MSc Program
Environmental Technology & International Affairs

Unwanted Pathways:
A Material Flow Analysis of Plastics from Production to the Ocean

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 28.05.2014

Affidavit

I, **VERA KELLEN**, hereby declare

1. that I am the sole author of the present Master's Thesis, "UNWANTED PATHWAYS: A MATERIAL FLOW ANALYSIS OF PLASTICS FROM PRODUCTION TO THE OCEAN", 103 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 28.05.2014

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Abstract

The accumulation of microplastics in the world's oceans has been all over the media since the discovery of the Great Pacific Garbage patch in 1997. Although the impacts of plastics on the marine ecosystem and the amounts in the gyres have by now been quite extensively covered in literature, research regarding the journey of the plastic debris from source to sink is still scarce.

Consequently, this thesis aims to identify the major pathways of synthetic polymers from anthropogenic sources to the 5 accumulation zones in the oceans, including closer scrutiny on how the Tohoku tsunami of 2011 impacted the flows and stocks. The results are based on thorough literature review and are presented as a global material flow analysis (MFA) to point out the extent to which each source contributes to the prevalence of plastic in the five gyres of the world's oceans. The presentation of the results as an MFA aims to support future policy-making and provide research incentives in marine pollution prevention.

The research shows that of the 285Mt of plastics produced in 2014, 4.76Mt entered the marine environment as beach litter, depositions on the seafloor and microplastics in the gyres. The main flows towards the gyres were identified as 0.4Mt/year extra-gyral input of beach litter as well as 0.3Mt/year inflow from anthropogenic pre-and postconsumer plastic stocks in the case of a tsunami. The flow of litter towards the beach stemmed mainly from uncollected plastics, amounting to 0.56Mt/year, and dumpsite leaking, equaling 4.19Mt/year as of 2014. The study further showed that the shipping industry and related export activities have only a minor impact on the plastic abundance in the ocean, with an input of a mere 0.044Mt/year. Additionally, the comparison between every year flows and tsunami induced flows showed a doubling of the input to the gyres caused by a single event in one region of the world. This underlines the role of efficient waste management prior to the event, as well as quick disaster response, in reducing the input of plastic material to the gyres.

The overwhelming scarcity of data in this section of marine debris research made it necessary to base a substantial part of this thesis on extrapolation and estimations: It is therefore concluded that further research needs to be done to properly quantify the different flows of plastic to the ocean and identify the most efficient way in preventing plastic from damaging the marine ecosystem.

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Furthermore and foremost, I wish to thank my family for their infallible encouragement and love throughout my life. I thank my parents for allowing me to dream and for helping me fulfil them; I thank my sister, for I wouldn't be here if she didn't know me better than I know myself; and, last but not least, I thank my brother and my sister-in-law for giving me plenty of reasons to finish before summer.

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"The last fallen mahogany would lie perceptibly on the landscape, and the last black rhino would be obvious in its loneliness, but a marine species may disappear beneath the waves unobserved and the sea would seem to roll on the same as always." (Ray, 1988: 45)

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List of Abbreviations/Acronyms

ABIPLAST	Associação Brasileira da Indústria do Plástico Brazilian Plastics Industry Association
ACRR	Association for Cities and Regions for Recycling
CIA	Central Intelligence Agency
DDT	Dichloro-diphenyl-trichloroethane
EPRO	European Association of Plastics Recycling and Recovery Organisations
EPS	Expanded polystyrene
HDPE	High density polyethylene
ICC	International Coastal Cleanup
IMO	International Maritime Organisation
IOG	Indian Ocean Gyre
ISWA	International Solid Waste Association
LDPE	Low density polyethylene
LLDPE	Linear low-density polyethylene
MARPOL	International Convention for the Prevention of Pollution from Ships
MSW	Municipal Solid Waste
NASG	North Atlantic Subtropical Gyre
NO	Nonylphenol
NOAA	National Oceanic and Atmospheric Administration
NPSG	North Pacific Subtropical Gyre
OP	Octylphenol

OSPAR	Oslo Paris Convention for Protection of the Marine Environment of the Northeast Atlantic
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PBDE	Polybrominated diphenyl
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
PVDF	Polyvinylidene fluorid
SAP	Superabsorbent polymers
SASG	South Atlantic Subtropical Gyre
SOLAS 74	UN Convention on the Safety of the Life at Sea, 1974
SPSG	South Pacific Subtropical Gyre
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environmental Programme
WtE	Waste to Energy

1 Introduction

1.1 The Problem

The discovery of the North Pacific Garbage Patch in 1997 by Charles Moore sparked media hype around the world. Pictures of marine animals entangled in plastic bags, animal corpses filled with garbage and islands covered by plastic debris were published in newspapers all around the globe and on the Internet. This lead to a general questioning of one of todays most highly praised resources: plastics[1]. Plastics are often compared to diamonds not only in terms of their value to economic development but also in terms of longevity. The special characteristics of the polymers have made them an integrative part of everyday life, and in the past years, a lot has been invested into recycling and waste to energy recovery of plastics. Nevertheless, their special characteristics and longevity are also exactly what caused them to become a thorn in the flesh of marine environmentalist. The damage plastics cause in the marine environment is undeniable[2] and closely linked to their slow decomposition rate in the seawater. As the ICC report (Ocean Conservancy, 2010) shows, while common non-plastic marine debris such as paper towels, cardboard boxes and waxed milk cartons are decomposed within weeks to months, plastic stays in the environment over decades to centuries. Although the image created by the media about "plastic islands" is a distorted one, an extensive body of serious research in the area has proven the existence and shed light on its extent of plastics in the open sea, focusing especially on the five major accumulation zones of ocean circulation.

Despite reliable data of global plastic production and consumption of plastics, "[i]t is not possible to obtain reliable estimates of the amount of plastic debris that reaches the marine environment" on a yearly basis (Derraik, 2002: 843). The estimates vary between 6.4 million metric tonnes (Allsopp et al., 2006) and 10 million metric tonnes per year (European Commission, 2013). In fact, only little research focuses on a quantitative analysis of possible pathways from land to ocean, despite the Ocean

[1] 'plastics' is used to encompass the wide range of synthetic polymeric materials that are characterized by their deformability and can thus be moulded into a variety of three-dimensional shapes, including a common materials such as polypropylene, polyethylene, polyvinyl chloride, polystyrene, nylon and polycarbonate.

[2] See Annex V for further elaboration on the environmental damage plastics cause in the marine environment

Conservancy (2010) estimating that 60-80% of the debris stem from land-based activities. As ocean-based sources such as the shipping industry are by now already been quite extensively regulated by national and international legislation[3], inefficient plastic disposal in waste management systems as well as plastic input from natural disasters seem to be the next factors to investigate.

1.2 Objective and Research Question

It is the objective of this paper to quantify the amounts of plastics reaching the five accumulation points in the open sea by analysing the life cycle of plastics from production to disposal. This analysis will be done based on a quantitative description of global plastic flows and stocks. The ocean and the beaches will in this context be addressed as *unwanted sinks* of plastics while landfilling and other means of disposal in the waste management system are referred to as *wanted sinks*. The results will be presented in form of two material flow analyses (MFAs), which will help deduce the difference between the yearly business-as-usual inflows of plastic material and the input induced by tsunamis.

The research question of this paper is to what extent the various origins of plastic contribute to plastic pollution of the 5 gyres. To uncover which are the major inputs in general and in the case of a tsunami, the different origins, pathways and sinks need to first be investigated on a quantitative basis. To that end, the first part of the thesis will give an overview of the research and literature on anthropogenic plastic production and consumption. The second part will look into the quantities reported in the ocean and the gyres and the potential sources for the plastic fragments. The third part will present the global origins, pathways and sinks identified in the literature review of the first two chapters. Finally the results will be presented on the basis of two separate global material flows, which will then be discussed in light of the different results discovered over the course of the work and the assumptions made thereon.

The main hypothesis for this research is that natural disasters contribute a far more extensive quantity of plastics to the marine environment than land-based and ocean-based activities. To investigate this hypothesis, the 2011 Tohoku tsunami will be used as a case study to determine how much the annual plastic input to the ocean is influenced by such a disaster.

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[3] See Annex VI for further elaboration of the legal framework on marine pollution

1.3 Methodology

Each part of the thesis will be based on a thorough literature and research review, taking into account the major findings of national and international organisations concerning the amount of plastic in the anthropogenic metabolism and in the ocean. The results will be analysed through a material flow analysis of plastics including all possible pathways and sinks of plastic both wanted, as in landfilling, and unwanted, as in beach littering. The purpose of using a material flow analysis to present the results is to show the extent to which each of the analysed pathways contributes to the plastic in the gyres in a clear and concise way. Although it is not the goal of this thesis to make policy assumptions, it aims at delivering data relevant to assess strategies and concepts currently in place to reduce the flows of plastics to the oceans.

1.3.1 Data collection

The data used in this paper was not collected by the author, but is extracted from statistics and reports of national environmental protection agencies and ministries as well as from conference reports and publications of international and national non-governmental organisations.

The sources include the most recent publications by the European Union Commission as well as the International Solid Waste Agency. The results in the MFA will be based on the data and evaluations presented in preceding chapters and literature review.

The data on the plastic quantities in the gyres has been collected both by stomach analysis of marine animals and water probing with trawl or other devices. The difficulties inherent to using this data will be outlined within the chapter and will be included in the assessment of the data.

The data on plastic production, consumption and post-consumer pathways include some extrapolation, as it was not possible to collect data for the global plastic sector and waste management treatment of 2014. However, these assumptions are made clear within the thesis and the uncertainties are included in the conclusion drawn from the results.

2 Plastics and Society

Although humans have been in contact with plastic already 1600 BC, when natural rubber was used to make plastic figurines by the Mesoamericans, it is only in the 1930s that mass production of plastics saw its beginning when the process of producing polymers from petroleum, and thus production of synthetic polymers, was discovered (PlasticsEurope, 2014a; Andrady and Neal, 2009). Synthetic polymers are contingent to almost every aspect of life, as we know it today. The appeal of plastics is not only due to its chemical and physical characteristics, but also to the comparatively low prize and wide range of applicability (PlasticsEurope, 2014a).

This chapter aims to outline the current anthropogenic plastic cycle. First, the different areas in which plastics is being used are described to give a better understanding of the applicability of the material and potential leakages. The second and third parts outline the global plastic production and consumption respectively. In these two sub-chapters, the quantities and potential pathways from the production side to the ocean will be pointed out. The fourth part will estimate the anthropogenic stock of plastics both currently in use and in landfills via three scenarios. The fifth part is dedicated to waste management. Here the global postconsumer plastic waste will be quantitatively defined, detailing which amount will end up in controlled landfills, uncontrolled dumpsites, and/or general waste management facilities, such as recycling or Waste to Energy (WtE) plants. It is assumed that inefficient waste management of plastic is the source of pollution that can be reduced most easily. This assumption was deduced from a recent study on seabird stomach analysis (Ryan, 2008). The study showed that the composition of plastic in the stomachs of fulmars had changed from being mainly industrial pellets to being mainly user plastics (Ryan, 2008). Although not being entirely conclusive, such a change could indicate that the industry initiatives to reduce the loss of pellets have been successful. This study is the basis of seeing high potential in reducing plastics in the ocean with increased waste management. It is the goal of this part to identify the leakages in the land-based activities.

2.1 Plastic usage

Nowadays, the plastic industry provides a wide range of plastic polymers ranging from Polystyrene (PS), Polyvinyl chloride (PVC) and Acrylic polymers to synthetic fibre, Polyamides (for example nylon), Polyolefins (for example polypropylene), and Polyethylene (PE) (PlasticsEurope, 2014a). The latter is the most extensively produced polymers nowadays and is applied in the form of high-density (HDPE) and low-density polyethylene (LDPE) in kitchenware, containers, and packaging and as component of plastic bottles (American Chemistry Council, 2014). The formation of plastics happens over several steps from small molecules, yielded from petroleum, to the various products we refer to as plastics (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014).[4] Thanks to their distinct characteristics, polymers are used in a vast variety of applications. 80% of today's plastic production consists of thermoplastics (e.g. HDPE, LDPE, PET, PVC, PP) and the remaining of thermosets (Polyurethane, epoxy, phenolic) (ACRR, 2004: 21-22).[5] The physical and chemical parameters of each polymer vary highly from good barrier characteristics (PET), to impact and electricity resistance (HDPE), to good insulating properties (PVC) (ACRR, 2004). Their adaptability to different applications results in usage across various sectors including packaging, building and construction, sport, leisure, design, transportation, electronics, agriculture, medical and health care (PlasticsEurope, 2014c).

Today, 50% of plastics are used for single-use disposable applications such as packaging, agricultural films, and disposable consumer items (Science for Environment Policy, 2011). Usually, special attention is paid to packaging due to its one-time usage and high consumption. Packaging plastics are characterised by their lightness, strength, impermeability and resistance to microorganisms, thus providing a sterile way of packing and storing food and other items (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014). According to PlasticsEurope (2014c), more than half of all European goods are packaged in plastics, although this does not necessarily mean that the whole packaging consists of plastic.

Further, plastics are also in direct contact with the human body in the medical and health sector as they are used in syringes and intravenous blood bags as well as in prostheses, coronary stents, plastic pill capsules and hearing aids (PlasticsEurope, 2014c). When it comes to leisure time and clothing, plastics have also highly contributed to the development of sports tools and clothing fibres. To mention only one specific, ocean-related activity, fishing gear is made up of PE, PP and nylons.

[4] For further information on the chemistry behind synthetic polymer formation, see Annex III.

[5] Thermoplastics harden when cooled and soften when heated, whereas thermosets cannot be re-melted or re-moulded. For more information see Annex III.

All three are strong and yet elastic with low perceptibility in the water column making them perfect for the usage in fishing activities. PE and PP have a low density and are thus being used for trawls, which have to float on water, whereas nylon is used for nets, as it sinks into the water. (Andrady, 2000)

Another major field of plastics usage is in the Building and Construction sector, in applications that are often forgotten by the consumer. Plastics are used in piping, insulation, window frames and interior design. Their low maintenance and high resitance have been the great propulsion factor in this sector. The leading(??) polymer in Bulding and Construction is PVC, which is also used in fire safety intruments and tools (PlasticsEurope, 2014c). According to PlasticsEurope (2014c), the European Building and Construction sector consumed 9.54 million tonnes of plastic in 2010, which makes up more than one fifth of the total plastic consumption. Plastics are also used in transportation, constituting for example 30% of aeroplanes nowadays (PlasticsEurope, 2014c), and agriculture, allowing vegetables to grow at any season of the year in greenhouses. The agricultural sector employs are wide variety of plastics including polyolefin, polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate copolymer (EVA), polyvinylchloride (PVC) and, less frequently, polycarbonate (PC) and poly-methyl-methacrylate (PMMA) (PlasticsEurope, 2014c). This data is important when looking at long-term plastic usage as most of the plastic in the construction and agriculture sector remains in use over a longer period (>1 year).

2.2 Plastic production

The plastics industry is a fast growing industry with a yearly expansion rate of 8.7% between 1950 and 2012 (PlasticsEurope, 2013). In 2012, total global plastic production amounted to 288 Million tonnes (Mt) of which 47 Mt were classified as “other plastics”[6] (PlasticsEurope, 2013). The evolution of global plastic production from 1950 to 2014, according to the average annual increase in production by 8.7%, is shown in Figure 1 below.

[6] The report “Plastics – The Facts 2013” does not indicate, which plastics fall under the category other plastics. Upon request, it was notified that it refers to duroplastes, elastomers, adhesives, coatings, sealing compounds and PP-fibres. Henceforth, it is therefore assumed that 241 Mt was the global production in 2012. The same rationale has been used with respect to the other values displayed in the graphic on this page.

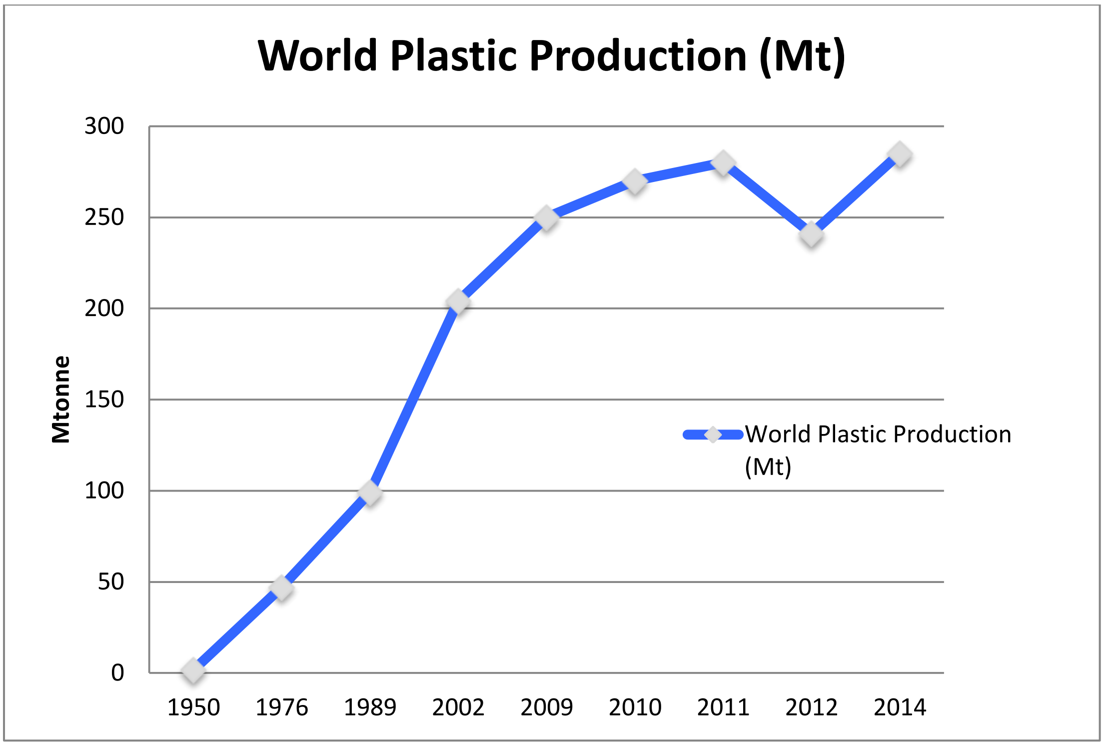


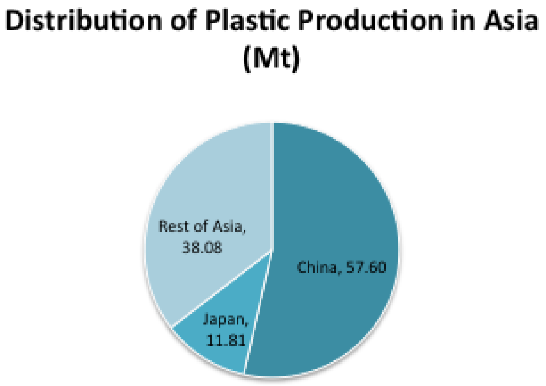
Figure 1: Global plastic production (1950-2014). Including thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants, and PP-fibers. Not included are PET-, PA-, and polyacryl-fibers. (PlasticsEurope, 2013:10)

Assuming that economy has picked up again, the estimated amount for 2014 would lie at 285Mt global plastic production according to a continuous 8.7% increase of production per year[7].

However, not every country contributes to the global plastic production to the same extent. Thus, for example, the Asian continent accounts for 44.6% of global production whereas the North American continent only accounts for 19.9% of it (PlasticsEurope, 2013). The major contributor to the Asian share is being done by China, the world's largest producer with 57.6 Mt in 2012 (PlasticsEurope, 2013). Almost half of this production stems from secondary material imported from Europe and North America. Latin America is the smallest plastic producer with 11.81 Mt, producing as a whole region only as much as Japan as a single country (PlasticsEurope, 2013). Interestingly, of the 4.9% of global production taking place in Latin America, 2% is covered by Brazil (ABIPLAST, 2012). The following figure 2 will

[7] For detailed calculations on plastic production per year according to 8.7% annual increase, see Annex II.

give an overview of the distribution of plastic production around the globe (with basis 241 Mt).



