bed;
- S3 is litter deposited on a riverbank, waiting to be transported by a high water wave or a change in wind-direction.
- S4 and S5 is litter stored in a floodplain of the river or from tributaries in the whole watershed, either by direct emission or by deposition at a previous high water period.

These processes should be included in the monitoring programs and the modelling software.

3. TRANSPORT MEASUREMENTS OF PLASTIC LITTER

The monitoring of plastic litter on beaches and in seas has developed more in the last decade than the monitoring of plastic litter on river banks and in rivers. Monitoring of debris including plastic litter is regularly conducted on beaches according to OSPAR protocols (Hanke et al, 2013). In rivers there are no standard monitoring programs yet, even though there are many clean-up actions depending largely on volunteers. For plastic litter specific standard methods for monitoring and data storage in databases are needed to be widely accepted.

Seawater samples of floating and suspended plastic litter are mostly taken by nets and most studies have used Neuston nets. The main advantage of nets is that large volumes of water can be sampled quickly. Nets differ from each other in the mesh size and the opening area. A Manta net, which is an improved design of the Neuston net (Brown et al, 1981), is discussed by the Joint Research Center of the EU (Hanke et al, 2013) as a potentially good technique for the monitoring of floating litter within the EU. Manta nets are already being used to measure the plastic pollution on the oceans (for example (Eriksen et al, 2013) and (Reisser et al, 2013)).

Another instrument that is deployed on a global scale and that has also been used for microplastic sampling is the continuous plankton recorder. The UNEP (UNEP, 2009) and (Hanke, 2013) recommended a line transect method to identify the presence of plastic litter on a seabed. The major challenge for a diver survey following a line transect is locating and swimming the correct transect line and distance. In rivers the sight under water is often too limited to apply that method successfully. A standard method to monitor the bed load transport of plastic litter in rivers is still missing.

Instead of using nets plastic litter can be sampled by pumping sea water through a filter on-board a ship. Sea water is collected from the side at specified depths, mostly ranging between 4 m and 1 m below the water surface (Maes et al 2012).

Remote sensing techniques are under development to identify floating plastic litter and in the future also plastic litter in suspension. The expectations of these techniques are high as a supplement to other monitoring methods (UNEP, 2009).

In a recent survey the level of pollution in EU rivers from plastic litter was identified and the level of inputs of plastic litter was estimated from the rivers into four European regional seas (Wal et al, 2015). The sampling covered the whole spectrum of litter categories, both microplastics and macroplastics, since these items were caught by two different samplers. Microplastic was mainly sampled with a Manta net without wings. The larger particles were sampled with a sampler recently developed by Waste Free Waters (WFW), see figure 3. However, the bed load transport of plastic litter was not sampled, but the plastic litter in fishing nets at the bottom of the Rotterdam harbor demonstrated the presence of plastic litter at the bottom of a river.

The Manta net has an internal width of 60 cm and mainly samples litter floating near and on the surface, skimming the surface to a depth of 10 cm. The sieve size of the net is 0.3 mm. The sampling time was a maximum of 30 minutes, depending on the amount of silt and other organic material (turbidity) in the water, because of the risk of clogging of the net. The reliability of the Manta net decreases if samples are taken in waves, since the amount of water sampled is difficult to determine accurately and the trap efficiency might reduce.