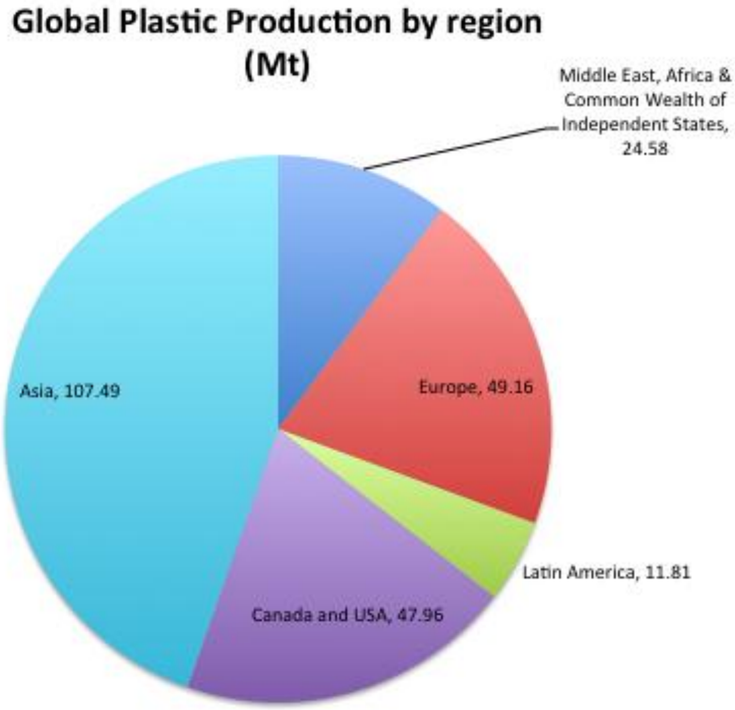


Figure 2: Plastic production per region in million tonnes (Mt) based on data global production of 241 Mt (PlasticsEurope, 2013)

2.3 Plastic consumption

Similar to production, consumption of plastics also varies highly from country to country. In general, plastic consumption is closely related to the economic development of the country (Lebreton et al., 2012). For example, the plastic consumption per capita in the U.S. was about 140kg in 2009 (Shen et al., 2009) compared to less than 35kg in Brazil in the year 2012 (ABIPLAST, 2012). Further, economic growth is usually accompanied by an increase in plastic consumption over all the sectors. Maybe the best example for this is Kenya, which has seen an immense consumption growth of 10-20% per year in accordance with its economic development (Africa Business Pages, n.d.). As Africa and Middle East jointly make up for only 7.2% of global plastic production, the majority of the plastic demanded have to be imported from overseas (PlasticsEurope, 2013; Africa Business Pages, n.d.). In 2012, Europe was a net exporter of 8.32 Mt of plastics within the plastics producing sector, and 1.06 Mt within the plastic products sector being exported (PlasticsEurope, 2013).

Plastic consumption also varies highly between the different plastic types as each sector employs different plastic types to a different extent. Polypropylene (PP), for example, is used in all sectors and is the major type of plastics in the transport and electronics sector (PlasticsEurope, 2013). In 2012, it was the most highly consumed type of plastic polymer on the European market with a demand of 8,700 kilo tonnes (kt) followed by LDPE and LLD-PE with 8,000kt and HDPE with 5,500kt (PlasticsEurope, 2013). Unfortunately, as will be explained in Chapter 2.4 and 2.5, most of these plastics end up in Municipal Solid Waste within less than a year as it is used for packaging or other single-use applications with almost 40% of European plastic consumption having a short service life (PlasticsEurope, 2013: 22).

2.4 Plastic stocks

According to the Material Flow Analysis (MFA) as presented by Brunner and Rechberger (2004), a stock is defined as the total amount of material stored within a process. It can be seen as a material reservoir, or the mass of material that remains in the process and is not transferred to the next process or outside the system (Brunner and Rechberger, 2004: 4). Two different types of stock are of interest in analysing the pathways from the anthropogenic system to the ocean. First, the stock of plastics “in use” is important, because it is this stock, which will be “released” to the natural environment in the case of natural disasters. This stock will also put into perspective the amounts of material found in the reservoir “ocean”. Secondly, the second stock in the waste management system in general and more specifically in landfills is of interest. Plastic does not simply disappear, but remains in landfills over a long period of time. It is therefore of interest to see how much of this plastic stock is potentially released to the ocean in the case of a tsunami.

The data on the stocks can be calculated from produced/consumed plastics and the output to the waste stream within one year. Data of plastic production was available for the years 1950, 1976, 1989, 2002 and 2009-2012 and showed an average increase of 8.7% per year. By this production rate, the global plastic production in the past 64 years amounted to a total of 4,213 Mt[8]. It will be assumed that the amounts of short- and long-living material increased at the same rate. Short-living

[8] See Annex II for detailed calculations.

plastics refer to plastics, which end up in the waste stream within a year whereas long-living plastics remain in use for over a year, averaging at a residence time of 15 years. This means that the 1,246.38 Mt of plastic produced in the years between 1950 and 1999 have by now ended up either in a final waste management facility (e.g. landfill or dumpsite) or in an unwanted sink, such as the ocean. Of the remaining 2,966.58 Mt produced in the past 15 years, the 285Mt produced in 2014 are assumed as not having entered the waste stream as of yet. Thus, 2,681.82Mt of plastics are left to have partly remained in use and partly ended up in the waste stream.

To assess the actual plastic stock "in use" and "in waste" as well as the annual flows towards them, three scenarios will be analysed for to cover the most probable situations of the period 2000-2014. Starting point for al three scenarios is a total global plastic production of 2,681.82Mt over the past 15 years.

2.4.1 Scenario 1: 20% short-living, 80% long-living plastics

Scenario 1 assumes that 20% of globally produced plastics will be disposed of within 1 year whereas the remaining 80% have an average residence time of 15 years.

Table 1: Scenario 1 - Stock and flow calculations with 20% short- (residence time <1 year) and 60% long-living (residence time between 1 and 15 years) plastics in global plastic production between 2000 and 2014

Time period	Total production (Mt)	Short-lived plastics (Mt)	Long-lived plastics (Mt)	Average flow to stock "in waste" per year (Mt/year)	Average flow to stock "in use" per year (Mt/year)
1999-2014	2,681.82	536.36	2,145.46	35.76	143.02

According to these calculations, 35.76Mt of plastics would be considered postconsumer plastics per year, whereas the anthropogenic stock would have increased by an average of 143.02Mt each year in the past 15 years. This is an increase per capita of almost 20kg per year, calculated with a world population of 7,166,371,000 people (United States Census Bureau, 2014).

In 2014, the anthropogenic plastic stock "in use" is of 2,145.46Mt with a stock increase of 228Mt/year, whereas the discarded plastic waste of the past 64 years amounts to a total of 1,782.74Mt with an annual increase of the stock of 57Mt/year.

2.4.2 Scenario 2: 40% short-living, 60% long-living plastics

Scenario 2 assumes that 40% of globally produced plastics will be disposed of within 1 year whereas the remaining 60% have an average residence time of 15 years.

Table 2: Scenario 2 – Stock and flow calculations with 40% short- (residence time <1 year) and 60% long-living (residence time between 1-15 years) plastics in global plastic production between 2000 and 2014.

Time period	Total production (Mt)	Short-lived plastics (Mt)	Long-lived plastics (Mt)	Average flow to stock "in waste" per year (Mt/year)	Average flow to stock "in use" per year (Mt/year)
1999-2014	2,681.82	1,072.73	1,609.09	71.52	107.27

According to these calculations, 71.52Mt of plastics would be considered postconsumer plastics per year, whereas the anthropogenic stock would have increased by an average of 107.27Mt each year in the past 15 years. This is an increase per capita of almost 15kg per year, calculated with a world population of 7,166,371,000 people (United States Census Bureau, 2014).

In 2014, the anthropogenic plastic stock "in use" is of 1,609.09Mt with a stock increase of 171Mt/year, whereas the discarded plastic waste of the past 64 years amounts to a total of 2,319.11Mt with an annual increase of the stock of 114Mt/year.

2.4.3 Scenario 3: 60% short-living, 40% long-living plastics

Scenario 3 assumes that 60% of globally produced plastics will be disposed of within 1 year whereas the remaining 40% have an average residence time of 15 years.

Table 3: Scenario 3 – Stock and flow calculations with640% short- (residence time <1 year) and460% long-living (residence time between 1-15 years) plastics in global plastic production between 2000 and 2014.

Time period	Total production (Mt)	Short-lived plastics (Mt)	Long-lived plastics (Mt)	Average flow to stock "in waste" per year (Mt/year)	Average flow to stock "in use" per year (Mt/year)
1999-2014	2,681.82	1,609.09	1,072.73	107.27	71.52

According to these calculations, 107.27Mt of plastics would be considered postconsumer plastics per year, whereas the anthropogenic stock would have increased by an average of 71.52Mt each year in the past 15 years. This is an increase per capita of almost 10kg per year, calculated with a world population of 7,166,371,000 people (United States Census Bureau, 2014).

In 2014, the anthropogenic plastic stock “in use” is of 1,072.73Mt with a stock increase of 114Mt/year, whereas the discarded plastic waste of the past 64 years amounts to a total of 2,855.47Mt with an annual increase of the stock of 171Mt/year.

2.4.4 Evaluation of the Three Scenarios

The outcomes of all three scenarios have quite different implications for the plastic flows and stocks. Although scenario 3 is the closest, none of the scenarios reports the actual flow of plastics to waste as reported by the World Bank, namely 176Mt in 2012 (Hoornweg and Bhada-Tata, 2012)**.** Further, European plastic production assumes a 40% of plastics are single-use applications ending up in the waste stream within a year, which would come to the assumption of scenario 2 (PlasticsEurope, 2013: 22). For the year 2014, this would mean that from the 285 Mt of plastics produced in 2014, 114 Mt can be considered postconsumer waste. The remaining 171 Mt are considered as stock. This numbers is the exact opposites of what is postulated in the report “What a waste”, which indicates 176 Mt (76% of production) of plastic waste in municipal solid waste (MSW) already in 2012 (Hoornweg and Bhada-Tata, 2012). This difference could very well be due to the different economic development of the industrialised world as has been noted in consumption already. Therefore, the third scenario will be taken as basis for anthropogenic stock “in use” and flow to stock “in use”, as it comes closest to globally presented data. The stock and flow to waste will be further discussed in Chapter 2.5.

2.5 Postconsumer plastic treatment

According to the definition by the American Chemistry Council (2014: 1), *postconsumer plastics* refer to “a material or finished product that has served its intended use and has been diverted or recovered from waste destined for disposal, having completed its life as a consumer item”. The percentage of plastic waste in Municipal Solid Waste (MSW) varies highly from country to country[9] and ranges between 1-24.7% with an average at 9.27% in 2012 (D-Waste, 2013). However,

[9] For further detail on plastic rate in MSW per region and/or economic development see Annex I.

several estimations for global MSW generation can be found ranging from 907 million tonnes (Mt) of which 181 Mt are processed in Waste-to-Energy (WtE) plants and 726 Mt are landfilled (Themelis and Zhang, 2010), to 1.9 billion tonnes, of which 209Mt are treated by WtE, 361Mt are recycled and 1,330Mt are landfilled (D-Waste, 2013). The latter numbers stem from the most comprehensive data collection in the area of waste management and incorporate research from all over the world, including research by Themelis, the author of the former numbers. The third scenario presented in Chapter 2.4 estimated a global plastic waste generation of 171Mt. Being fairly close to the data provided on the webpage of the Waste Atlas and in the Waste Atlas Report 2013 (D-Waste, 2013) as well as data provided by The World Bank report “What a Waste: A Global Review of Solid Waste Management” (Hoornweg and Bhada-Tata, 2012)**,** the following calculations will be based on 1.9 billion tonnes of MSW and 171Mt of plastic waste generated in 2014.

It should be noted that the numbers in the report “What a Waste” enclose plastic in MSW and not all plastics waste. It will be assumed that industry waste does not end up in the ocean, except under the circumstances of natural disasters as presented in Chapter 4.4.

Waste management systems range from dumpsites to waste to energy (WtE) incineration and usually correlate with the economic development of the country. To simplify matters, three different types of waste management will be differentiated in the following: general waste management, landfill and dumpsite. General waste management will include all forms of recovery of material such as recycling, WtE, incineration, etc. Landfill includes only controlled and sanitary landfilling and will be assumed a more or less closed and final sink of waste plastics. Dumpsites will include all forms of waste management that are uncontrolled or present in another way an open access to outflow of material. Further, it has to be noted that overall, 30% of global MSW, and consequently plastic, is not collected (D-Waste, 2013). In 2014, this would amount to 570Mt of 1.9billion tonnes MSW, including 51.3Mt plastics of 171Mt total plastic waste generated. A rather high percentage of the 51.3Mt potentially flows into the ocean, seeing as most human settlements are close to a water resource, be it a river or the ocean.

In 2012, 19% of all MSW generated globally was recycled and 11% were treated with WtE. Due to a lack of better data, it is assumed that these percentages also apply to plastics, although, in general, the percentages for plastics in waste management are higher due to the high efforts being made in this area. As plastics make up 9.7% of collected MSW, the flow to general waste management in 2012 was thus of approx. 37Mt plastics out of 123 Mt collected plastics. Of the remaining 86 Mt, only 34.5 Mt reached controlled landfills whereas almost 52 Mt ended up in uncontrolled dumpsites. Of the waste reaching general waste management, several million tonnes are exported to overseas for the recycling and are being downgraded for further usage. The export of waste and pre-consumer products will be further discussed in Chapter 4.2. The table 4 sums up the waste flow data as presented here above. As mentioned, the flow to General Waste Management System (WMS) reflects the 19% recycling and 11% WtE rate. The flow to uncontrolled waste management is noted as 42% as an average between the 38% indicated in the Waste Atlas Report and the 48% indicated in the UN-Habitat report (D-Waste, 2013). The values in plastic waste are calculated according to an average 9.27% of plastics in each of the WMS flows under the assumptions explained above.

Table 4: Global plastic waste flows in million tonnes (Mt) calculated according to 9.27% of plastics in global Municipal Solid Waste (MSW). The flows to general waste management system (WMS), dumpsite and landfill are calculated based on the quantity of collected waste (D-Waste, 2013; scenario 3 Chapter 2.4)

	Amount generated	**Collection coverage**	**Flow to General WMS**	**Flow to Dumpsites**	**Flow to Landfill**
MSW (%)	100	70	30	42	28
MSW (Mt)	1,900.00	1,330.00	399.00	558.60	372.40
Plastic waste (Mt)	171	119.7	35.91	50.27	33.52

The calculations show that of the entirety of postconsumer plastics, more than half are not properly treated: 30% are not collected at all and 29% go to uncontrolled dumpsites. In 2014, this amounted to a total of 101.6Mt of plastics polluting the environment. More than half of this amount is uncollected plastics, which are located all over the planet and not necessarily close to rivers or coastlines. Nevertheless, there is a high incidence of waste ending up in the ocean due to the human settlements being located close to waterways. Nevertheless, it will be assumed that only 1% of uncollected plastics ends up in the ocean, amounting to 0.5Mt. Further, the other 50Mt ends up in uncontrolled dumpsites. While the sanitary landfill stock is only of risk to the marine environment in the case of a tsunami (see chapter 4.4), the dumpsites, often located at the coastline, have a higher incidence of input to the ocean. It will be assumed that 10% of the dumpsite plastics, thus 5Mt per year, will end up in the marine environment.

To give a few examples of different waste management systems, the US and Europe (EU-27 plus Norway and Switzerland) will be explained outlined. In Europe, postconsumer plastic waste has increased by 2.5% over the past 15 years and amounted to 25 Mt in 2012 (PlasticsEurope, 2013: 4). However, thanks to the many recycling and energy recovery efforts, the landfilling rate of plastic has decreased to an average 40% of European postconsumer plastic wastes produced in 2012 and amounts to 10 Mt per year (PlasticsEurope, 2013: 4). Further, households generate more than half of the postconsumer plastics, while industry and trade are responsible for only 37% (EPRO, 2012). Collection for recycling amount to 6.4 Mt (and 8.6 Mt for energy recovery), of which only 3 Mt are handled within Europe whereas the remaining 3.4 Mt are exported mainly overseas to China (Velis and Cooper, 2013).

In 2012, the total flow of plastic waste in the United States amounted to 32 Mt with only 9% recovery rate for recycling (US EPA, 2014). According to these numbers, approx. 29 Mt of valuable material was dumped into landfills. However, as another study reported a 6.5% recycling rate and 7.7% energy recovery rate already in 2009 (Themelis et al., 2011), it can be assumed that in 2012 another 8%, or 2.56 Mt of plastics were recovered for energy to waste treatment. Still, the amount of plastics reaching the landfill is extensive and the stock within it ever growing. Further, of the plastics collected for recycling, only around 42% are processed in the United States or Canada, whereas the majority is send overseas with more than 4Mt going to China (Moore Recycling Associates Inc., 2014b; Moore Recycling Associates Inc., 2014a; Moore Recycling Associates Inc., 2011).

To conclude, although a lot of effort is being put into recovering plastics and returning them to the production industry for re-usage, almost 52 Mt of plastic are not collected at all and the majority of the collected plastics end up in waste dumps that are more or less uncontrolled.

3 Plastic and the Ocean

> "Plastic marine pollution is a major environmental concern, yet a quantitative description of the scope of this problem in the open ocean is lacking"
> (Law et al., 2010: 1185)

This part aims to give a clear overview of the research done in the field of plastic garbage patches. First, the degradation process of plastic will be explained to facilitate estimations of the outflow of plastic from the gyres. The second and third part will present the different data collection methodologies and the ocean circulation models upon which they are based, to better understand the evaluation of the data presented in the studies. The fourth part of this chapter will describe the current state of the art of open sea plastic pollution in terms of location, size, composition, current mass (in kg), density (in kg/km^2) and concentration (pieces/km^2) of plastics in the gyres of the North and South Atlantic, North and South Pacific and the Indian Ocean.

3.1 Plastic degradation process: From plastic bag to microplastics

> "Every little piece of plastic manufactured in the past 50 years that made it into the ocean is still out there somewhere", Andrady said, "because there is no effective mechanism to break it down"
> (Baztan et al., 2014-in press)

The lack of knowledge about the actual degradation process at open sea has caused much distress to environmentalists, policy-makers and researchers alike. Depending on its mechanisms, the degradation has not only an influence on the size and composition of the plastics but also on their impact on the environment.[10] Plastics owe their specific properties to several chemicals, such as Bisphenol A, phthalates, and flame retardants, which are released during the degradation process (Teuten et al., 2007). If this release happens in controlled circumstances, such as recycling facilities, incinerators or sanitary disposal sites, the environment is not exposed to the toxic substances (Boote, 2009). In the open sea, however, the release is not isolated and thus contaminates the natural cycle.

[10] For further details on the impacts on the marine ecosystem, see Annex V.

In fact, the release of said toxic additives occurs even in absence of the ocean wave mechanisms as a study by Loyo-Rosales et al. (2004) points out. The study analysed the release of Nonylphenol (NP), used as oxidant and plasticizer, and Octylphenol (OP) to the water in PVC, PET and HDPE bottles. The results showed that the water from both HDPE and PVC contained high concentrations of NP and all the water of all three contained OP (Loyo-Rosales et al., 2004). In the ocean, this release of additives is higher due to the break down of the plastics when exposed to sunlight and the direct leaching happening at open sea (Teuten et al., 2007).

To properly understand the degradation process at sea, it is important to look at the anthropogenic degradation process induced in recycling and recovery mechanisms. The breaking down mechanism of plastics consists mainly of two processes: oxidation and photodegradation. Biological polymers break down due to an autoxidation reaction with free radicals and form as primary products hydroperoxides. The radical chain reaction is controlled thanks to oxidisable compounds, as for example carbonyl compounds. Hydroperoxides are the most important photo-initiators during the early stages of photoxidation. The formation of hydroperoxides leads to production of aldehydes, ketones, and carboxylic acids along or at the end of the polymer chain. In the case of synthetic vinyl polymers, the polymerisation reaction may be reversed at high temperatures (150-350°C) to give the starting monomer again. This is one of the reasons why additives are needed to give a thermal stability to the polymers, such as in polystyrene (PS). Another degradation reaction happens for polyvinylchloride (PVC). When heated in absence of air, PVC eliminates the pendant groups along the chain to hive a highly unsaturated polymer. Polyolefins like polypropylene (PP) are the most susceptible for photoxidation and are thus not suited for outdoors. Further, polyethylene has been proven to show signs of biodegradation if exposed to light, however, it maintains its polymer structure. (Grassie and Scott, 1985; University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014)

The degradation at sea happens due to the same basic processes: photodegradation by solar actinic radiation (UV-B radiation of around 290-315 nm) and oxidation (Andrady, 2000). In addition, hydrolytic degradation is caused by the wave mechanisms at the ocean's surface (Law et al., 2010). Most plastics are prepared with a light-stabilizer to reduce the undesired degradation due to solar UV radiation of the supposedly life-long appliance of plastics (Andrady, 2000). Thus, the effect of sunlight is only limited. Further, the oxidation process due to the oxygen in the air also happens at a very slow rate, but does facilitate breakdown and wave mechanisms fragment the already brittle plastics at the ocean's surface (Andrady, 2000). For some polymers, such as polyester, polyamides and polyurethanes, chemical breakdown by water induces the decomposition of the polymers (Grassie and Scott, 1985). However, hydrolysis does, for example, not apply to plastics used in fishing gear (Andrady, 2000). Ultimately, there seems to be no effective break down mechanism for plastics.

Furthermore, the degradation of plastics at sea has been proven to happen even slower than in an exposed outdoors on land (Andrady, 2000). The only exception to this rule so far is Styrofoam, as Styrofoam breaks down into smaller particles faster at sea than at land (Andrady, 2000). The generally slower rate of breakdown at sea can be linked to two characteristics of the marine environment. First of all, plastic in the ocean is often partially covered by water and thus undergoes fouling. This fouling forms a protective cover over the polymer and reduces the light-induced breakdown (Andrady, 2000). The fouling process may also modify the density of the plastic and cause it to sink to the seafloor (Law et al., 2010). However, as there are no studies as of yet on offshore seafloor accumulation of plastics, this is only a hypothesis (Law et al., 2010). Secondly, material on land builds up heat due to the absorption of infrared light while the temperature of the seawater lowers this effect and keeps the plastic cooled so as to degrade slower. (Andrady, 2000).

The increasing knowledge on the degradation process of plastic polymers will open up new possibilities to avoid the negative impacts plastic has on the marine ecosystem. By carefully balancing the needed characteristics for the consumer and the ones required for faster breakdown at sea, the plastics could be influenced to break down into brittle material in a short period of time (Andrady, 2000). Such a proposal has been made for polyethylene products to better absorb UV-B radiation and could be a viable strategy for the future (Andrady, 2000). However, it has also been proven that such a chemical transformation would only lead to solving the aesthetical problem at beaches, whereas the powdery fraction remaining after embrittlement still resides in the marine environment (Andrady, 2000). An experiment on photodegradation also showed that the polymer remained in its polymer structure but saw a reduction of molecular weight to 11,000 - an amount not biodegradable anymore in any practical human life time scale (Andrady, 2000). Important to know in this context is that the molecular weight of plastics is usually between 10,000 and 1,000,000 and the higher the weight, the higher the rigidity of the plastics (PlasticsEurope, 2014b). The estimated decomposition rates of common marine plastic debris items are presented in the table 5 below.

Table 5: Estimated decomposition rate at sea of the most common plastic items as indicated in the 2010 ICC report (Ocean Conservancy, 2010) and the associated polymer as deduced from the Conference to the Parties to the Basel Convention (2002)

Plastic Debris Item	Possible plastic material	Life-time at sea
Plastic grocery bags	HDPE, LDPE, LLDPE, PP	1 to 20 years
Foamed plastic cups	PS, EPS	≤50 years
Plastic beverage holders	HDPE, PET, PS, PP	≤400 years
Disposable diapers	SAP	≤450 years
Plastic bottles	HDPE, PET; PS, PVC-P, EPS, PP	≤450 years
Monofilament fishing line	Nylon, PVDF, PE	≤600 years

Although the degradation may happen slowly, it is clear from the microplastics collected in the gyres that embrittlement and fragmentation does take place. In their study in the North Atlantic Ocean, Morét-Ferguson et al. (2010) identified a change in the size of the collected plastics. While the plastics were between 10.66±1.60mm in the study from 1991 to 1995, the average particle size in the study from 2004 to 2007 was only 5.05±0.35mm (Morét-Ferguson et al., 2010). As every transformation reaction adds history and degrades the properties of the material, it will be necessary to have a more detailed timeline to better understand the change in particle size and density at sea (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014). Studies on the abundance of plastics in the ocean need to take the change of density into consideration when classifying the materials. A possible way to still identify the right plastic type after exposure to weathering, photochemical breakdown and mechanical abrasion is to compare the carbon to nitrogen ration in the plastics (Morét-Ferguson et al., 2010). This method shows the amount of biomass accumulation and thus the possible chemical and physical property changes due to microbial fouling (Morét-Ferguson et al., 2010). Considering density measurements and nutrient measurements in the data collection could provide a better picture of the rate at which degradation is happening and help identify the future development of the plastic at sea (Morét-Ferguson et al., 2010). For the purpose of this study, the average annual outflow due to the degradation process will be estimated at 0.1% of the material contained in the gyres.

3.2 Data collection on marine plastic pollution

The data of marine debris stems mainly from four different sources: beach litter collection, animal stomach analyses, water probing and computer-based modelling. Each of these sources entails its own uncertainties and only in combination can they give a comprehensive picture of the amounts of plastic in the marine environment.

As several studies (Wilber, 1987) and models (Lebreton et al., 2012; Eriksen et al., 2013) point out, beach litter is a rather regional problem. Based on the differentiation between intra-gyral and extra-gyral inputs and different input scenarios, Lebreton’s model (Lebreton et al., 2012) indicated 40% beaching for impervious watershed areas and only 28% from maritime input over shipping routes. This indicates that beached litter does account for marine debris from extra-gyral inputs, meaning inputs from land-based activities or vessels operating close to the shore (Wilber, 1987). In fact, beach litter seems to be mainly resulting from terrestrial activities rather than from open-ocean dumping (Lebreton et al., 2012). Looking at the pathways of drifters, Maximenko (IPRC, 2008) extended this finding by showing that debris being pushed ashore once entering the convergence zones in the open ocean is little probable. Thus, the results from beach litter collection activities are of minor importance when trying to describe the content at high sea, but of major importance when looking at the pathways from land to sea (Lebreton et al., 2012).

The results from necropsies, on the other hand, have had a big influence on understanding the extent and impact that plastic at high seas has on the marine ecosystem (European Commission, 2013; Derraik, 2002; Williams et al., 2011; Science for Environment Policy, 2011; Ryan et al., 1988). Although this method is a cost-efficient way of assessing the abundance of plastic at sea, the uncertainties involved with these studies cannot be discarded (Ryan et al., 2009). Stomach analyses are opportunistic observations: While the uptake of plastics through ingestion happens at sea, the analysis can only take place if and when the animal reaches the shore (Williams et al., 2011). Additionally, several uncertainties exist regarding the migratory patterns of the species as well as possible accumulation, degradation and decaying processes taking place inside the stomach (Avery-Gomm et al., 2012; Williams et al., 2011). Thus, the results of such studies can contribute only in a limited way to determining the specific location, quantity and composition of the plastics including changing trends in the composition and qualitative analyses of the impacts associated with plastics in the marine environment.

The third corpus of data comes from direct water probing. The results of these studies have varied highly due to three reasons: different meteorological conditions at the time of collection; different methodology of collection; and random site selection (Williams et al., 2011; Moore et al., 2001). This discrepancy complicates the comparison of compare previous studies to nowadays' results and makes it thus basically impossible to know if the amounts of plastic input to the oceans have increased or decreased over the years (Eriksen et al., 2013; Law et al., 2010).

The states of the sea at the time of the collection influence the result of water probing, as they determine which plastics are floating at the surface or are hidden in the depths of the water (Eriksen et al., 2013). While the meteorologically induced differences cannot be completely avoided, they are usually included in the uncertainty treatment of the results thanks to computer-based calculation.

On the other hand, the solution for differences induced by the methodology of collection was addressed by trying to standardise the collection techniques (5 Gyres Institute, 2014). Most of the studies employed nowadays collect Neuston samples, a term which refers to a sample collected in the uppermost layer of the water from the surface with marginally 25 cm of net submerged under the water, with a net meshed at around 300-350 micrometres (usually 335 micrometre mesh with a 0.5x1 meter opening) (Wilber, 1987; Morét-Ferguson et al., 2010). Despite the effort being put into collecting the samples with uniform trawl, several results still stem from hand-picking the material out of the sea, counting from aboard the ship upon sight or other techniques (Thiel et al., 2013; Morét-Ferguson et al., 2010).

The third reason for an inconsistency in the results of water probing studies stems from site selection. However, thanks to computer-based ocean current modelling, the site selection has become less random and therefore gives certain insurances that results are relevant for the whole marine environment. In fact, the shipping routes for most water probing expeditions undertaken nowadays are based on two models, which have identified the major sites of plastic abundance in the ocean and will be explained in detail in the next section (Eriksen et al., 2013).

3.3 Ocean current modelling

The first model developed by Maximenko et al. (2012) (hitherto referred to as Maximenko's model), aimed to provide an improved global map of ocean currents at 1m depth. The surface currents were determined thanks to data from 12,000 drifters, satellite altimetry as well as wind and gravity measures (IPRC, 2008). The combined data, showed the mean geostrophic and Ekman circulation in the upper ocean layer based on which a probable trajectory of marine debris could be simulated on a global scale (IPRC, 2008). The model is not only of importance in tracking marine debris, but shows a global picture of the movements in the ocean. It includes the velocity of the ocean currents as well as documentation of areas of divergence and convergence (IPRC, 2008). Maximenko's model further predicts five areas of higher debris density corresponding to the centres of the five subtropical gyres: the North Pacific Subtropical Gyre (NPSG), the South Pacific Subtropical Gyre (SPSG), the North Atlantic Subtropical Gyre (NASG), the South Atlantic Subtropical Gyre (SASG) and the Indian Ocean Gyre (IOG).

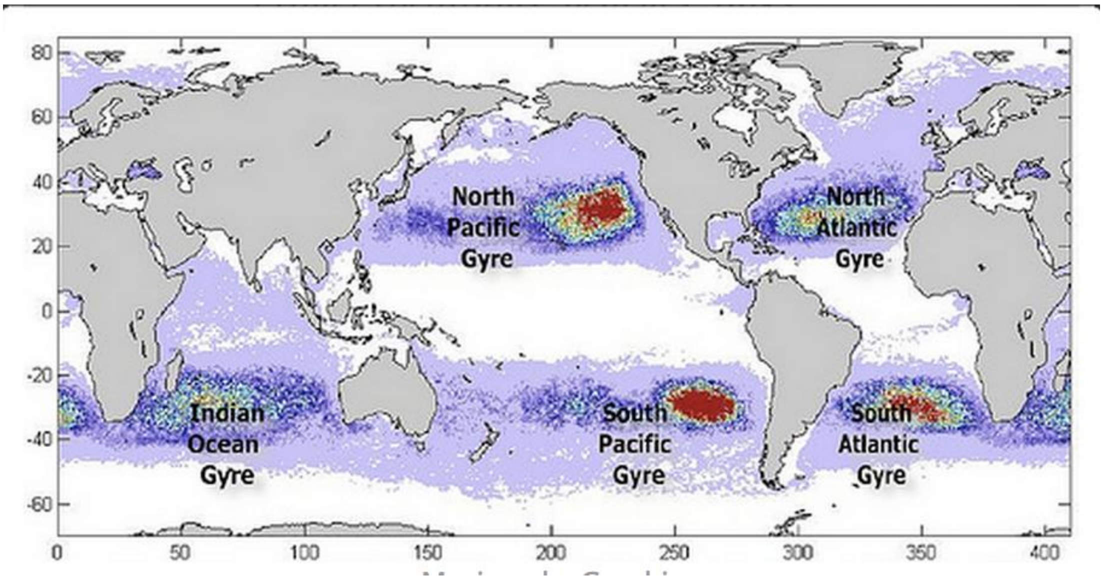


Figure 3: Model of the Accumulation zones in the different oceans as presented by Maximenko (IPRC, 2008)

The second model, developed by Lebreton et al. (2012) and hitherto referred to as Lebreton's model, shows the transport, distribution, and accumulation of floating marine debris taking into account changes in production and disposal worldwide. The goal of this model was to provide a framework, which could be extended according to the changes in production a disposal of plastics worldwide. Lebreton's model determined the relative contribution of the different regions to the total amount of material in the respective accumulation zone. In contrast to Maximenko's model, Lebreton et al. (2012) analysed different scenarios simulating 30 years of material being released to the ocean taking into account dispersion in the ocean as well as sources and pathways both from land and from the ocean. Superimposing their different scenarios, Lebreton et al. (2012) presented a model with five accumulation zones in the subtropical latitudes of the major ocean basins.

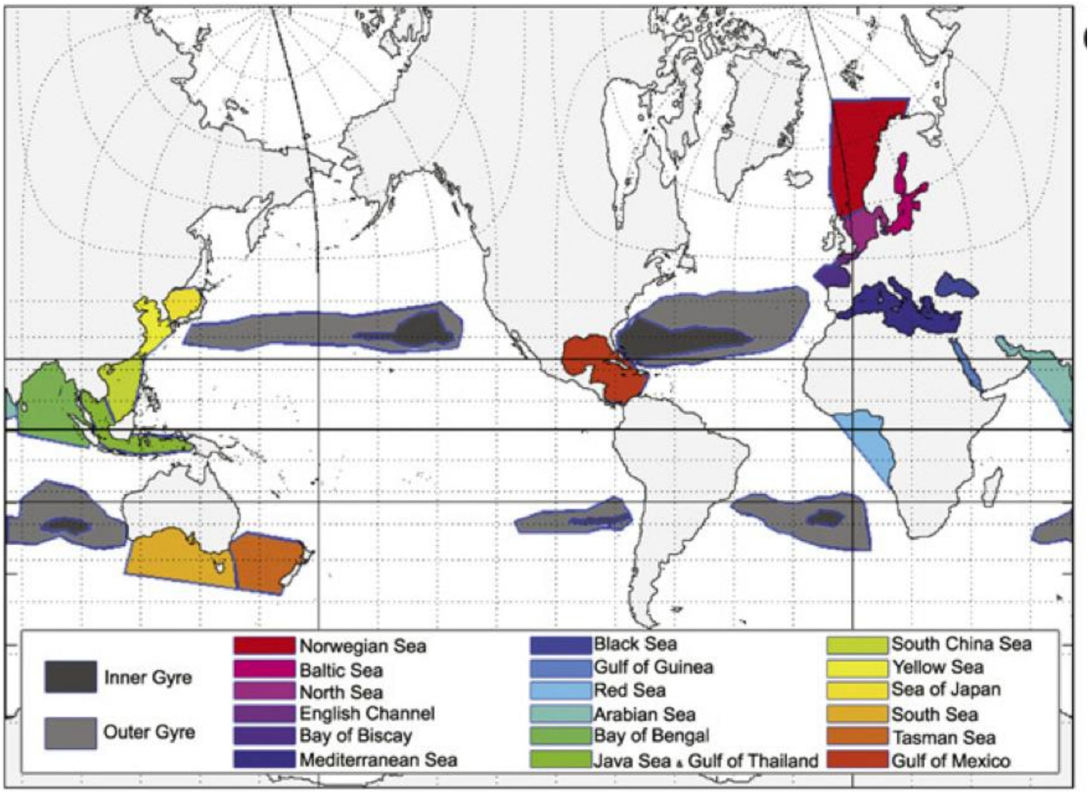


Figure 4: Model of the Accumulation zones in the different oceans as presented by Lebreton et al. (2012: 657)

Both models show the five accumulation zones corresponding to the five gyres. However, the predicted quantities of debris in the gyres differ. While Lebreton's model shows a dominance of accumulation in the gyres of the Northern hemisphere, Maximenko predicts a 150 times higher density of accumulation in the South Pacific compared to a 45 times higher density in the North Pacific (Eriksen et al., 2013). This difference in prediction is partly due to the fact that Maximenko's model focuses on the flow of debris while Lebreton's model considers the concentration. Taking into account the closeness of the southern gyres to islands, Maximenko's result suggests that the difference lies within the size of the particles released into the ocean in the Northern and Southern hemisphere (Eriksen et al., 2013). Additionally, ocean currents indicate that the South Pacific Gyre could be an accumulation zone for particles deriving from the South Atlantic and Indian Ocean (Eriksen et al., 2013). Nevertheless, the results predicted in Lebreton's model have been proven consistent with reality (Morét-Ferguson et al., 2010; Moore et al., 2001; Law et al., 2010).

Both models have shown to be of great importance in the field of research on marine debris. Not only do they both give useful indications as to how to plan water probing routes but the consistency with reality seen in Lebreton's model means that a lower number of probes need to be taken to calculate the quantities of debris in the ocean. The studies used for the present analysis based their site selection on either Lebreton's or Maximenko's model.

3.4 Plastic Concentration and Composition at sea

In the following, the current mass (in g), concentration (in pieces/km2) and density (in g/km2) of plastics in the five major gyres will be presented. If indicated in the studies, an overview of the most represented plastic types or items will also be given. As not all research had the same collection criteria, the size range of collected debris will further be indicated to give a better understanding of the mass of plastics collected. The size range will be described differentiating between major and minor size range, referring to the size range, which covered the majority or the minority of the material.

3.4.1 North Pacific Gyre

> "The garbage patches [in the North Pacific] are not an island of trash. They are more akin to a soup of widely distributed plastic pollution in sizes ranging from microplastic dust to 1 ton tangled masses of nets."
>
> (Algalita Marine Research Foundation, 5 Gyres Institute & Pangaea Exploration, 2012: 7)

The Great Garbage Patch in the North Pacific Ocean was the first one to be discovered and is nowadays estimated to cover an area of around 3.43 million km^2 (Science for Environment Policy, 2011). Latest literature distinguishes between three zones of accumulation related to the three oceanographic regimes in the North Pacific Ocean: The Gulf of Alaska Gyre, the California Current System and the Transition Zone between them (Avery-Gomm et al., 2012). Data suggest that the accumulation in the Eastern Patch is the centre of accumulation compared to the Western patch (South of 30°N) and the Convergence Zone (Lebreton et al., 2012; Maximenko et al., 2012). The research done on the North Pacific Gyre is the most extensive, but mainly covers the area between Hawaii and California (North of 30°N), also referred to as Eastern Garbage Patch, which is characterised by slack winds and sluggish currents (Weiss, 2006; Williams et al., 2011). The area is further described to be of low biological standing stock, i.e. little plankton (Moore et al., 2001). This information is relevant for assessing the fouling and degradation process the microplastics undergo in this zone as well as determining the environmental impact on the ecosystem as a whole.

The extent of accumulation in this zone is far bigger than in the other gyres, which can be due to an increased input in the Northern hemisphere (Lebreton et al., 2012). Another possible reason is also the lack of other sinks in the North Pacific Ocean, as there are few islands except near coastal boundaries, which could take up some of the plastics on its way to the gyre (Moore et al., 2001). The main data collected in the North Pacific Gyre by water probing is summarised in the following table.

Table 6: Core data of plastics in the North Pacific subtropical gyre as collected by Moore et al. (2001)

Characteristic	**Data**
Area (km^2)	3,340,000
Maximum concentration (pieces/km^2)	970,000
Average concentration (pieces/km^2)	334,271
Major size range (mm)	0.355-0.999
Minor size range (mm)	1-2.79
Mean density (g/km^2)	5,114
Residence time (years)	12
Industrial plastics (%)	4
User plastics (%)	96
Types/Composition	Thin films, PP/monofilament line, Miscellaneous fragments, Styrofoam,
Potential Sources	Offshore fishing activity, Offshore shipping activity, Pollution off SW coast of Canada Pollution off NW coast of USA

3.4.2 South Pacific Gyre

The plastic accumulation in the South Pacific Gyre has only been discovered thanks to the models by Maximenko et al. (2012) and Lebreton et al. (2012). Computing Langrangian trajectories of debris has shown an accumulation in the eastern-central region of the South Pacific subtropical gyre (Martinez et al., 2009). Nevertheless, very little research has been made in this area between Robinson Crusoe Island and Pitcairn Island (33°05’S, 81°08'W to 24°49'S, 126°61'W) (Eriksen et al., 2013). The gyre is bound by the equator in the north, Australia to the west, the Antarctic Circumpolar Current to the south and South America to the east. In terms of biota, very little organism growth and a slow flux of organic material to the ocean floor is taking place in the gyre.

Research on marine debris in the South Pacific Gyre has indicated a prevalence of macroplastics rather than microplastics as can be seen in the North Pacific Gyre (Eriksen et al., 2013). This could be due to increased input of waste coming directly from the islands in the South Pacific. The following table sums up the core data collected in the South Pacific subtropical gyre by water probing.

Table 7: Core data of plastic in the South Pacific subtropical gyre as collected by Eriksen et al. (2013)

Characteristic	**Data**
Area (km^2)	Missing data
Maximum concentration (pieces/km^2)	396,342
Average concentration (pieces/km^2)	24,898
Major size range (mm)	1.00-4.749
Minor size range (mm)	<1.00
Mean density (g/km^2)	70.96
Residence time (years)	Missing data
Industrial plastics (%)	Missing data
User plastics (%)	Missing data
Types/Composition	Fragments of foamed PS, Plastic bags, Food sacks from salmon farms, Pellets (9.6% of total weight), Lines and thin films
Potential Sources	Aquaculture, Beach and shore activities along Chile, Plastics from South Atlantic and Indian Ocean, Transfer of debris near shores (Indonesia and Ecuador) from North Pacific to South Pacific

Unfortunately, it was not possible to find data for several of the characteristics mentioned for the North Pacific Gyre including the estimated size of the gyre, the residence time and the percentage of industrial and user plastics collected. According to the NOAA National Geophysical Data Center, the total area of the South Pacific Ocean is 84,750,000km^2, which makes this part of the Pacific Ocean 7million km^2 bigger than its northern counterpart (Eakins and Sharman, 2010). At eyesight, the accumulation zone of the southern gyre should therefore be approximately the same size as the North Pacific Gyre, which of course does not imply that the concentration of pieces is the same as well.