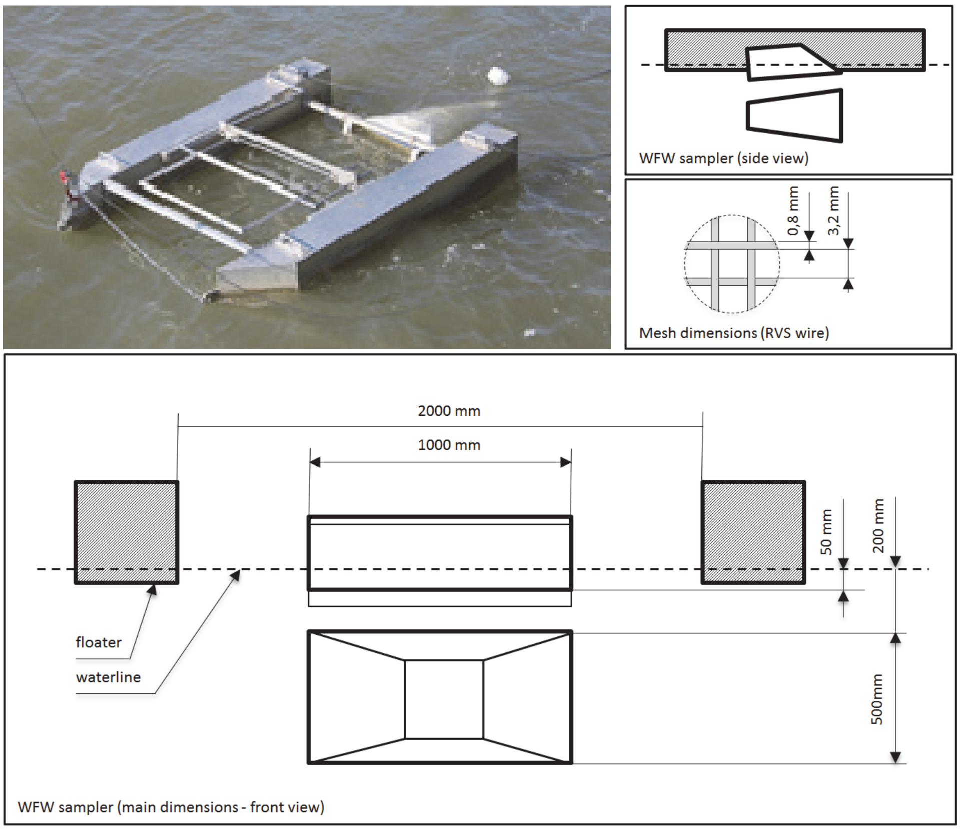

Figure 3 The Waste Free Waters sampler combined with Manta-net sampler as used in Rotterdam Harbor, 2014, G. Tweehuijsen

The Waste Free Waters sampler (WFW-sampler) consists of two floating bodies with two metal nets in between: a surface net and, below the waterline, a suspension net. Both nets have a width of 1 m and the square sieve size is 3.2 mm. The leading edge of the surface net is 3-5 cm below the water surface. The suspension net collects samples at a depth of 0.2 to 0.7 m below a horizontal water surface. However, in conditions with wind and ship-induced waves these figures will change in a complex way. It is recommended to develop and to standardize samplers and procedures to monitor the transport of plastic litter in rivers.

4. MATHEMATICAL PLASTIC LITTER TRANSPORT MODELS

Depending on the type of plastic litter in a river (floating, suspended in the water column or bed load), different transport processes are of importance. This should be taken into account in the mathematical model that is used to simulate the transport of plastic debris.

In the oceans floating and suspended plastic litter has been modelled in several ways. Statistical models based on observed drifter trajectories have been used to simulate the pathways of individual plastic particles (Maximenko et al, 2012) and (Sebille et al, 2012). Numerical particle tracking models that use the water movement as calculated by a hydrodynamic model have also been used to determine the behaviour of fully submerged, neutrally buoyant particles (Lebreton et al, 2012). Both types of models calculate the advection of plastic particles by the surface- or near-surface flow.

Individual pathways of microplastic particles have also been modelled in the North Sea (Stuparu et al, 2015). In this model, each particle is influenced by advection, diffusion and settling. The settling velocity is a function of the particle density and size. Different types of microplastic particles have been modelled, simulating the rising of lighter particles and sinking of heavier particles. In the future, improvements will be made to include degradation (by fragmentation or microbial decay) and fouling of plastic particles.

In on-going work, floating macroplastic transport is being modelled in (amongst others) the North Sea and the Guanabara Bay in Brazil. In these models the direct forcing due to wind is taken into account. The forcing depends on the size and density of the particles, since this determines how large an area is above the water surface and influenced by wind. Direct forcing by wind is of particular importance in the Guanabara Bay, where the tidal current and wind influence are the dominant transport processes of floating macroplastics. In rivers, wind has also an important influence.

The bed load transport of plastic litter on river beds has not previously been modelled. However, several sediment transport and morphological models exist. These models form a good basis for modelling bed load plastic litter transport.

5. CONCLUSIONS AND RECOMMENDATIONS

Scientific studies and surveys show that litter pollution (especially plastic litter) accumulates in the marine environment and that most marine litter comes from land based sources and are transported by rivers. For an effective policy it is necessary to understand the transport process and to identify the contribution by different sources in the catchment of a river.

Individual monitoring campaigns in the field are a first step to increase the knowledge of the transport of plastic litter by rivers. However, they are expensive and time consuming and therefore they need to be combined with mathematical modelling of the transport process. It is recommended to reach agreement about standard monitoring equipment and procedures for monitoring campaigns.

The transport process of plastic litter in a river can be divided in several sub-processes: transport of floating plastic litter, transport of litter in suspension and transport of plastic litter as bed load. The division between these sub-processes is in the first place by density of plastic litter and secondly by the shape and size.

Rivers function as transport route and as a temporary storage of plastic litter. Only a part of all plastic litter transported by a river will be discharged into a sea. The long term effects on flood plains and riverbeds that act as a sink need to be investigated more in depth.

It is recommended to set up a European (international) database of monitoring data and sources of plastic in river basins. Contractors and volunteers in clean-ups should be able to add their data according to a standard data protocol in a separate section of the database. Research data could then be shared through European databases for each river catchment.

Different types of mathematical models will contribute to the knowledge needed to understand the transport process of plastic litter in rivers. Existing plastic transport models that are used in the oceans and seas as well as sediment transport models can be used and expanded to model plastic transport in rivers. Models using transport formula, plastic litter concentrations and modelling of individual pathways need to be calibrated using monitoring data. The setup of monitoring surveys should be tuned to the use of monitoring data for the calibration of mathematical models.

ACKNOWLEDGEMENTS

This work was based on a study awarded by the Dutch Public Works Department, Rijkswaterstaat and a study awarded by the European Commission DG Environment under Framework Contract No ENV.D.2/FRA/2012/0025 to a consortium of Eunomia Research and Consulting, Deltares and Institute for Water of the Republic of Slovenia. We are especially grateful to Lex Oosterbaan, Bert Bellert and Ronald van Dokkum of Rijkswaterstaat and to Leo de Vrees, Nigel Smith and Michail Papadoyannakis, all of the European Commission DG Environment, for their guidance and advice.

REFERENCES

1. Gasperi J., R. Dris, T. Bonin, V. Rocher, B. Tassin, 2014, Assessment of floating plastic debris in surface water along the Seine River, Environmental Pollution 195, Elsevier, pp 163 – 166
2. Leslie, H., M.D van der Meulen, F.M. Kleissen and A.D. Vethaak, 2011. Microplastic Litter in the Dutch Marine Environment. Providing facts and analysis for Dutch policymakers concerned with marine microplastic litter. Deltares, report 1203772-000, Delft, Netherlands.
3. Brown, D.M., Cheng, L., 1981. New Net for Sampling the Ocean Surface. Marine Ecology Vol. 5, pp 225 – 227.
4. Hanke 2013, Guidance on Monitoring of Marine Litter in European Seas, European Commission,Joint Research Centre, Institute for Environment and Sustainability, ISBN 978-92-79-32709-4 (pdf), ISBN 978-92-79-32710-0 (print)
5. Eriksen, M., Maximenko, M., Thiel, M.,Cummins, A., Lattin, G., Wilson, S., Hafner, J., Zellers, A., Rifman, S., 2013. Plastic pollution in the South Pacific subtropical gyre, Marine Pollution Bulletin 68, pp 71 – 76.
6. Reisser, J., Shaw, J., Wilcox, C., Hardesty, B.D., Proietti, M., Thums, M., Pattiaratchi, C., 2013. Marine Plastic Pollution in Waters around Australia: Characteristics, Concentrations and Pathways, PLOS ONE Vol. 8.
7. Maes, T., M. Nicolaus, D. Stephens, J. Van Der Molen and A. Reese, 2012, Marine Litter Monitoring, Centre for Environment, Fisheries & Aquaculture Science, CEFAS, report 5112, 31 March 2012
8. Morritt, D., P. V. Stefanoudis, D. Pearce, O. A. Crimmen, P. F. Clark, 2014, Plastic in the Thames: A river runs through it, Marine Pollution Bulletin 78, Elsevier, pp 196 - 200
9. Paassen, J. van, 2010, Plastic afval in rivieren, Onderzoek naar hoeveelheid en samenstelling (Plastic litter in rivers – amount and composition), University Utrecht, Netherlands
10. Technische Adviescommissie voor de Waterkeringen, 1995. Druk op de dijken 1995 (Pressures on the dykes 1995), Delft (in Dutch),
11. Tweehuijsen, G., 2013, Onderzoek naar de aanwezigheid van grof en fijn rivierafval in de Maas (in Dutch)
12. Tweehuijsen, G., 2013, Indicatieve resultaten van 5 metingen in oktober 2012 (in Dutch).
13. United Nations Environment Programme/IOC, 2009, Guidelines on Survey and Monitoring of Marine Litter UNEP, Regional Seas Reports and Studies No. 186, IOC Technical Series No. 83, Nairobi, Kenya, ISBN 978-92-807-3027-2
14. Wal, M. van der, M.D. van der Meulen, E.W.M. Roex, Y. Wolthuis, G. Tweehuysen en A.D. Vethaak, 2013, Summary report plastic litter in Rhine, Meuse and Scheldt, contribution to plastic litter in North Sea, project 1205955, Deltares, Delft
15. Wal, M. van der, M. van der Meulen, G. Tweehuijsen, M. Peterlin, A. Palatinus, M. Kovač Viršek, L. Coscia, A. Kržan, 2015, SFRA0025: Identification and Assessment of Riverine Input of (Marine) Litter, Eunomia Research & Consulting Ltd, Bristol, United Kingdom
16. Maximenko, N., Hafner, J., Niiler, P., 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters, Marine Pollution Bulletin 65, pp 51 – 62.
17. van Sebille, E., England, M.H., Froyland, G., 2012. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters, Environmental Research Letters 7.
18. Lebrton, L.C.M., Greer, S.D., Borrero, J.C., 2012. Numerical modelling of floating debris in the world's oceans, Marine Pollution Bulletin 64, pp 653 – 661.
19. Stuparu, D., van der Meulen, M., Kleissen, F., Vethaak, D., El Serafy, G., 2015. Developing a transport model for plastic distribution in the North Sea, IAHR Conference Paper, The Hague, Netherlands.