3.4.3 North Atlantic Gyre

The North Atlantic Gyre is located 26°N, 60°W to 34°N, 70°W in a large subtropical convergence zone with current velocity below 2cm/s (Law et al., 2010). In their study, Law et al. (2010) present the plastic content on the surface of the North Atlantic Ocean between 1986 and 2008. Although a rapid increase of plastic production took place during this time period, no trend in increased plastic fragments between the western North Atlantic Ocean and the Caribbean Sea could be observed (Law et al., 2010).

Further, research on the density of the material in the North Atlantic Gyre has been done extensively. In fact, 99% of samples were less dense than seawater, but showed a quick increase in density due to rapid biofilm formation and subsequent aggregation of fouling organisms (as explained under degradation process) (Law et al., 2010; Morét-Ferguson et al., 2010). The collected plastic fragments presented the industrial density known for HDPE and PS, but elemental analysis confirmed it to be PP and PE (Morét-Ferguson et al., 2010). This insight is of extreme importance in finding the origin of the marine debris. First of all, it helps identify the percentage of beach litter stemming from the open sea, as litter dumped on site by beach-goers is subject to different degradation mechanisms. Secondly, identifying the material from which the plastic fragments stem will provide additional information for efficient policy-making in the area of marine pollution prevention.

Studies on the NAG have reported an average concentration in the middle part of the gyre of 20,328 pieces/km^2 with a mean density of 0.05 g/km^2 (Law et al., 2010). This mass is orders of magnitude smaller than the indicated mean density for the North Pacific Gyre. One reason for this could be that the inflow of plastics is from industrial plastics of smaller size and mass already to begin with. However, industrial pellets constituted only 1-16% of the collected material. Another possibility is that the fouling process takes place at a quicker rate in the North Atlantic. The following table summarises the main data collected in the North Atlantic Gyre by water probing.

Interestingly, the study by Law et al. (2010) showed no correlation between plastic content increase in Municipal Solid Waste (MSW) and in the ocean. However, the types of plastic found in the gyre make up 50% of total plastic waste in MSW (Law et al., 2010).

Table 8: Core data of plastics in the North Atlantic Gyre as collected by Law et al. (2010)

Characteristic	**Data**
Area (km^2)	Missing data
Maximum concentration (pieces/km^2)	167,000
Average concentration (pieces/km^2)	20,328
Major size range (mm)	<10, mainly between 2-6
Minor size range (mm)	0.41-420
Mean density (g/km^2)	0.05
Residence time (years)	10-100
Industrial plastics (%)	Missing data
User plastics (%)	Missing data
Types/Composition	PP, HDPE, LDPE, Fragments/chips, Sheets, Industrial plastic pellets, Fishing/marine line, PS foam
Potential Sources	Subtropical western North Atlantic as origin of the debris

3.4.4 South Atlantic Gyre

The garbage patch in the South Atlantic Gyre is located between 25°S, 0°W and 35°S, 20°W with an area of lower litter density in the Benguela region off the west coast of South Africa (Ryan, 2014). This patch has only been discovered and documented very recently and features a 97% plastic content in the accumulation of debris (Ryan, 2014). The main type of plastic found offshore originated from fishing gear whereas closer to shore packaging debris were most abundant (Ryan, 2014). Previous research in the South Atlantic has been conducted in the 1980s and found PE and PP pellets in remote areas away from industrial activities ranging between 1333-3600 pellets/km^2 (Morris, 1980).

A recent study by Ryan (2014) shows that the litter has been drifting some time before reaching the gyre, as the seaweed growth is low in high litter density areas. However, this study did not only collect litter in the centre of the gyre but also in coastal areas and was conducted as an on-ship observation. This entailed that the particle size is in average above 5 cm. The data is therefore only partially comparable to the data presented for the Pacific Ocean and North Atlantic. Nevertheless, the study has induced awareness of a garbage patch in the South Atlantic and should therefore not be disregarded. Although the results show the highest concentration of pieces close to Cape Town (>100pieces/km^2) and 30% of the litter found in the coastal region, the contribution from the South American continent is assumed to be much higher (Lebreton et al., 2012). Furthermore, the South Atlantic sees little to no ship traffic and only little high seas fishing efforts, which means that the main input stems from coastal and land-based activities.

Table 9: Core data of plastics in the South Atlantic Gyre as collected by Ryan (2014), only open ocean and not coastal region considered

Characteristic	**Data**
Area (km^2)	Missing data
Maximum concentration (pieces/km^2)	6.2
Average concentration (pieces/km^2)	<10
Major size range (mm)	>50
Minor size range (mm)	<10
Mean density (g/km^2)	Missing data
Residence time (years)	Missing data
Industrial plastics (%)	25
User plastics (%)	75
Types/Composition	Packaging (43%), fishing related items (27%), bags (15%), bottles (13%), polystyrene, food wraps, tubs/cups, lids and lid-rings, buckets, shoes/gloves/hats
Potential Sources	Land-based or coastal activities 60-80% from South America (Lebreton et al.2012)

3.4.5 Indian Ocean Gyre

Although the Indian Ocean Gyre (IOG) has been identified in several ocean circulation models, including Maximenko's (2012) and Lebreton's model (2012), no research in this area has been done to this day. A survey on seabirds sampled in the South Atlantic and Western Indian Ocean has indicated a high percentage of plastic ingestion by said seabirds, but makes no statement in regard of the presence of an Indian Ocean garbage patch (Ryan, 2008). However, the population-based scenario analysed by Lebreton et al. (2012) showed a high contribution to the OG from South East Asia and India as well as Africa and the Middle East. Moreover, the model showed that the particles of the IOG only constitute a maximum 6% of all marine debris while more than 25% are accounted for by the North Atlantic Gyre and 20% by the North Pacific Gyre. Thus, the accumulation of debris in the Indian Ocean Gyre amounts to almost the same quantity as the debris found in the Mediterranean Sea. In 2008, an off-boat observation of marine litter in the Mediterranean Sea reported an average 2.1 items per km^2, of which 83% were plastics, thus an average 1.74 plastic items/km^2 (UNEP, 2009b: 97). The average density indicated in the report was 239kg/km^2, which would results in an average 113 kg per item – a rather unimaginable mass and utterly unbelievable considering that plastic made up 83% of all items. As no details regarding the average weight of the plastic items were provided, no estimate for the IOG can be drawn from this report in terms of density. Nevertheless, according to Lebreton et al. (2012), the IOG holds double the amount accumulated in the Southern hemisphere gyres, which would be 141g/km2. Looking at the models by Lebreton et al. (2012) and Maximenko et al. (2012), one can assume the surface area of the Indian Ocean Gyre to be around one third of the size of the North Pacific Ocean Gyre, which amounts to 1.7 million km^2 (Science for Environment Policy, 2011).

Table 10: Estimated core data of plastics in the Indian Ocean Gyre deduced from UNEP (2009), Lebreton et al. (2012), Maximenko et al. (2012) and Science for Environment Policy (2011).

Characteristic	**Data**
Area (km^2)	1,700,000
Maximum concentration (pieces/km^2)	Missing data
Average concentration (pieces/km^2)	1.74
Major size range (mm)	Missing data
Minor size range (mm)	Missing data
Mean density (g/km^2)	141.00
Residence time (years)	Missing data
Industrial plastics (%)	Missing data
User plastics (%)	Missing data
Types/Composition	Missing data
Potential Sources	Missing data

3.4.6 Collected data of plastic in the Ocean

To facilitate comparison of the data presented so far, the following table 11 has been put together consisting of own calculations based on the research presented under Chapter 3.4. The surface area of the respective gyre had sometimes to be deduced from other sources such as the calculation of the volumes of the World's Ocean by NOAA's ETOPO1 program (Eakins and Sharman, 2010). Further, the 80Mt of estimated plastic content in the Atlantic and Pacific Ocean is a number published in the UNEP's report "Marine Litter: A global challenge" (2009) and subsequently cited in several publications, including the Grünbuch by the European Commission (2013). As can be seen from the calculations thus far, the water probing research has so far not proven this number to be correct. The yearly input of plastics from land is estimated as well and ranges from 7 million tonnes to 18.15 Mt, with no clear indication as to where the numbers come from (ISWA, 2013; Velis, 2014).

As table 11 shows, approximately 204 kt of plastic have thus far been recorded by water probing and stomach analysis studies. This amount is far from the 80Mt postulated by UNEP (2009). It is clear at this stage of analysis that 204kt cannot account for the inflow to the gyres from land-based sources. As no clear indication could be found as to where UNEP got this number from, the following analysis will nevertheless remain with the 204kt of plastics in the gyres, assuming that the gyres are not representative for the plastic pollution of the world’s oceans as the inflow expected at this stage from the anthropogenic system is much higher than 204kt per year.

Table 11: Collected data on the amounts of microplastics collected in the North Pacific Gyre (NPG), South Pacific Gyre (SPG), North Atlantic Gyre (NAG), South Atlantic Gyre (SAG) and Indian Ocean Gyre (IOG). Accumulated weight given for each study area as calculated by the data provided in the results of the study.

Study	Gyre(s)	Data presented by the study	Accumulated mass (kg)	Remarks and Calculations
A	NAG, SAG, NPG, SPG	[a] 100Mt of waste in the area, [a] 80% of the waste is plastic	80,000,000,000.000	No indication as to where this quantity of 100Mt in the ocean comes from. Weight calculated according to mass of plastic in the waste **Calculation A:** 100*0.8*10^9 = 80*10^9kg
B	Eastern NPG	[b] 36.8±9.8 pieces/bird, [b] 0.385g±0.087 g/piece, [b] 67 bird necropsies undertaken	0.949	Fulmar stomach analysis, not useful for total plastic accumulation calculations, due to lack of knowledge about exact number of species involved **Calculation B:** 36.8*0.385*67*10^(-3) = 949*10^(-3)kg
C	Eastern NPG	[c] 85,184 pieces/km^2 [c] 1.929kg/km^2 [d] 3.43 million km^2 surface area	6,616,470.000	**Calculation C**: 1,929*3.43*10(^6)=6,616,470 kg
Dmax	NPG	[e] 970,000 pieces/km^2 microplastics, [f] 5,114g/km^2 mean density, [f] 35 million km^2 surface area,	178,990,000.000	Maximum density recoreded in the NPG **Calculation Dmax**: 5,114*10^(-3)*35,000,000=179*10^6 kg
D	NPG	[e] 334,271 pieces/km^2 microplastics, [f] 5,114g/km^2 mean density, [f] 35 million km^2 surface area,	178,990,000.000	Size of the NPOcean north of 20°N and not only the Eastern Garbage patch **Calculation D:** 5,114*35000000*10^(-3) = 179*10^6kg
E	Eastern NPG	[e] 334,271 pieces/km^2 microplastics, [e] 5,114g/km^2 mean density, [d] 3.43 million km2 surface area,	17,541,020.000	Most comprehensive research in this area, however 13 years old, so would need an update **Calculation E:** 5,114*3430000*10^(-3) = 17*10^6kg
Fmax	SPG	[g] 396,342 pieces/km^2 microplastics, [g] 732g/km^2 weight, [a] 3,542,674 km^2 surface area	1,028,100,000,000.000	Maximum density recorded in the SPG. This area contained 1102 pieces and a total weight of 2.032g. The calculation assumes such a count over the whole area of the SPG. **Calculation Fmax**: 732*10^(-3)*396,342*3,543,674kg

Study	Gyre(s)	Data presented by the study	Accumulated mass (kg)	Remarks and Calculations
F	SPG	g) 26,898 pieces/km^2 microplastics, g) 70.96g/km^2 mean density, a) 3,542,674 km^2 surface area	251,459.107	Size of pieces in this gyre bigger than in its northern counterpart **Calculation F:** 70.96*3,543,674*10^(-3) = 251*10^3kg
Gmax	NAG	h) 580,000 pieces/km^2 microplastics, h) westernmost end of North Atlantic, h) 1.36*10(-5) kg/piece weight, h) 1100 metric tons total mass	1,100,000.000	Maximum density recorded in the NAG; surface area for 1100 metric tons calculation not indicated in the paper: according to the result, it should be 139,452 km^2 which is only 1/300th of the total North Atlantic surface area (Eakins and Sharman, 2010) **Calculation Gmax**: 580,000*1.36*10^(-5) =7.888 kg/km^2 and multiplied by an area of 139,452 km^2 results in 1100 tons
G	NAG	h) 20,328 pieces/km^2 microplastics, h) Westernmost end of the North Atlantic, h) 1.36*10(-5) kg/piece weight,	3,718.950	Calculation of the average mass over the whole area using the area indicated in the paper (139,452 km^2) which is only 1/300th of the total North Atlantic surface area (Eakins and Sharman, 2010) **Calculation G**: 1.36*10^(-5)*20,328*139,452=3,718.95 kg
H	NAG	i) 8.0 pieces/bird, i) 2.97±3.97 mg/bird, i) 83 bird necropsies undertaken	0.000247	Cory's shearwater stomach analysis, same comment as for study B on fulmar stomach analysis **Calculation H**: 2.97*83*10^(-6)= 0.000247 kg
I	NAG	j)7 48 particles, less than 10mm in j) size, less than 0.05g/piece (average 0.032g/piece)	0.037	Purpose of this paper was to show the change in composition from mainly pellets/nurdles (industrial waste) to mainly plastic bags (consumer waste), therefore not really representative average for the North Atlantic Gyre **Calculation I**: 748*0.05*10^(-3)=0.0374 kg
J	SAG	k) 191 items collected, k) no data on weight or size, k) >100pieces/km^2 in coastal area, k) between 1 to 6.2 pieces/km^2 at sea		Data collection in the waters around South Africa just show high amounts of debris and their location but included no data regarding mass

Study	Gyre(s)	Data presented by the study	Accumulated mass (kg)	Remarks and Calculations
K	SAG	[l] 1,500-3,600 pellets/km^2		Not enough data to fill this table
L	IOG	[a] 1.74 pieces/km^2, [m] 141 g/km^2, [m+n+d] 1.7 million km^2	239,700.000	No data for Indian Ocean Gyre to be found except for even less helpful stomach analysis than under F and B, thus own estimations out of the references **Calculation L**: 141*10^(-3)*1.7*10^6=239,700kg
M	NPG; SPG; NAG; SAG; IOG		203,642,369.044	While Calculation A indicated 80Mt of plastic to be in the ocean, Calculation M gives a total of 0.2Mt: 400 times less than indicated in by UNEP (2009). This can be due to various reasons - see discussion. **Calculation M**: 949*10^(-3)+6,616*10^3+179*10^6+17*10^6 +17,541*10^3+251,459+3,719+247*10^(-3)+37*10^(-3) +239,700 =203*10^6 kg
Mmax	NPG; SPG; NAG; SAG; IOG		1,028,280,090,000.000	Sum of maximum values extrapolated over the area of the NPG, SPG, NAG, SAG, IOG in the different studies if indicated; it is clear that the high density in the SPG is the main contributor to this result. **Calculation Mmax**: 178,990,000+1,028,100,000*1,100,000=1,028.28*10^9
References: [a] UNEP, 2009; [b] Avery-Gomm et al., 2012; [c] Carson et al., 2013; [d] Science for Environment Policy, 2011; [e] Moore et al., 2001; [f] Lebreton and Borrero, 2013; [g] Eriksen et al., 2013; [h] Law et al., 2010; [i] Rodriguez et al., 2012; [j] Morét-Ferguson et al., 2010; [k] Ryan, 2014; [l] Morris, 1980; [m] Lebreton et al., 2012; [n] Maximenko et al., 2012.				

4 Global origins, pathways and sinks of plastic

As Law et al. (2010: 1186) state in their study, "[…] the geographic origin of debris cannot be easily determined from current pattern or from the recovered plastic samples themselves." Potential land-based sources for plastic debris include poorly managed landfills, riverine transport, untreated sewage and storm water discharges, industrial and manufacturing facilities with inadequate controls, wind-blown debris, recreational use of coastal areas, and tourist activities (Barnes et al., 2009). The relevance of each of these sources varies highly according to the analysed region since not every region has high fishing or recreational activity. Potential ocean-based sources include input from industrial and recreational shipping as well as oil and gas platforms and aquaculture facilities (Kershaw et al., 2011; Barnes et al., 2009).

Four activities are repeatedly mentioned in the literature as origin of marine debris: inefficient waste management, plastic pollution by the shipping industry, beach littering, and natural disasters. The topic of waste management has already been mostly covered in the Chapter 2.5, but the identified leakages from the waste management system and will be briefly summed up in the following. The shipping industry encompasses in this case all transport of plastics overseas as well as fishing activities offshore and along the coast. Beach littering is often considered one of the major sources and has led to global clean-up activities on the coasts of our world. The contribution of beach litter to the gyres as well as the role of even remote beaches as removal pathway for plastic in the gyres will be presented. Finally, natural disasters, such as tsunamis, increase the plastic input into the ocean in a single event by overcoming the natural ocean circulation patterns along the coastline as well as the quantity of input from the anthropogenic stock. In the following, the extent to which each of the four mentioned phenomena contributes to the plastic in the five gyres will be outlined.

4.1 Leakages in the anthropogenic waste management system

Plastics are considered of high value even after first usage as they can be easily recycled and reused as a downgraded material or used as fuel in WtE incinerators thanks to their high calorific value. However, uncollected waste, waste in dumpsites and waste exports for recycling purposes constitute potential inflows to the marine environment.

According to the Waste Atlas, 30% of municipal solid waste (MSW) is not collected (D-Waste, 2013). Consequently, the average 9.27% plastics contained in this fraction of the MSW are also not collected. Of the 171Mt of plastic generated in 2014, a total of 51.3Mt were not collected. Not the entirety of this plastic will end up in the marine environment nor the open sea for that matter. Due to the nature of this waste plastics, no data could be found on the exact input from this source to the marine environment. However, an estimated 4 billion people live within 60 km of the coastline and 75% of all large cities are located at the coast: the extent of beach litter stemming from uncollected plastic wastes is therefore expected to be high (UNEP and IOC, 2009). In fact, in 2010, 39% of the US population lived near the coast in 2010 and more than half of Asia's population (excluding India) live in coastal areas (NOAA, 2013; Hinrichsen, n.d.). Seeing as these numbers only consider permanent residents, an increase during touristic high season is to be expected.

Despite the frequency of urban settlements close to waterways, it is estimated that only a small part of uncollected plastics finds its way to the coastline due to river runoff, wind blows, precipitation, and sewage canal overflows (Allsopp, 2006). This is based on the fact that, for example, uncollected waste in landlocked states may be collected in river runoffs of downstream states with a better waste management system spread out over large areas. For the purpose of this thesis, a mere 0.1% flow to the beach will be assumed from uncollected waste plastics. Consequently, 0.0513Mt of plastic ended up on the beach due to inefficient waste collection.

Further, of the total plastic waste generated in 2014, 33.52Mt end up in sanitary landfills and 50.27Mt in dumpsites. The plastic waste in sanitary landfills is expected to only be of risk to the marine environment in cases of natural disaster (see Chapter 4.4.). Dumpsite spillovers are mainly due to lack of control and covering. Although no reports exists on the exact amount of plastics leaking from dumpsites, the amount of plastic outflow to the marine environment from inefficient waste management is postulated to amount to 7Mt by the Waste Atlas (D-Waste, 2013), 6.4Mt by the Regional Seas (Allsopp, 2006) and 10Mt by the European Commission (European Commission, 2013). However, as no references or research for this amount could be found, it will be estimated that 5% of the plastic being dumped into uncontrolled dumpsties would leak to the beach on an annual basis, amounting to 4.19Mt in 2014. This means that the plastic stock in the landfills and dumpsites increases by 79.6Mt/year in 2014, rather than 83.79Mt.

Together, these two inflows amount to 5.4Mt of plastic input from inefficient waste management, 1.6 tons less than the estimated 7Mt inflow postulated by the Waste Atlas (D-Waste, 2013). As seen so far, the leakages from inefficient waste management are first transported to the beach via sewage and river-runoff. How much of this fraction ends up in the five gyres will be treated in Chapter 4.3. As most of the recycling that is not being treated domestically is shipped overseas, the fraction of this plastic that ends up in the ocean will be treated in Chapter 4.2.

4.2 Shipping industry and illegal dumping

In the 1970s, the shipping industry experienced rising criticism as polluter and has subsequently been extensively covered by international, regional and national legislation.[11] Thus, overseas transportation of plastics as well as all other shipping related activities should have a zero input of plastics to the ocean. However, the high percentage of plastic that is being exported as pre- and postconsumer items overseas creates a risk of pollution in any case. Further, the recreational activities and fishing have been reported to be a source of pollution in a wide range of literature on marine debris (Andrady, 2003; Derraik, 2002; European Commission, 2013; Law et al., 2010). Nevertheless, fishing close to shore as well as recreational activities close to shore will mainly increase the amount of beach litter rather than the plastic content of the gyres. Therefore, these sections of shipping industry will be considered under Chapter 4.3.

An aspect of the shipping industry that is often neglected as a high polluter at sea is cruise and ferry traffic. These vessels can carry several thousand passengers and crew, which means that they are comparable to cities in terms of volume of waste produced during a travel. During a typical one-week voyage, a large cruise ship (with 3,000 passengers and crew) is estimated to generate 210,000 gallons of sewage; 1 million gallons of grey-water (wastewater from sinks, showers, and laundries); more than 130 gallons of hazardous wastes; 8 tons of solid waste; and 25,000 gallons of oily bilge water (Copeland, 2008). Those wastes, if not properly treated and disposed of, can pose risks to human health, welfare, and the

[11] For further detail on the legal framework covering the shipping industry, see Annex VI.

environment in the same way as they do on land. Therefore, a number of international protocols have been established to govern the treatment of waste streams on cruise ships, but are not necessarily complied with (US GAO, 2000). A report by the U.S. General Accounting Office found that between 1993 and 1998, foreign flag cruise ships were involved in 87 confirmed illegal discharge cases in U.S. waters (US GAO, 2000). A few of the cases included multiple illegal discharge incidents occurring over the six-year period. However, the major discharges were oil or oil-based products rather than plastics (US GAO, 2000). Nevertheless, infringements are often covered up to keep a clean image to the public, which is important to attract tourists (Copeland, 2008).

Additionally to the waste entering the marine environment due to lack of regulation and waste treatment, the passengers on board of the liners potentially dump the same amount of litter as they would on land. However, no study on this kind of littering has been made thus far.

On a different account, overall 90% of the world's international trade is done overseas (Griffin, 1994). Unfortunately, no clear percentage could be found for the amount of plastic being exported overseas neither for pre-consumer plastics. The only data available was 11.1 Mt net export by the EU-27, Norway and Switzerland, as well as almost 7 Mt export by the United States and Canada in 2012. This represented 22% (Europe) and 15% (North America) of their respective production of that year. It can be assumed that Europe and North America are the biggest exporters overall, and thus the global export rate will be estimated at 15% of global production. In 2014, this would amount to 42.75Mt of overseas shipping at pre-consumer stage. As high amounts of dumping or collisions by plastic cargos are rare, an estimated 0.1% dumping rate should reflect the pre-consumer plastics entering the ocean via the shipping industry. In total, it will thus be assumed that 0.043Mt of plastic end up in the open sea due to exports.

As mentioned under Chapter 2.5, a high percentage of plastic waste intended for recycling is being exported overseas. China imports approx. 23 Mt per year, accounting for 73.1% of global plastic waste exports (Velis and Cooper, 2013). Deduced from this number, the global postconsumer plastic exports amount to 31.5 Mt in 2013. According to an annual increase of production of 8.7% from the reported 241Mt in 2012, the plastic production in 2013 would have been 261.97Mt. With 60% of this plastic ending up in the waste stream within a year, 157.18Mt of waste were generated in 2013 and 110 Mt were collected by waste management systems. Thus, 31.5Mt of exported waste represent almost 29% of total collected waste.

However, this cannot represent the fraction of recycling plastics only, as in 2013, only 20Mt were collected for recycling[12]. There are two possible explanations for this discrepancy. First, the plastics exported for recycling were not only plastics suited for recycling, but also plastic that would end up in landfill or dumpsites in other countries. Secondly, the rate of recycling waste was indicated only for domestic recycling purposes counting the exported waste as a different stream. Both those explanations are reasonable in this situation. However, for neither one was it possible to find proof. Thus, it will be assumed that 29% of collected waste is exported overseas for recycling purposes. In 2014, the exported postconsumer plastic would have amounted to 34.71Mt, leaving only 1.2Mt to be recycled and incinerated for energy recovery on a domestic or regional level.

Due to the illegal character of the discharges of plastic, there is little concrete data on the amounts being dumped per year. To cover for accidental dumping and ship collisions and accidents at sea, it will therefore be assumed that 0.1% of the exports, thus 0.0035Mt in 2014, end up in the ocean per year.

4.3 Beach littering and beaching

The world's coastlines are considered both as sink and as source of plastics to the open sea. The amount of beach litter reaching the open sea and being washed ashore is not yet clearly defined nor is the amount being introduced via extra-gyral forces. A study by Kim (2013) shows that plastics enter the open sea only when introduced 20miles off the coast. Thus, the plastics leaking from the anthropogenic waste management would remain permanently on the coastline as beach litter. However, a study by Kako et al. (2011) showed that the quantity of debris on the beach does not increase constantly over time but rather fluctuates over a period of 1.5 to 2 months. This means that during this period, the beach also acts as source for plastic input to the open sea. Ocean circulation patterns do suggest a certain amount of exchange between coast and open sea in both directions.

Furthermore, plastic debris has become a common feature on remote beaches in the Bermuda and the Bahamas, underlining that the beaches act as removal path

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[12] Own calculations based on the fact that 19% of collected plastics, or 13% of all generated plastics, are recovered for recycling.

for litter from the gyres (Law et al., 2010). However, this exchange takes a long time from one side of the ocean to the other with for example a 1year and 9 months interval for a plastic item released in Japan to reach the west coast of the U.S. (Matsumura et al., 2013).

Moreover, ocean current models have shown that only a small percentage of the plastic in the sea stems from the beach as the circulation keeps extra-gyral and intra-gyral input separated (Wilber, 1987).[13] Therefore it will be assumed that 10% of beach litter are transferred to the open sea and subsequently to the gyres as extra-gyral input. On the other side, it will be assumed that only 1% of the plastic entering the gyres on an annual basis ends up on the beach as beached litter.

As mentioned under Chapter 2.5, more than a fourth of global municipal solid waste is not covered by waste collection systems (Hoornweg and Bhada-Tata, 2012). One of the places these 30% of non-collected plastics go to is the beaches and river shore, mainly close to cities but also in remote areas. Thanks to global coastal clean-up initiatives, reasonably accurate numbers for beach litter are available. During the International Coastal Cleanup in 2009, more than 10 million items were collected on the beaches and inland waterways (25% of items) of over 108 nations. The top 10 items of all collected items during the International Coastal Cleanup in 2009 (ICC 2010), accounting for more than 83% of all collected items, are summed up in table 12.

Table 12: Top Ten Items found during the International Coastal Cleanup in 2009 and making up for 83% of total debris (ICC, 2010: 11)

Rank	Debris item	% of total debris
1	Cigarettes/Cigarette filters	21
2	Bags (Plastic)	11
3	Food wrappers/containers	9
4	Caps/Lids	9
5	Beverage bottles (Plastic)	9
6	Cups, Plaste, Forks, Knives, Spoons	5
7	Beverage bottles (Glass)	4
8	Beverage Cans	4
9	Straws, Stirrers	4
10	Bags (Paper)	3

[13] For further detail on ocean circulation, see Annex IV

All top 10 items stem from shoreline & recreational as well as smoking-related activities. Several of these items are either 100% plastic (plastic bags and beverage bottles) or partly made up of plastic. For the purpose of the following calculations, it was estimated that food wrappers/containers, caps/lids were 50% made of plastic (the rest being paper or aluminium), and cups, plates, forks, knives, spoons as well as straws and stirrers being 75% made of plastic. This would mean that of all items to be found on the beach, 35.5% are made of plastic (see table 13 below).

Table 13: Estimated percentage of plastic in total items collected on the beach in 2009 (ICC, 2010: 11)

Rank	Debris item	% of total debris
2,5	estimated to be made of 100% plastic	20
6,9	estimated to be made of 75% plastic	6.75
3,4	estimated to be made of 50% plastic	9
Sum	estimated total plastic content	35.75

The total weight of 3.2 kt[14] plastic indicated in the report was taken as reference for calculating the estimated beach litter on the entire coastline of the world. The ICC covered 23,101.45 km of beaches[15], which gives an average density of 139.91kg/km.[16] Based on the global coastline of 804,855.9km indicated in the CIA World Factbook (2014), the coastline bordering the oceans, excluding the uninhabited coast of Antarctica, was calculated to equal roughly 360,000km. Thus, applying the 139.91kg/km average density given by the ICC Report, there would be about 50.37kt of debris lying on the world's beaches.[17]

Unfortunately, the percentage of total weight that plastic accounts for was not indicated in the report. Further, the majority of countries that were not participating in the ICC in 2009, are on the African continent, where less plastic is being produced. It should therefore be clear that the 50.37kt are an absolute maximum of beach litter rather than a moderate average. In fact, marine pollution studies have estimated the daily input by coastal inhabitants to be 1kg of for every 100,000 people living on the

[14] The ICC repoprt (ICC, 2010: 49) states that 7,125,693 pounds of debris were collected, which equals 3,232,193kg, or 3.2 kilo tonnes.
[15] The ICC report (ICC, 2010 : 49) states that 14,322.90 miles of beaches were covered, which equals 23,101.45 km.
[16] Calculated according to 3,232,193kg divided by 23,101.45 km equalling to 139.91kg/km.
[17] Calculated according to 139.91kg/km * 360,000km =50,367,600kg

coast (Yoon et al., 2010; Lebreton and Borrero, 2013). With 4 billion coastal residents, this would amount to as 40t per day or 14.6kt per year of beach litter. Nevertheless, considering that divided by 4 billion people living on the coastline, an annual beach litter of 50.37kt would come down to 12.6g per person being left unattended at the beach, ergo barely one plastic bottle[18] per person, the 50.37kt could very well be true as well.

The calculated amount of 0.050Mt represents 0.1% of the total 51.3Mt uncontrolled postconsumer plastic in 2014. Thus, the before hand estimated 0.1% of uncollected plastic waste reaching the beaches is proven to be consistent with reality.

However, uncontrolled postconsumer plastics were only one of the sources of plastic debris on the beach. Additionally to beach littering, the amount of beached items per year are estimated to equal 1% of plastics at open sea for the purpose of this paper. In 2014, this amounted to 0.046Mt of plastic from the gyres to the beach. Further, the 4.19Mt of plastic from dumpsite leakages should reach the shores as well. As both these values are not accounted for on the amount of debris found on the world's coastline, it stands to reason that a flow of 4.25Mt of plastics result in its entirety as sea floor debris, which are not included in beach clean-ups.

As it is not possible to identify the source of the different debris once they reach the beach or the sea floor, the beach litter will be taken as a stopover on the way to the floor. This is not entirely representing the reality, as the quantity on the sea floor will include plastic debris at the bottom of rivers and in-land waterways as well. However, in terms of quantities, the flows reflect reality. The flow from the beach to the sea floor amounts thus to 4.25Mt/year as of 2014.

Two further removal pathways of beach litter need to be mentioned at this point. Thanks to coastal cleanup events, 6% of the beach debris from uncontrolled littering are collected once per year and discarded to landfills and dumpsites[19]. According to this rationale, the coastal cleanup of 2014 would have removed 0.006Mt of debris from the beaches and river shores. As mentioned above, an estimated 10% of the beach litter, or 0.005Mt, reaches the open ocean and the gyres. The remaining

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[18] By own measurments, a plastic bottle of 0.5L weighs 15g.

[19] Calculated with 3.2kt collected during the ICC 2009 dividedby the 50.37kt lying on the beaches, equaling 6% of total debris. Not accounting for the 4.25Mt from dumpsite leaking which will end up on the sea floor. Here as well, the origin is not representative for the reality, but the quantities are.

0.045Mt remain on the beach and undergo a slow degradation process there. Thus, the beaches of the world have an estimated stock increase of 0.045Mt per year. Given the lack of data, it was not calculated how much the stock at this point would be.

4.4 Tsunami: A scenario analysis of the 2011 Tohoku tsunami

The input of debris to the ocean by natural disasters is often overlooked, as the destruction on land usually the main concern. As a result, the quantities of plastic input to the gyres from natural disaster are little documented. However, several studies on tropical storms and tsunamis, have reported that around 30% of the material swept into the ocean in the context of natural disasters does not sink to the bottom right away and is thus not be included in the clean up missions (Doong et al., 2011; Prasetya et al., 2012; NOAA, 2013a). In the following, a brief overview of the 2011 Tohoku tsunami is presented, as this tsunami will be taken as prototype for the calculations of debris released to the ocean by natural disasters. Secondly, different scenarios will be considered to show the impact of the damage caused by the tsunami on the amount of plastic input to the North Pacific Ocean.

4.4.1 Overview of the natural disaster

On 11th March 2011, the earthquake and resulting tsunami, called Great Tohoku Tsunami, hit the Japanese coastline causing more than 15,500 deaths and a damage amounting to around $US210 billion in mainly 3 prefectures (NOAA, 2013a). At the time of the event, the total population of the three prefectures of Fukushima, Iwate and Miyagi was reported to be 5,696,795 (NOAA, 2013a). Due to its magnitude of 9.0 and the wave height of 37.88m, the Fukushima nuclear power station was partially destroyed (NOAA, 2013a; UNEP, 2012). In the aftermath of the event, more than 400,000 people were displaced, and 1,075,199 buildings were damaged of which 12% collapsed fully, 24% collapsed partially, and 64% were damaged (UNEP, 2012).

The extent of the damage and the potential release of radioactive material to the marine environment increased the interest in managing marine debris in the aftermath as well. International reporting and monitoring efforts have been set up to track and identify tsunami debris in the open sea and on the coasts both of Japan and North America. The current status of debris sighting (as of January 2014) can be seen on the website of NOAA's Environmental Response Management Application[20].

In March 2012, the government of Japan estimated that the tsunami swept 5 million tons (Mt) of debris into the ocean of which 70% sunk to the ocean ground close to the coast (UNEP, 2012).[21] This means that 1.5Mt of material are floating in the North Pacific Ocean and 3.5Mt of material added to coastal sea floor. In this mass, no indication to the amount of plastics nor the origin of the debris was given. Although plastics are nowadays found in many applications, their lightweight character usually entails them to represent only a small fraction of total weight. For the purpose of this thesis, it will therefore be assumed that plastics made up 1% of the 3.5Mt that sunk to the ocean floor and 90% of the 1.5Mt that were transported to the open sea, the remaining 10% being mainly represented by metal, glass and wood. This repartition has been reported for other marine debris (UNEP, 2012; Derraik, 2002). The tsunami swept thus a total of 1.235Mt of plastic to the marine environment, 0.035Mt of which are considered sea floor litter and 1.2Mt are considered to end up in the gyres within 4 years (Lebreton and Borrero, 2013).

To determine the origin of the debris, it is necessary to look at the stocks of waste facilities and consumers. In 2011, Japan accounted for 5% of global plastic production of 265Mt (PlasticsEurope, 2011). Japan thus produced 13.25 Mt of plastics. The reported plastic consumption for 2006 amounted to 11Mt for the whole country and 90kg/cap (Feldmann, 2006). Applying the growth rate of consumption in OECD states, this would have been about 12Mt and 100kg/cap in 2011. The World Bank reports Japan's municipal solid waste to be composed of 9% plastics (Hoornweg and Bhada-Tata, 2012). With 1.71kg/cap MSW being generated per day, the plastic waste generated per person in Japan amounts to 0.154kg/cap/day or 56kg/cap/year (Hoornweg and Bhada-Tata, 2012). Thus, the stock of plastics per person prior to the event totalled roughly 44kg/cap/year.

Seeing as roughly 5.7 million people were affected by the tsunami, the tsunami may have swept a maximum of 0.25Mt of plastic from private households. The remaining

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[20] webpage as of April 22, 2014:
http://marinedebris.noaa.gov/sites/default/files/JTMD_ERMA_January.pdf

[21] The export report of selected cities in the three prefectures reported more than 22Mt of debris in total (UNEP, 2012).

0.985Mt thus stem from waste facilities and uncollected waste. Identification of the origin of debris is a difficult task in disaster areas and thus no rate of contribution to the waste flow of each one of these sectors could be found. Further, the consumer stock calculated does not include industries, which means that the fow from waste management facilities includes the percentage of industrial plastics released during the tsunami. Due to the lack of data, the calculated consumer stock will include industrially induced plastics for the following evaluations.

Furthermore, it will be estimated that flow of plastic sinking to the bottom right away stems to an equal rate from consumer stock and from postconsumer plastics. In the case of Japan, the rate of postconsumer plastics stemming from recycling plants should be highest as they have a highly efficient waste management system with only 3% landfilling and 100% waste collection (Hoornweg and Bhada-Tata, 2012). However, as the 2011 tsunami will be used as prototype for the whole world, it will be assumed that the postconsumer plastics stem equally out of uncollected waste, recycling waste and landfills.

To summarise, a mass of 0.035Mt of plastics was washed towards the open sea but sunk to the bottom of the ocean close to shore. This amount is counted as beach litter and stems to equal portions of 0.0175Mt from the consumer stock and the waste facilities (0.006Mt from general waste management, landfills and uncollected waste respectively). Additionally, a mass of 1.2Mt of plastics was swept into the open sea and is floating towards the gyres. This mass stems to 0.23Mt from the consumer stock [22] and to 0.97Mt from waste facilities (0.33Mt general waste management, landfills and uncollected waste respectively). The above mentioned uncertainties and assumptions in terms of values will be included in the evaluation of the results.

4.4.2 Three scenarios of tsunami induced debris distribution

Due to the magnitude of the tsunami, a fear existed that the marine debris that got swept away may reach the west coast of North America and Hawaii in a wave of debris. Although this fear has been widely calmed, tracking the marine debris floating in the open ocean has become of interest to assess the accumulation of plastics in the North Pacific gyre. Three scenarios will be discussed here below

[22] Of the maximum 0.25Mt consumer stock, 0.2325Mt remain after deduction of the 0.0175Mt having sunk to the ocean floor close to shore.

representing three distribution patterns of the 1.2 Mt of plastic debris released to the open sea.

Scenario 1 is based on the assumption that 1.2 million tons of plastic were released into the ocean to spread evenly over the entity of the 77,010,000 km^2 surface area of the North Pacific Ocean (Eakins and Sharman, 2010)

Assuming that the material will distribute evenly over the 77million km^2 area of the North Pacific Ocean, this results in a density of approximately 16kg/km^2 given that 1,200,000,000 kg divided by 77,010,000 km^2 amounts to an average density of 15.58kg/km^2 (own calculations).

Scenario 2 is based on the assumption that 1.2 million tons of plastic were released into the ocean to accumulate in the 35million km^2 surface area of the North Pacific Ocean northern of 20°N (Lebreton and Borrero, 2013)

Lebreton and Borrero (2013) modelled the transport of material using a global circulation model and found a consistency with the debris locations reported thus far. Their model further showed that the bulk of tsunami debris would eventually accumulate in the North Pacific Ocean subtropical gyre, as the debris will take 2.5 years to progress from 50°N to 40°N (eastward speed of 5cm/s) (Lebreton and Borrero, 2013). According to this model, Lebreton and Borrero (2013) estimated the density to be approx. 42.86kg/km^2 seeing as the distribution zone of the 1.5Mt debris they accounted for would lie north of 20°N leaving an area of approx. 35 million km^2.

Calculating on the same area but considering only 1.2Mt of plastic rather than all debris, the density would be approximately 34kg/km^2 given that 1,200,000,000 kg divided by 35,000,000km^2 amounts to an average density of 34.29kg/km^2 (own calculations).

Scenario 3 is based on the assumption that 1.2 million tons of plastic were released into the ocean to accumulate in the 3.43million km^2 surface area of the North Pacific Gyre (Science for Environment Policy, 2011; Lebreton and Borrero, 2013)

Using the surface area of 3.43million km^2 given by EU Commission's DG Environment Report on the Ecological and Human Health Impacts of plastic waste (Science for Environment Policy, 2011), the average density in the North Pacific

Gyre due to the tsunami would be approx. 350kg/km^2 as 1,200,000,000 kg divided by 3,430,000 km^2 results in an average density of 349.85kg/km^2 (own calculations).

4.4.3 Evaluation of the 3 Scenarios for tsunami induced debris distribution

The results of the three scenarios as calculated in Chapter 4.4.2 are summarised in table 14.

Table 14: Density of plastic at sea surface due to tsunami: different release and accumulation scenarios with starting point of 1.5 million tons of material being released into the North Pacific Ocean (UNEP, 2012)

Scenario	**Plastic rate (%)**[c]	**Area considered**	**Size of area (km^2)**	**Plastic density (kg/km^2)**	**Calculation**
1	90	NPO	77,010,000[b]	15.58	1.2*10^9/77,010,000 =15.58 kg/km^2
2	90	NPO northern of 20°N	35,000,000[c]	34.29	1.2*10^9/35,000,000 =34.29 kg/km^2
3	90	NPG	3,430,000[d]	349.85	1.2*10^9/3,430,000 =349.85kg/km^2
References: [a] UNEP, 2012; [b] Eakins and Sharman, 2010; [c] Lebreton and Borrero, 2013; [d] Science for Environment Policy, 2011					

The extreme difference in density attributed to scenarios 1-3 show how important knowledge about the distribution patterns is. Nevertheless, the ocean circulation patterns suggest that scenarios 2 is the most probable in overall distribution, whereas scenarios 3 is the most relevant when analysing the amounts of plastic ending up in the gyres within 4 years after the event. The currently reported density in the North Pacific gyre is roughly 5kg/km^2, which means that whichever scenario becomes true, the density in the North Pacific gyre will increase at least threefold and maximum 70times. In either case, the amount of plastics released to the marine environment in case of a natural disaster, have a big impact on the density in the gyres.

4.4.4 Changes in global plastic flow due to a natural disaster

Based on the information provided in this Chapter, the tsunami created an input of plastics to the marine environment on different levels of the anthropogenic system. Two different streams of disaster debris were distinguished for the 5Mt of debris swept away by the tsunami: a flow of debris from anthropogenic stocks to the sea floor within weeks and a flow to the open ocean and the gyres within 4 years.

To recap, a mass of 0.035Mt of plastics was washed towards the open sea but sunk to the bottom of the ocean close to shore. This amount is counted as beach litter and stems to equal portions of 0.0175Mt from the consumer stock and the waste facilities (0.006Mt from general waste management, landfills and uncollected waste respectively). Additionally, a mass of 1.2Mt of plastics was swept into the open sea and is floating towards the gyres. This mass stems to 0.23Mt from the consumer stock[23] and to 0.97Mt from waste facilities (0.33Mt general waste management, landfills and uncollected waste respectively).

Although a closer analysis will follow in the material flow analysis, this short overview has already shown that a single event such as the 2011 Tohoku tsunami can have a big impact on the plastic debris in the ocean. However, this results is linked to a certain amount of uncertainties and assumptions.

The first assumption was made according to the plastic composition in the 5Mt of material released. This uncertainty highly modifies the input of plastic to the environment bot on the sea floor and in the gyres. A different rate of plastic will induce a big change in debris reaching the gyre as part of the material will decompose or sink to the bottom of the sea along the way. However, the assumption were based on the previously accounted for percentage of plastic in marine debris and thus a total of 1.2 million tons representing a 90% fraction is reasonable especially as the debris pushed into the open sea by the tsunami must have enough buoyancy to not sink to the floor with the sediments of the tsunami.

Furthermore, the final accumulation of the post-disaster debris in the gyres has not yet been proven by scientific research. Following the Tohoku tsunami, an extensive study on post-disaster debris tracking was launched to gather more knowledge on the distribution patterns (Matsumura et al., 2013). In several incidences, Matsumura et al. (2013) released three types of plastic items 20km off the coast of Iwate, Miyagi and Fukushima. The three types of items consisted of floating debris (10% underwater, barrel shaped), standard debris (50% underwater, PET bottle shaped), and subsurface debris (80%underwater, disk shaped). They concluded that the drift

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[23] Of the maximum 0.25Mt consumer stock, 0.2325Mt remain after deduction of the 0.0175Mt having sunk to the ocean floor close to shore.

routes varied greatly over the first month depending on the release point even if released at the same time, but that following 1-3 months they followed almost the same route at different speed. However, as the batteries on their tracking devices stopped working between 6 and 12 month, the rest of the route remained unknown. Some items have been retrieved on the coast of Japan while others have reached North America (Matsumura, 2013). Still, for the purpose of this thesis, it will be assumed that the 1.2Mt of plastic released to the open sea will end up in its totality in the North Pacific Gyre within 4 years, as was postulated by Lebreton and Borrero (2013).

5 Results and Discussion

5.1 The terms and values used in the MFA

The terms used in the MFA have been explained at the respective point of their introduction in the earlier chapters of this thesis. For reasons of clarity, they will be repeated here in alphabetical order, including the respective values of stocks and flows.

5.1.1 The processes and stocks (in Tg = Mt)

Beach litter (P8)

The process *Beach litter* encompasses all postconsumer plastics found on the coastlines of the world. The origin of this debris is threefold: a first fraction of *beach litter* (F11) stems from the uncollected plastic waste of households and industry as well as the litter left at the beach by beach-goers and recreational activities close to shore. The second fraction stems from *dumpsite leaking* (F13) and ends up on the beach due to sewage overflow, precipitation, wind and other dispersion mechanisms. Further, *Beach litter* includes plastic fragments that reach the beach from the open sea, *beached litter* (F15), and are thought to have passed through the gyres beforehand. Thanks to *coastal cleanup* (F12) initiatives, a small fraction of the beach litter is being collected and transferred to landfills. Another fraction of 10% is being transferred to the open sea as *extra-gyral input* (F14). The biggest chunk of the beach litter sinks to the sea floor and is represented as the flow *sinking* (F26). The stock of beach litter increases by 0.045Mt/year. The stock at this point of 2014 was not calculated due to lack of data on the collection coverage between 1950 and 2009.

Consumption (P3)

The process *Consumption* contains the entire anthropogenic plastic consumption and demand. The stock of this process is all plastics that are “in use”, in the households and industries. The input to the process stems mainly from *consumer plastic I* (F3) and from *consumer plastic II* (F4). The outflow of the process *Consumption* does not equal its input, as an estimated 40% of consumed plastics are long-living plastics with an average residence time of 15 years (see Chapter 2.4). Thus, the stock of this process amounts to 1,072.73Mt with an annual increase of 114Mt/year in 2014.

Export I (P2)

The process *Export I* reflects *overseas shipping* (F2) of plastic products at pre-consumer stage. As explained in Chapter 4.2, the amount of plastic being exported is difficult to estimate. Almost the entire input to *Export I* will be flowing towards the process *Consumption* (P3) as *consumer plastics II* (F4), except for a 0.1% *dumping* rate, which will end up in the gyres (F5). Thus, the process *Export I* has no stock.

Export II (P10)

The process *Export II* reflects the overseas shipment of plastic products at postconsumer stage. As explained in Chapter 4.2, a high percentage of waste is being shipped overseas for recycling purposes. The input to this process stems from *waste export* (F10) and includes the fraction of plastics collected for recycling purposes but not treated domestically or regionally. This process has no stock as it is assumed that 99.9% of the plastic find their way back into consumption as *recycled plastics II* (F21) or end up being dumped at sea and represented by the *flow dumping II* (F22).

General WMS (P7)

The process *General WMS* stands for the entity of all collected plastic waste that is not transferred to the landfill right away. This process includes waste management methods such as recycling and WtE incineration plants. The input to *General WMS* stems from the *recycling and recovery* flow (F9) and represents 21% of all generated waste. As presented in Chapter 2.5 and Chapter 4.1, this amounts to 35.91Mt in 2014. It is assumed that *General WMS* has no stock, since 96.67% of recycling products will be exported overseas for recycling, *waste export* (F10), 3.32% will be reintroduced into the consumption system after domestic recycling, *recycled plastic I* (F20) and 0.01% will be entering a landfill after incineration, *incinerated plastic* (F23).

Gyres (P9)

The process *Gyres* represents an unwanted sink of plastics. The quantity of plastic fragments accumulating in the five gyres in the Atlantic, Pacific and Indian oceans constitute the stock of the *Gyres* and represent the amount of plastic pollution at open sea. The stock of the *Gyres* is postulated as 0.204Mt according to the evaluation done in Chapter 3.4.6. The input to the *Gyres* originates from one land-based and two ocean-based activities. The land-based source is a fraction of 10% input from the beach litter, called *extra-gyral input* (F14). The two ocean-based sources of pollution are both illegal dumping. An estimated 0.1% of pre-consumer plastics, represented by the flow *dumping I* (F5), as well as 0.1% of postconsumer plastics, represented by the flow *dumping II* (F22), are assumed being dumped at sea during export. There are two outflows from the gyres happening at a very slow rate. The first outflow is *beached litter* (F15) ending up on the coastlines after travelling the ocean waters for a long time. The second outflow reflects the *degradation* (F16) of the plastic fragments in the gyres. As degradation happens only at a very slow rate, this outflow is estimated at 0.1% per year of the stock of all five gyres. The stock of the gyres is increasing by 0.46Mt/year.

Landfill (P6)

The process *Landfill* covers the part of collected postconsumer plastics that is being transferred both to sanitary landfills and uncontrolled dumpsites. The input stems from total waste generation flow to *landfilling waste* (F7). The stock of this process reflects the amount of plastic that has reached the landfill as final sink. It amounts to the total plastic waste generated in the past 64 years, namely 2,855.47Mt, and has an increase of 79.59Mt/year in 2014. The outflow of the landfill, (F13) to the gyres reflects the 5% *dumpsite leaking* (F13) explained in Chapter 4.1.

Production (P1)

The process *Production* refers to the global plastic production industry and was dealt with in Chapter 2.2. The production process has no stock, as it is assumed that all produced plastics will reach the consumer within a year. Thus, the entire inflow of *global production* (F1) will be flowing towards the processes *Export I* (P2) and *Consumption* (P3).

Seafloor litter (P12)

Seafloor litter stands for the fraction of plastic debris that sinks to the bottom of all waterways both in-land and on the coastline. Although this process has an input from *Beach litter* (P8) only, it also accounts for riverbed depositions and other continental waterways in the following MFAs. In 2014, the input to this process amounted to 4.25Mt/year. This process is regarded as a final sink in this MFA.

Uncontrolled littering (P5)

Uncontrolled littering presents the vast body of postconsumer plastics that are not covered by waste collection. The input to this process stems thus from the flow of *uncontrolled waste* (F8). However, it was estimated that only 0.1% of the uncontrolled waste actually enters the marine environment via *beach littering* (F11) and 1% enters the marine environment via *postconsumer plastic II* (F19). Therefore the remaining 98.9%, amounting to 50.74Mt/year are the stock increase of *Uncontrolled littering*. No stock at this point can be indicated, as data on collection coverage rates over the past 64 years is missing.

Waste generation (P4)

The process *Waste generation* stands for the entity of all 171Mt/year of *postconsumer plastics I* (F6) generated in 2014. The process has no stock, as all waste will be distributed between the outgoing flows: 30% goes to *uncollected waste* (F8), 49% goes to *landfill waste* (F7), and 21% goes to *recycling and recovery* (F9).

5.1.2 The flows (in Tg/a = Mt/year)

Beached litter (F15)

The flow called *beached litter* incorporates all plastic debris that is being washed ashore from the open sea, assumingly originating from the gyres. Due to ocean circulation patterns, the amount of *beached litter* is estimated at 1% of total input to the gyres, thus 0.0046Mt/year in 2014.

Beach littering (F11)

Beach littering represents the flow of postconsumer plastics to the beach. This includes litter by beach-goers and recreational activities close to the shore. The flow is estimated at 0.01% of non-collected plastic waste generated per year. In 2014, this amounted to 0.050Mt/year.

Coastal cleanup (F12)

Coastal cleanup presents the amount of coastal debris collected during the annual International Coastal Cleanup and thus removed from the beaches. This flow equals 6% of the amount of litter reaching the beach every year. Thus, in 2014, the flow amounted to 0.006Mt/year.

Consumer plastics I (F3)

Consumer plastics I represents the flow of domestic or regional plastic production to the consumer without passing through overseas shipping. An estimated 85% of global annual plastic production is not shipped overseas, amounting to 242.25Mt/year in 2014.

Consumer plastics II (F4)

Consumer plastics II refers to the estimated 15% of global plastic production, which are being exported overseas before reaching the consumer. In 2014, this flow amounted to 42.75Mt/year.

Degradation (F16)

The *degradation* represents one of the two outgoing flows from the *Gyres* (P9). It is estimated at 0.1% per year of the stock of plastics in the five gyres. In 2014, a mere 0.0002Mt/year of plastics degraded in the gyres.

Dumping I (F5)

The flow *dumping I* encompasses the estimated 0.1% of floating pre-consumer plastics that are being (illegally) dumped at sea every year during export. Due to their buoyancy, they are assumed to end up in one of the five gyres. In 2014, *dumping I* totalled 0.04Mt/year.

Dumping II (F22)

The flow *dumping II* represents the estimated 0.1% of floating postconsumer plastics that are being (illegally) dumped at sea during the overseas shipping of plastic waste intended for recycling. Same as for the dumped pre-consumer plastics, this flow of plastics is assumed to end up in one of the five gyres. In 2014, *dumping II* totalled 0.0035Mt/year.

Dumpsite leaking (F13)

The flow of plastics from the *Landfill* (P6) to the marine environment is called *dumpsite leaking* and refers to the annual potential outflow of plastic material from dumpsites. This flow is estimates at 5% of all material being discarded into a landfill or dumpsite and it equalled 4.19Mt/year in 2014.

Extra-gyral input (F14)

The *extra-gyral input* represents the annual flow of plastic debris from the beach to the open sea and consequently the gyres. Due to ocean circulation patterns, the amount of *extra-gyral input* is estimated to be 10% of the total plastics reaching the beach per year, thus 0.44Mt/year in 2014.

Global production (F1)

The flow *global production* represents the input of material to the system. The value of global plastic production was calculated according to an annual increase of 8.7% starting at the 241Mt of plastic produced globally in 2012. Thus, a total of 285Mt/year of plastic entered the system in 2014. This amount incorporates all material being transferred to the consumer and thus includes recycled plastics.

Incinerated plastic (F23)

The flow of *incinerated plastic* stands for the annual flow of plastic material from *General WMS* (P7) to the landfill after having been burned in a WtE plant. It represents a clean transfer without losses of a mere 0.01% of all plastics entering the *General WMS*. This percentage is so low due to the fact that the mass of plastic exiting a WtE plant is basically zero seeing as it is the fuel for the incineration. In 2014, the *incinerated plastic* amounted to 0.0035Mt/year.

Landfill waste (F7)

Landfill waste represents the annual quantity of postconsumer plastics that is being collected and disposed off in landfills and dumpsites. This amounts to an average 49% of all generated plastic wastes or 70% of the collected plastic waste and totalled 83.79Mt/year in 2014.

Overseas shipping (F2)

Overseas shipping represents the annual quantity of the global plastic production that is being exported overseas before reaching the consumer. On average, it represents 15% of annual production. In 2014, *overseas shipping* amounts to 42.75Mt/year.

Postconsumer plastics I (F6)

Postconsumer plastics I stand for the entire body of plastic waste generated within a year. In concordance with scenario 3 presented in Chapter 2.4.3, *postconsumer plastics I* present 60% of annual plastic production, since 60% of plastics are thought to be single-use plastics with a residence time of less than one year. In 2014, the *postconsumer plastics I* totalled 171Mt/year.

Postconsumer plastics II (F19)

Postconsumer plastics II represents the fraction of *Uncontrolled littering* (P5), which is being transferred to the marine environment and partially to the seafloor later on. This fraction is calculated as 1% of input to the uncontrolled littering based on the fact that most human settlements are close to waterways and thus, the floating, non-collected plastics easily make their way to the open sea. In 2014, *postconsumer plastics II* amounted to 0.51Mt/year.

Recycling and recovery (F9)

Recycling and recovery represents the annual quantity of postconsumer plastics that is being collected and treated in recycling and WtE plants. This amounts to an average 21% of all generated plastic wastes or 30% of the collected plastic waste and totalled 35.91Mt/year in 2014.

Recycled plastic I (F20)

Recycled plastic I represents the fraction of postconsumer plastics that re-enters the cycle after having been reprocessed in a domestic or regional recycling facility. For reasons of simplicity, it is assumed that the recycled plastic is contained in the initial input to the *Production* process (P1) and consequently, the flow of *recycled plastic I* leaves the system. It is further assumed that 3.32% of the plastic waste collected in *General WMS* (P7) is processed domestically, amounting to 1.19Mt/year in 2014.

Recycled plastic II (F21)

Recycled plastic II encompasses the fraction of postconsumer plastics exported overseas for recycling purposes and re-entering the cycle the same way as *recycled plastic I* (F20) via the initial inflow to *Production* (P1). It is assumed that 99.9% of exported waste plastics find their way back into production phase, equalling a flow of 34.68Mt/year in 2014.

Sinking (F26)

The flow *sinking* represents the amount of debris sinking to the bottom of the sea or rivers. It represents the 4.25Mt/year of plastic that are being transferred to the marine environment but due to their characteristics sink to the floor of waterways both inland and onshore. The flow originates from *Beach litter* (P8) for reasons of simplification.

Uncollected waste (F8)

Uncollected waste represents the annual quantity of postconsumer plastics that is not covered by the waste management system and is thus left in the environment uncontrolled. Globally, 30% of all generated plastic wastes are not collected, amounting to 51.3Mt/year in 2014.

Waste export (F10)

Waste export represents the annual quantity of the global plastic waste generation collected in the *General WMS* (P7) and intended for recycling overseas. An annual 96.67% of all postconsumer plastics collected in *General WMS* are exported, amounting to 34.71Mt/year in 2014.

5.1.3 Changing stocks (in Tg=Mt) in case of a tsunami

The changes in stock caused by the 2011 Tohoku tsunami are taken as prototype for the calculations of stock changes induced by a hypothetical tsunami in 2014. Only the changes are indicated here below: Those parts of the process that remain the same as in the everyday annual material flow analysis, will not be repeated.

Beach litter (P8)

Although in reality the amount of litter on the beaches changes completely, this is not accounted for in this thesis, as it would be part of the post-disaster clean up and is considered as being cleaned to 100%. The only change in flow accounted for in this process is the input from *beached litter*, which represents 1% of litter ending up in the gyres and will thus increase due to additional inflow to the gyres.

Consumption (P3)

The process *Consumption* sees a stock decrease due to the tsunami as a part of plastic debris is assumed to stem from households and industries rather than waste management facilities. Due to the two new outflows *Tsunami sinking I* (F17) and

Tsunami ocean debris I (F25), the anthropogenic stock "in use" is reduced by a total of 0.25Mt representing the stock of the 5.7 million people inhabiting the region affected by the event. The stock increase is reduced to 113.75Mt on a single year basis.

General WMS (P7)

The process *General WMS* stands for the entity of all collected plastic waste that is not transferred to the landfill right away. In the case of a tsunami, the collected plastics in these facilities are part of the debris since waste facilities are damaged. The input to *General WMS* remains the same, but the output changes as a flow to the *Seafloor litter* (P12) as well as a flow to the *Tsunami Ocean Debris* (P11) is added and reduces the amounts in the domestic flows, *recycling plastic I* (F20) and *incinerated plastic* (F23), by 0.34Mt in total.

Gyres (P9)

The inflow to the process *Gyres* is influenced by the event of a tsunami and continues to represent an unwanted sink of plastics. The *Tsunami gyre debris* (F24) flow of plastics from the open ocean to the gyre happens at a slower interval with only 25% of the floating plastics reaching the gyre within a year. Still, it represents an increase of inflow by 0.3Mt/year, almost doubling the yearly inflow. The stock of 0.204Mt is hence increased at a rate of 0.76Mt/year. This increase influences the outflow of *beached litter* (F15), which amounts to an estimated 1% of the sum of all annual inputs to the gyres.

Landfill (P6)

The input to the process *Landfill* remains the same in the case of a tsunami – the input after the tsunami will increase enormously for the region where the natural disaster occurred, but this increase is not considered in this work. The stock in the landfill will be reduced by a total of 0.34Mt due to the tsunami adding an outflow of 0.006Mt/year to *Seafloor litter* (P12) and 0.33Mt to *Tsunami Ocean Debris* (P11) additionally to the annual 5% *dumpsite leaking* (F13) under normal conditions.

Seafloor litter (P12)

Seafloor litter stands for the fraction of plastic debris that sinks to the bottom of all waterways both in-land and on the coastline. In the case of the tsunami, the input to this process does not only stem from *sinking* beach litter (4.25Mt/year) but also from the fraction of tsunami debris that sinks to the ocean floor close to shore, amounting to 0.035Mt/year as calculated with a 1% plastic content in the 3.5Mt of debris swept towards the ocean and sinking close to shore due to the tsunami.

Tsunami Ocean Debris (P11)

The process *Tsunami Ocean Debris* encompasses the entity of plastic debris floating around the ocean on their way to the respective gyre. The ocean refers to the part of the world's ocean in which the natural disaster takes place, e.g. the North Pacific Ocean in the case of the 2011 Tohoku Tsunami. The stock of this process amounts to the total floating debris minus the outflow. In this case 1.2Mt originating from the anthropogenic stock "in use" and the waste management systems reduction represented by *Tsunami ocean debris I* (F25) and *Tsunami ocean debris IIa, b and c* (F26) respectively. The outflow from the process is 25% of initial input per year, thus -0.3Mt/year.

Uncontrolled littering (P5)

Uncontrolled littering presents the vast body of postconsumer plastics that are not covered by waste collection and is impacted by the tsunami in the sense that a higher amount of uncontrolled litter is swept towards the coastline. The input to this process remains the same, but - additionally to the 0.55Mt outflow to *Beach litter* (P8) via *beach littering* (F11) and *postconsumer plastic II* (F19) – there is an outflow to *Seafloor litter* (P12) and *Tsunami Ocean Debris* (P11). The stock increases only by 50.40Mt/year for the year of the incident.

5.1.4 Changing flows (in Tg/a = Mt/year) in case of a tsunami

The changes in flows originating from a tsunami are also based on the data collected for the 2011 Tohoku tsunami. Their basis year will be 2014, meaning that the year of the incidence taking place is 2014. For this part as well, only the changes are indicated here below whereas the flows that remain the same are not repeated.

Beached litter (F15)

The *beached litter* is estimated to be 1% of total input to the gyres. The increased input to the gyres, hence, also influences this flow, entailing an increase of beached litter by 62%, resulting in 0.007Mt/year in 2014.

Degradation (F16)

The *degradation* of plastics in the *Gyres* (P9) is calculated to be 0.1% per year of the stock of plastics in the five gyres. The stock in the gyre at the time of the event is still 0.204Mt. Thus, the output by *degradation* remains 0.0002Mt/year.

Recycled plastic I (F20)

Recycled plastic I represents the fraction of postconsumer plastics that re-enters the cycle after having been reprocessed in a domestic or regional recycling facility. This flow is reduced in case of a tsunami by 0.34Mt/year for this one year due to damage to waste treatment facilities and amounts to 0.85Mt/year.

Tsunami gyre debris (F24)

Tsunami gyre debris I represents the flow of plastics from the T*sunami ocean debris* (P11) to the *Gyres* (P9) as caused by a tsunami such as the 2011 Tohoku Tsunami. This flow amounts to 25% of total 1.2Mt per year, thus 0.3Mt/year.

Tsunami ocean debris I (F25)

Tsunami ocean debris I represents the flow of plastics from the stock of the anthropogenic stock “in use”, *Consumption* (P3) to the open sea that has not yet made it to the gyres and is thus still floating at open sea. In 2014, this flow amounts to 90% of total 1.5Mt, meaning 1.35Mt/year.

Tsunami ocean debris IIa (F27)

Tsunami ocean debris IIa represents the flow of plastics from the stock of the *General WMS* (P5) to the open sea that has not yet made it to the gyres and is thus still floating at open sea. This flow amounts to 0.33Mt/year

Tsunami ocean debris IIb (F27)

Tsunami ocean debris IIb represents the flow of plastics from the stock of the *Landfill* (P6) to the open sea that has not yet made it to the gyres and is thus still floating at open sea. This flow amounts to 0.33Mt/year.

Tsunami ocean debris IIc (F27)

Tsunami ocean debris IIc represents the flow of plastics from the stock of the *Uncontrolled Litter* (P7) to the open sea that has not yet made it to the gyres and is thus still floating at open sea. This flow amounts to 0.33Mt/year.

Tsunami sinking I (F17)

The flow *tsunami sinking I* represents the flow of plastics from the anthropogenic stock “in use”, *Consumption* (P3) and sinking to the bottom of the sea close to shore. It represents the 0.0175Mt/year of plastic that are being transferred to the marine environment in a single event due to the force of nature.

Tsunami sinking IIa (F28)

The flow *tsunami sinking IIa* represents the flow of plastics from the *General WMS* (P5) and sinking to the bottom of the sea close to shore. It represents the 0.006Mt/year of plastic that are being transferred to the marine environment in a single event due to the force of nature.

Tsunami sinking IIb (F18)

The flow *tsunami sinking IIb* represents the flow of plastics from the stock of the *Landfill* (P6) and sinking to the bottom of the sea close to shore. It represents the 0.006Mt/year of plastic that are being transferred to the marine environment in a single event due to the force of nature.

Tsunami sinking IIc (F28)

The flow *tsunami sinking IIc* represents the flow of plastics from the stock of the *Uncontrolled Litter* (P7) and sinking to the bottom of the sea close to shore. It represents the 0.006Mt/year of plastic that are being transferred to the marine environment in a single event due to the force of nature

5.2 The MFA

The first MFA represents the global plastic flow from production to the different sinks in everyday conditions for the year 2014. The second MFA shows the global plastic flow from production to the different sinks in the case of a tsunami for the year 2014. The stock (Mt) and flows (Mt/year) marked in bold are the changes induced by the tsunami.

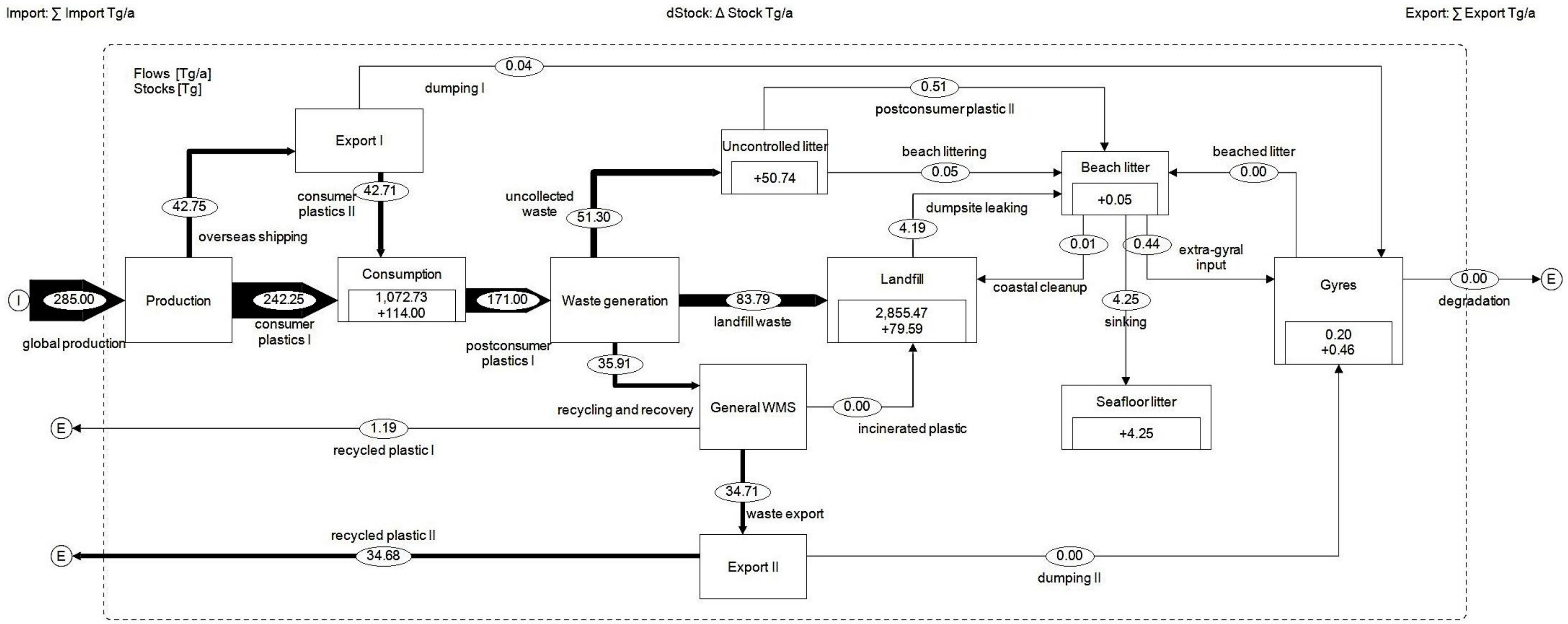

Figure 5: Global Plastic Flow from production to sink on everyday conditions, baseline year 2014

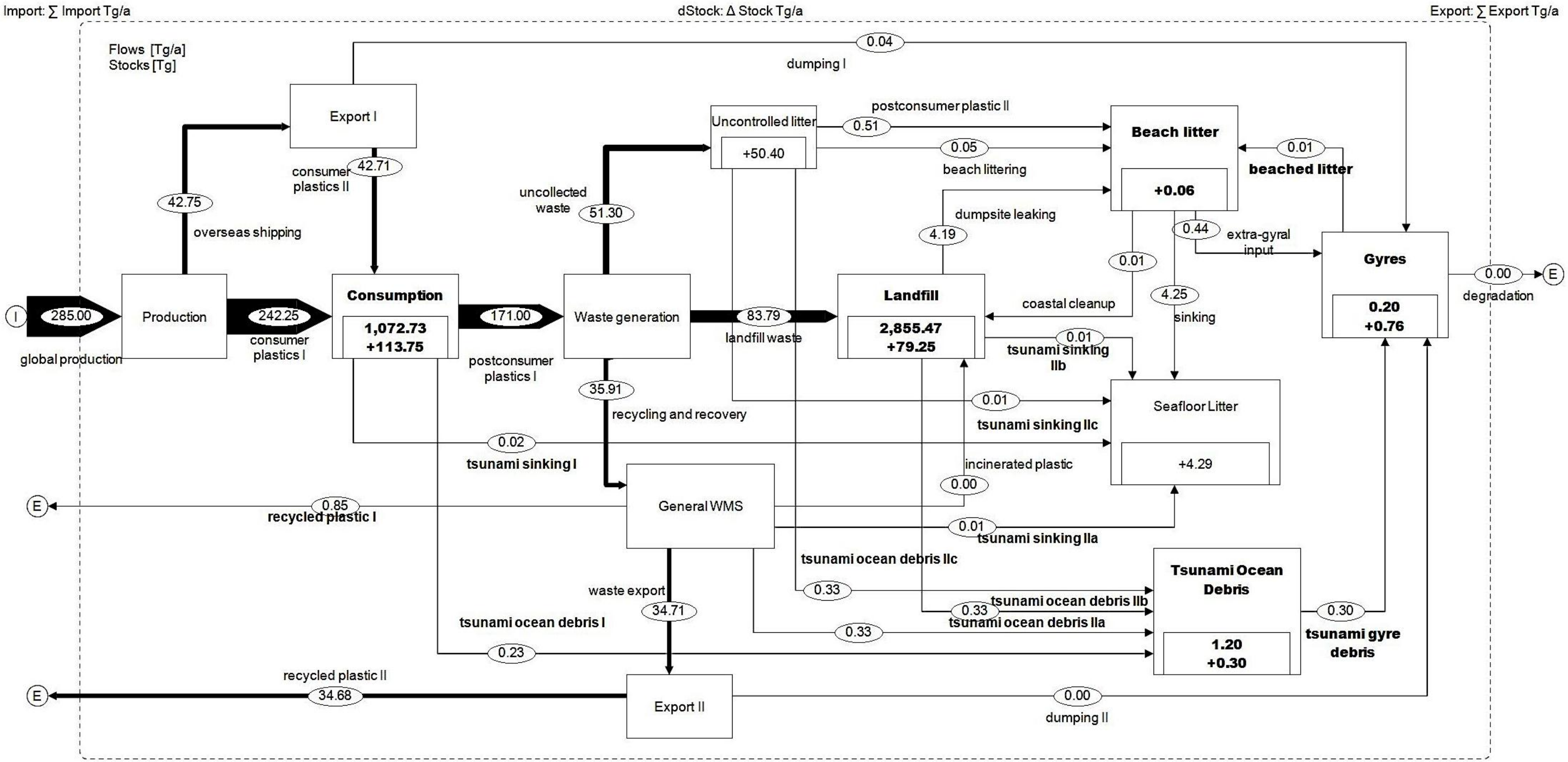

Figure 6: Global Plastic Flow from production to sink in the case of a tsunami, baseline year 2014

5.3 Discussion of the MFA

5.3.1 Plastic flow from Production to the Ocean in every year conditions

The global plastic flow in everyday conditions, represented by Figure 5, shows that the flow to the marine environment, including beaches, seafloor litter and the gyres, is only a minor flow of total plastics in the anthropogenic system. However, those 4.76Mt/year could easily be avoided as they stem from anthropogenic activities. The major pathway towards the marine environment stems from beach litter sinking to the bottom of the sea. This flow included all plastics landing on the bottom of river and inland waterways through processes such as sewage overflow and windblown non-collected or badly disposed off waste plastics. In terms of input to the gyre, the flow is of a 10 times lower magnitude with 0.44Mt/year extra-gyral input from the beaches being the biggest flow.

Unfortunately, several uncertainties and assumptions had to be made to determine the amount of extra-gyral input. First of all, the input represents a fraction of 10% of the debris accumulated on the beach. The total amount of litter on the beaches was extrapolated from the ICC report of 2009. The amount of plastics collected during this clean-up event may, however, not have been representative for the world's coastline. Further, the extrapolation was based on the assumption that the entire coastline around the oceans is inhabited in the same way. Even though the biggest unpopulated coastlines have been deducted from the total kilometres, the amount of plastic estimated to reach the beach might still have been exaggerated.

Further, the biggest input to the beach stems from dumpsite leakage. Dumpsite leakage has been reported to be a source of pollution to the marine environment, yet again without concrete data. The mass of plastic reaching the beaches due to dumpsite leakage was based on the indicated total amount of plastic inflow to the ocean postulated in international reports by Greenpeace and the Green Paper (Allsopp, 2006; European Commission, 2013). However, neither of the reports indicated a source of information nor the exact pathway to the marine environment, and thus the possibility of the dumpsite leakage ending up on the seafloor without contact to the beach is given. If this was the case, the amount of plastic flow to the beach would be a mere 0.56Mt/year instead of 4.74Mt/year. Thus, the 10% of extra-gyral input would only amount to 0.06Mt/year instead of 0.44Mt/year.

On the other hand, the amount of uncontrolled litter from non-collected plastic waste was calculated as only 0.1% of total 51.3Mt uncontrolled postconsumer plastic in 2014. This is rather low estimation, which could counterbalance exaggerations on the account of dumpsite leaking. All in all though, it can be said that the amount of plastic waste reaching the beaches was difficult to determine due to lack of concrete data on the origins of the debris or the flow from the different sources.

A second uncertainty in terms of extra-gyral input lies in the fraction of 10%. This fraction is based on a subjective evaluation of data and studies of ocean circulation patterns reporting different exchange patterns. While some studies report an exchange of debris between beach and open sea in a period of 2 months, others point out that there is zero exchange between the beach and the open sea until 20km offshore, unless there is a major force acting upon the debris (Kim, 2013; Matsumura et al., 2013; Eriksen et al., 2013; Kako et al., 2011; Wilber, 1987).

Thus, to better evaluate the extra-gyral input, more debris tracking from the beach to the ocean would be needed and an identification of the origin of debris on the beach. Further, a higher collection rate and closer scrutiny of dumpsite outflows would be the next step to take to prevent plastic pollution. Despite this high amount of uncertainties, it should not come as a surprise that the flow from the beach to the ocean would be the biggest input. It has repeatedly been stated that land-based activities make up between 60-80% of marine debris (Derraik, 2002). Compared to the inflow from dumping activities of roughly 0.04Mt/year, the land-based input does in fact account for 80% of debris in the gyre.

5.3.2 Plastic flow from Production to the Ocean in the case of a tsunami

In the case of a tsunami, presented by Figure 6, the flows to the marine environment have increased by almost 80% to roughly 6Mt/year. In this number, the major increase of beach litter due to the incident was not considered as it was assumed that this debris would be part of the post-disaster clean-up mission. The major flow to the gyre is even in the case of a tsunami still the extra-gyral input and underlies the same uncertainties as mentioned under 5.3.1. The flow of tsunami debris in the open sea rank second with 0.3Mt/year. Thus, the 2 major pathways of plastic to the gyres have been identified for both conditions.

The figure of 0.3Mt/year was based on the data reported by the Japanese government and UNEP expert team a year after the tsunami. There was no indication in the report as to the uncertainties or determination of the number (UNEP, 2012). As for most disaster situations, the amounts of damage are estimated based on satellite imagery and house damages. The amount of 1.5Mt reported to have been washed into the open sea should therefore represent a more or less 100% certain number. The deduction that 90% of this debris is plastic was based on the currently available data on marine debris being made of 80% plastic. It was thus assumed that the portion of debris swept into the ocean and not sunken to the seafloor at shore would be made up to the biggest extent of plastics as well. Further, a debris tracking model by Lebreton and Borrero (2013) indicated that the debris would take 4 years to reach the gyres. It was therefore assumed that 0.3Mt/year would reach the gyres in a one-year model as presented in figure 6.

The thesis started with the hypothesis that the tsunami would be the biggest contributor to the plastic in the gyres. Seeing as the extra-gyral input shows a bigger amount of annual input in the MFA (Figure 6), this hypothesis could be seen as disproven. However, the 2011 Tohoku tsunami, taken as basis for the calculations, hit a country with a highly efficient waste management system, thus reducing the inflow from final disposal facilities to the open sea. Plus, the response to the disaster in Japan was exemplary in every sense and had high international support. If such a disaster were to hit a country of lower level facilities in waste management, the increase in inflow would be far bigger.

Further, the 1.235Mt of plastic waste released to the marine environment by the tsunami represent 216.79kg/cap for the 5.7 million people affected by the disaster. This is equivalent to almost 4 years of plastic waste generation in Japan in a single event. Extrapolating this amount to the world population of 7.16 billion would create an input of 1.5 billion tons of debris. Even if we only consider the coastal population, it would still make 867 Mt of plastic released to the ocean. Consequently, the representation of plastic flow on a global level distorts the importance of the tsunami.

5.4 Overall assessment of the results: Assumptions, Approximations and Missing Data

One of the biggest deficits of the presentation of the plastic flow on a global level is the lack of transparency as to the contribution of each region of the world. As has been seen in Chapter 3.4, the input from the northern hemisphere is higher than from the southern, mostly due to a difference in economic development. This again stresses the importance of efficiently treating the plastics and disposing of them. Otherwise, the continuous increase in coastal population will turn our beaches into plastics instead of sands and create a new biota at sea.

The MFA further showed that the degradation rate of plastics is not influenced by an increase in input, as the ocean has no proper coping mechanism for plastics. Therefore, it is of utmost importance that such increases are prevented in the first place, by increasing the plastic collection rates and the efficiency of disposal. However, the timeframe and rate within which plastics are degraded in the gyres was based on an assumption. The scientific uncertainties linked to the degradation process highly influence the outflow from the gyres. It is known that the process takes a long time, but it is not known whether the plastic may leave a gyre in the mean time, sink to the ocean or undergo various other processes, such as fouling. The example of a piece of plastic found in an albatross stomach in 2005 and stemming from a seaplane shot down in World War II clearly shows the complexity of sea transport. The plastic item had passed through both the western and eastern island of the North Pacific Garbage Patch before ending up in the stomach of said albatross (Weiss, 2006). This means that the earlier assumption that the gyres are indeed the end-station for plastics in the ocean is false. Knowing exactly how long the plastic items remain in the gyres would give further indication as to the timeframe within which degradation is happening.

Moreover, it is also not clear whether the amount of plastic currently in the ocean is in fact still increasing and to what extent. Looking at the MFA, it seems clear that there is an input of less than 0.5Mt per year in everyday conditions and an output in orders of magnitude smaller. Some comparative data supports this statement having identified an average annual stock increase of 25% in the North Pacific Gyre between 1997 and 2011 (Williams et al., 2011).

On the other hand, Law et al. (2010) show that there has been no significant increase in plastic debris. Their study indicates that possible sinks for floating plastic debris could include fragmentation, sedimentation, shore deposition and ingestion by marine organism. The discrepancy may also be due to the different methods of collecting the information and size of the items considered. The lack of a standardised method for data collection in the field of marine debris has been criticised by several studies and is also one of the main challenges on the way to identifying the source of the plastic debris. This is one of the reasons why it is still difficult to quantitatively assess the sinks of plastics. Furthermore, a successful implementation of anti-dumping regulations could have reduced the input of plastic over time compared to 1950-1980 period thus giving the ocean time to remove the particles. Moreover, the plastic material entering the ocean could be majorily of a different density nowadays and can thus not be observed as floating items on the oceans' surface. Another explanation would be that the lack of knowledge on the removal pattern from the gyres creates an additional uncertainty in the data collection.

Furthermore, a closer chemical analysis would be of interest to determine if the plastic types in the gyres are the ones that are most or least susceptible to the degradation process. This could provide some insight into whether the sea floor is full of plastic sunk after fouling process started etc.

The limiting factors for the content of this paper might have a big influence on the outcome. Several of the numbers had to be assumed based on considerations and estimations presented in literature. Although most of the assumptions made throughout the thesis, have been proven by confirmed data, the flows to the gyres are still uncertain. Nevertheless, both MFAs give a good basis for future research, as they are easy to adapt if better data comes up.

6 Summary and Conclusions

It was the aim of this work to identify and quantify the various origins of plastic pollution in the marine environment. In the first part of the thesis, the initial purposes of plastics were outlined to identify the origins of plastics in the anthropogenic system. Through analysing the pre-waste usage of plastic in the different sectors as well as the postconsumer waste management systems involved in the plastic industry, potential land- and ocean-based sources for plastic pollution in the marine environment were identified. It was concluded that the main weak points in the anthropogenic system are dumping of plastics at sea both at pre-consumer and postconsumer stage of exports, dumpsite leaking and a global waste collection rate of only 70%. Difficulties in this part of the thesis mainly consisted in the lack of data on the quantities of plastics being dumped at sea, due to its illegal character and identifying the exact input of plastics from dumpsites, a source of pollution often mentioned but never clearly defined.

In the second part, the state of the art in the field of plastics at sea was established. After having explained the conditions under which both degradation and transport at sea takes place, the results of the research in the area of plastic accumulation in the five gyres was summed up. In this section, several uncertainties and assumptions had to be made due to lack or inconsistency of data. First of all, major discrepancies have been identified between the plastic amounts reported in water probing and stomach analysis studies, amounting to 0.204Mt, compared to international reports, reporting 80Mt of plastics in the Atlantic and Pacific gyres. Secondly, even the different water probing studies were not always comparable in terms of results, as their evaluation or collection criteria differed. For the purpose of this paper, the 0.204Mt of stock in the gyres calculated from the results of water probing and stomach analysis studies was taken as basis. The main conclusion to be drawn from this part is that there are too many scientific uncertainties to reach a valid quantitative result. These uncertainties have a big impact on the extent of the problem of marine debris and should therefore be excluded in future research before worldwide reports are being made public. The fact that the 80Mt of plastic reported in international reports could not be proven by the collected data on site and are still used as reference in media to explain the extent of the problem further underlines the importance of literature reviews and comparative research.

The third part of the thesis identified the four pathways from the anthropogenic system to the ocean, namely export of pre-and postconsumer plastics, beach litter, inefficient waste management and natural disasters, such as the 2011 Tohoku tsunami. This section concluded that extra-gyral input of beach litter and thus lack of efficient waste collection and disposal, is the main contributor to plastic pollution of the marine environment with more than 0.4Mt/year and this both in everyday conditions and in the case of a tsunami. The second biggest input of 0.3Mt/year, stems from tsunami debris of both pre- and postconsumer plastic stocks. This high input to the gyres will not take place on a single day, but increases the density of plastic in the ocean's gyres over a period of at least 4 years. Both major flows include a certain amount of uncertainties due to the lack of transparency in data or lack of them altogether. Interestingly, shipping is seen to be a minor input, which could be ascribed to the regulations that they underlie or to the lack of data on illegal dumping activities.

The results of the data collected throughout the thesis are presented in two material flow analyses. Both MFAs reflected the rate to which each pathway contributed to the plastic debris in the gyres. The first MFA shows that the stock of plastic in the gyres increases on an annual basis by 0.46Mt. The second MFA is based on a hypothetical 2014 tsunami behaving according to the 2011 Tohoku tsunami. This MFA further showed, that the final input to the gyres increased by 65% of every year inflow due to a single event.

One of the major issues when consulting the literature was found to be the lack of transparency of international reports as to where their numbers stem from. For example, the 80Mt of plastic debris in the Atlantic and Pacific Ocean reported by UNEP (2009) have been considered the truth and were cited in scientific papers as well as in everyday press. However, the data collected in this thesis could not confirm that number. The many assumptions made in construing the global plastic flow illustrate how poorly constrained the sources and pathways of plastic debris are.

Nevertheless, the model presented in this thesis could provide an important tool for future monitoring efforts, as well as a quantitative assessment to accurately inform the public and policymakers of the scope of this environmental problem. So far, the solutions proposed and carried out in terms of plastic abundance in the oceans have been short-term and/or regional initiatives, such as beach-cleanups or educational programs. This work has made it clear that the input from inefficient waste management facilities as well as non-collected waste is the biggest pathway of plastic from land to ocean on a daily basis. Improving this situation can only happen through long-term initiatives. Some options at the source would be an increased collection rate in all countries as well as an increased transferral to landfills rather than dumpsites. Further, the resistance to natural disasters of the facilities should be improved. In terms of research, quantification of the sources and pathways on a regional level should be intended, starting with debris tracking and followed by an extensive reporting of inefficient waste management systems.

To conclude, it still remains difficult to quantify the exact amounts of plastic input to the ocean from the different origins. The material flow presented here, shows that the biggest issue at hand in terms of sources of pollution is inefficient waste management. The input from the tsunami has been proven to contribute a higher amount on regional but not on global level. Nevertheless, it should not be forgotten that the main body of this research were microplastics, of which the weight is not representative for the damage they do to the marine biota. By eliminating the unknowns in terms of sources and pathways, plastics can be efficiently prevented and recovered before entering the marine ecosystem and consequently our food chain.

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Annex

Annex I: Municipal Solid Waste composition by region and economic development

The rate of plastic in Municipal Solid Waste varies highly from country to country, from region to region and also depends on the economic development of the country in question. The following tables are a summary of plastic waste in MSW by region and economic development as presented by The World Bank report "What a Waste: A Global Review of Solid Waste Management" (Hoornweg and Bhada-Tata, 2012).

The first table presented below looks at the waste composition according to the economic development of the countries and is divided into 4 categories. In total, the cities of 22 low-income countries, home to 343 million residents, are covered in the first category. The second category sums up 27 countries of lower middle-income with a total 1,293 million urban inhabitants. Further, 25 upper middle-income countries are covered in the third category with an urban population of 572 million. The last category of high-income countries reflects an urban population of 774 million in 35 countries. It should be noted that the sum of all countries (109 considered) does not add up to the same amount that is given as global plastics in solid waste given in the first table, but does come to the same amount as is given if looking at the countries region by region. It is assumed that the numbers of the first table include different variables, which have not been noted in the report.

Table I.1: Plastic waste generation in Municipal Solid Waste (MSW) considering waste composition in countries of different economic development (Hoornweg and Bhada-Tata, 2012: 16-21)

	Plastic (%)	Average waste generation per capita (kg/capita/day)	Total MSW (tons/day)	Plastic in MSW (tons/day)*	Plastic in MSW (Mt/yr)*
Global solid waste	10	1.2	3,532,252	353,225	128.93
Low-income Countries	8	0.6	204,802	16,384	5.98
Lower Middle-Income Countries	12	0.79	1,012,321	121,479	44.33
Upper Middle-Income countries	11	1.2	665,586	73,214	26.72
High-Income Countries	11	2.1	1,649,547	181,450	66.23

*own calculations according to the % of plastic in total MSW indicated by Hoornweg and Bhada-Tata (2012) and a year of 365 days

The second table sums up the plastic waste generation in different regions. AFR stands for Africa and considers the urban population of 19 Sub-Saharan African countries with a total of 260 million inhabitants. EAP stands for East Asia & Pacific and considers the cities of 17 countries, amounting to 777 million urban residents. Eastern and Central Asia (ECA) covers 227 million people living in cities of 12 countries. In Latin America and the Caribbean, the cities of 18 countries (and entities) are covered, comprising 399 million residents. SAR stands for South Asian region and covers the waste generation in the cities of 27 countries, home to 426 million people. The Middle East and North African (MENA) region sums up 10 countries and 162 million urban residents. Finally, the countries of the OECD, the Organisation for Economic Co-operation and Development, include 6 countries with urban population amounting to 729 million.

Table I.2: Plastic waste generation in Municipal Solid Waste (MSW) considering waste composition of different regions as presented by Hoornweg and Bhada-Tata (2012: 16-21)

	Plastic (%)	**Average waste generation per capita (kg/capita/day)**	**Total MSW (Mt/yr)**	**Plastic in MSW (tons/day)***	**Plastic in MSW (Mt/yr)***
AFR waste composition	13	0.65	62	22,082	8.06
EAP waste composition	13	0.95	270	96,164	35.1
ECA waste composition	8	1.1	93	20,384	7.44
SAR waste composition	7	0.45	70	13,425	4.9
MENA waste composition	9	1.1	63	15,534	5.67
LAC waste composition	12	1.1	160	52,603	19.2
OECD waste composition	11	2.2	572	172,384	62.92

*own calculations according to the % of plastic in total MSW indicated by Hoornweg and Bhada-Tata (2012) and a year of 365 days

The above indicated categories and divisions of the world's countries are explained and summarised in the table bellow for better overview.

Table I.3: Summary of the categories given in the tablesI.1 and I.2 the number of countries and urban population covered by the study (Hoornweg and Bhada-Tata, 2012)

Category	Number of countries	Explanation of the category name	Urban Population (millions)
Global	109		2982
Low-income Countries	22		343
Lower Middle-Income Countries	27		1,293
Upper Middle-Income countries	25		572
High-Income Countries	35		774
AFR	19	Africa, Sub-Saharan Africa	260
EAP	17	East Asia & Pacific	777
ECA	12	Eastern & Central Asia	227
LAC	18	Latin America & the Caribbean	399
MENA	10	Middle East & North Africa	162
OECD	6	Organization for Economic Co-operation and Development	729
SAR	27	South Asia	426

Annex II: Detailed calculations on global plastic production, stock and waste from 1950-2014

Table II.1 stipulates the world plastic production with an annual average increase of 8.7% since 1950.

Table II.1: Estimated world plastic production since 1950 based on an 8.7% increase per year.

Year	Plastic Production (Mt/year)	Annual increase of 8.7%	Sum of the total production in time periods (Mt)
1950	1.70	0.15	**period 1950-2014**
1951	1.85	0.16	**4,212.96**
1952	2.01	0.17	
1953	2.18	0.19	
1954	2.37	0.21	
1955	2.58	0.22	
1956	2.80	0.24	
1957	3.05	0.27	
1958	3.31	0.29	
1959	3.60	0.31	
1960	3.92	0.34	
1961	4.26	0.37	
1962	4.63	0.40	
1963	5.03	0.44	
1964	5.47	0.48	
1965	5.94	0.52	
1966	6.46	0.56	
1967	7.02	0.61	
1968	7.63	0.66	
1969	8.29	0.72	
1970	9.02	0.78	
1971	9.80	0.85	
1972	10.65	0.93	
1973	11.58	1.01	
1974	12.59	1.10	
1975	13.68	1.19	
1976	14.87	1.29	
1977	16.17	1.41	
1978	17.57	1.53	
1979	19.10	1.66	
1980	20.77	1.81	
1981	22.57	1.96	
1982	24.54	2.13	
1983	26.67	2.32	
1984	28.99	2.52	
1985	31.51	2.74	
1986	34.25	2.98	
1987	37.23	3.24	
1988	40.47	3.52	
1989	43.99	3.83	
1990	47.82	4.16	
1991	51.98	4.52	
1992	56.51	4.92	
1993	61.42	5.34	
1994	66.77	5.81	
1995	72.57	6.31	
1996	78.89	6.86	
1997	85.75	7.46	
1998	93.21	8.11	
1999	101.32	8.81	**period 1950-1999**
2000	110.14	9.58	**1,246.38**
2001	119.72	10.42	
2002	130.13	11.32	
2003	141.45	12.31	
2004	153.76	13.38	
2005	167.14	14.54	
2006	181.68	15.81	

2007	197.48	17.18	
2008	214.67	18.68	
2009	233.34	20.30	
2010	253.64	22.07	
2011	275.71	23.99	
2012	241.00	20.97	
2013	261.97	22.79	**period 2000-2014**
2014	284.76	24.77	**2,966.58**

In order to calculate the anthropogenic stock of plastic in use and in the landfills all around the world, 3 different scenarios have been analysed. Table II.2 lists the parameters for each one of the scenarios. Short-living plastics refers here to the percentage of global plastic production, which has an average residence time of 1 year, whereas long-lived plastics have an average residence time of 15 years.

Table II.2: Parameters underlying the three different scenarios to determine the global plastic stocks in use and in the landfill

Scenario	Rate of short-lived plastics (%)	Rate of long-lived plastics (%)
1	20	80
2	40	60
3	60	40

Tables II.3, II.4 and II.5 show the flow to waste and to stock "in use" for the production of 285Mt in 2014 according to each scenario.

Table II.3: Scenario 1: Flows to waste and to stock "in use" for world plastic production of 2014. Calculated with 20% short- and 80% long-living plastics.

Production (Mt)	Waste flow (Mt/year)	In use (Mt/year)
285	57	228

Table II.4: Scenario 2: Flows to waste and to stock "in use" for world plastic production of 2014. Calculated with 40% short- and 60% long-living plastics.

Production (Mt)	Waste flow (Mt/year)	In use (Mt/year)
285	114	171

TableII.5: Scenario 3: Flows to waste and to stock "in use" for world plastic production of 2014. Calculated with 60% short- and 40% long-living plastics.

Production (Mt)	Waste flow (Mt/year)	In use (Mt/year)
285	171	114

Tables II.6-8 sum up the increase in stock both in use and in the landfills for each one of the scenarios and give an average annual flow to each stock as could be estimated on over the whole period of 15 years.

Table II.6: Scenario 1 of plastic distribution within anthropogenic stocks. Calculated with 20% short- and 80% long-living plastics.

1/ Time period	Total production (Mt)	Short-living plastics (Mt)	Long-living plastics (Mt)	Average flow to stock "in waste" per year (Mt/year)	Average flow to stock "in use" per year (Mt/year)	Increase of stock "in use" per capita and year (kg/year)
2000-2014	2,681.82	536.36	2,145.46	35.76	143.03	19.95

Table II.7: Scenario 2 of plastic distribution within anthropogenic stocks. Calculated with 40% short- and 60% long-living plastics.

2/ Time period	Total production (Mt)	Short-living plastics (Mt)	Long-living plastics (Mt)	Average flow to stock "in waste" per year (Mt/year)	Average flow to stock "in use" per year (Mt/year)	Increase of stock "in use" per capita and year (kg/year)
2000-2014	2,681.82	1,072.73	1,609.09	71.52	107.27	14.90

Table II.8: Scenario 3 of plastic distribution within anthropogenic stocks. Calculated with 60% short- and 40% long-living plastics.

3/ Time period	Total production (Mt)	Short-living plastics (Mt)	Long-living plastics (Mt)	Average flow to stock "in waste" per year (Mt/year)	Average flow to stock "in use" per year (Mt/year)	Increase of stock "in use" per capita and year (kg/year)
2000-2014	2,681.82	1,609.09	1,072.73	107.27	71.52	9.98

Annex III: The Chemistry of Plastics

Plastics are polymers, which means that they are macromolecules with a high molecular weight made up of multiple repeating units (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014). These macromolecules are formed over several steps from small molecules, which are yielded from petroleum. First of all, heavy crude oil is distilled into lighter groups called fractions. These fractions are mixtures of hydrocarbon chains differing both in size and in structure. The most crucial fraction for the formation of polymer chains is Naphtha, because it is this fraction, which will be cracked (thermally split) to form smaller building blocks for the polymer chain synthesis, such as ethylene, propylene and butylene. (PlasticsEurope, 2014b)

There are two types of polymerization reactions. The chain-reaction, also called addition polymerization, consists of the reaction between a monomer and a catalyst (for example a free radical peroxide). Although this reaction has no by-product, it can have cross-linking and branching (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014). To give an example of polymer formation by addition, the reaction of polystyrene is given here below.

III.1 Addition polymerization

1. Initiation

Reaction of a styrene monomer with a free radical organic peroxide

$R–O^* + C_6H_5CH{=}CH_2 \rightarrow R–O–C_6H_5CH–CH_2^*$

2. Propagation

Reaction of the propagating polymer chain with another styrene monomer

$R–O–C_6H_5CH–CH_2^* + C_6H_5CH{=}CH_2 \rightarrow R–O–C_6H_5CH–CH–C_6H_5CH–CH_2^*$

3. Termination

Reaction of the propagating polymer chain with a free radical organic peroxide or with another propagating polymer chain

$R – O - CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_2^* + R – O^* \rightarrow R – O - CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}O\text{-} R$

$R – O - CH_2\text{-}CH_2^* + R\text{-}O\text{-}CH_2\text{-}CH_2^* \rightarrow R – O - CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}O\text{-}R$

The molecular form of polystyrene thus looks as follows:

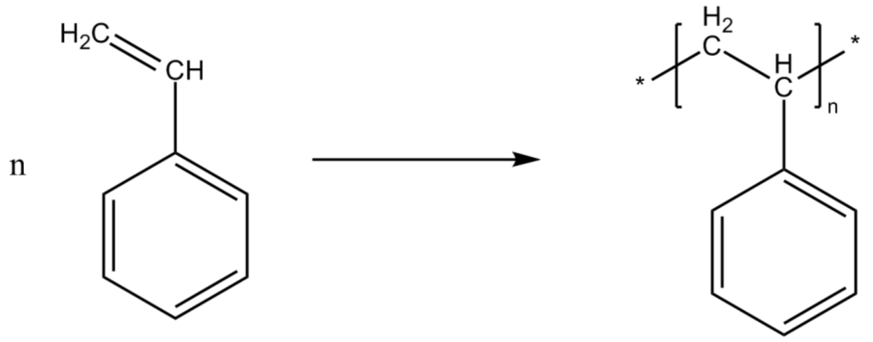

Figure III.1: Addition formation of polystyrene from a monomer with free radical organic peroxide

III.2 Condensation polymerization:

The second reaction type is a step-reaction or condensation polymerization. This reaction is usually used to produce polymers of lower molecular weight and consists of the reaction between two types of bi-functional monomers/end-groups. The by-products of this reaction are small molecules such as water or hydrochloride molecules, but there is usually no cross-linking or branching. (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014). To give an example of condensation polymerisation, the formation of nylon is explained here below. Nylon is formed through the reaction of hexamethylene diamine and adipic acid, two bi-functional monomers.

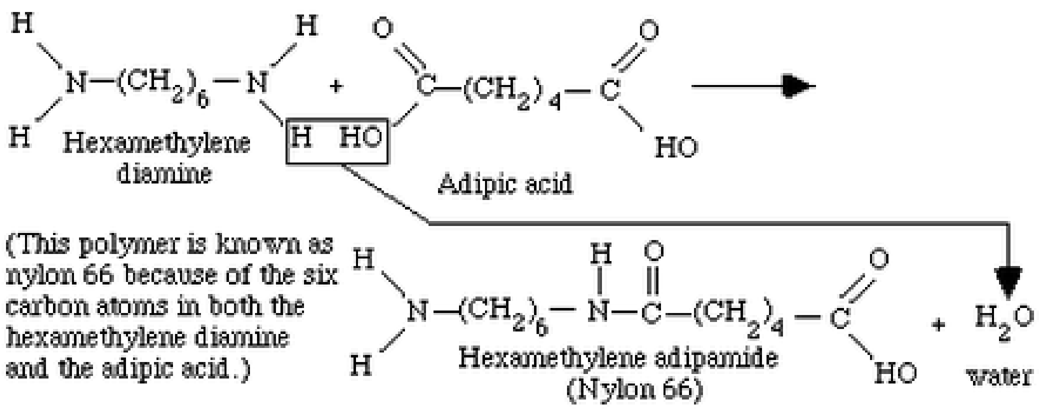

Figure III.2: The condensation reaction forming Nylon from two bi-functional monomers (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014)

Finally, two families of plastics can be distinguished according to their reaction to heat due to the different bonds of the chain. Thermosets have both Van der Waals and covalent bonds between the chains, are cross-linked and non-linear and thus resistant to heating (PlasticsEurope, 2014b). The only way to reshape thermosets plastics is through mechanical work. This means that thermosets are highly stable regardless of the temperature and have thus insulating properties. Additionally their resistance to deformation under load and lightweight gives them rigidity and dimensional stability. Examples of thermosets are polyester and polyurethane. (PlasticsEurope, 2014b; University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014)

Thermoplastics on the other hand are defined as carbon containing polymers with strong covalent bonds within the chain and weak Van der Waals bonds between the chains. The Van der Waals bonds of these linear polymers can be overcome by thermal energy and consequently reshaping of thermoplastics is rather easy (University of Illinois Urban-Champaign : Department of Materials Science and Engineering, 2014). Thermoplastics are classified according to their crystallinity, where 100% crystalline would mean that the polymer is not able to melt. Examples of thermoplastics are polyethylene, polypropylene and nylon (PlasticsEurope, 2014b).

Further, plastics are divided into organic and inorganic carbons, which differ in containing only carbon and hydrogen atoms (organic), respectively silicon or phosphorus and hydrogen atoms (inorganic) in their backbone. The most common organic carbons are polyethylene, polypropylene, polybutylene, polystyrene, and polymethylpentene as well as polyvinylchloride, which bind chlorine to every other carbon atom at their backbone (American Chemistry Council, 2014).

For each specific usage, the properties of plastics can be adapted by adding chemicals, which change or enhance the mechanical properties of the polymer and their thermal stability (Andrady, 2000). Industrial resin pellets are here used as raw material to create the specific consumer plastics (Law et al., 2010). The impact of these additives is one of the major concerns of having plastic in the marine environment as an uncontrolled degradation process of plastics also induces unknown consequences over the whole food chain.

Annex IV: Short introduction to ocean currents

The oceans are a vast and dynamic body of water in constant movement on the horizontal and vertical axis. The main driving forces behind the continuous movement of seawater are two strongly interwoven circulation patterns, namely wind driven and density driven circulations (Levinton, 2011). The wind driven circulation mainly influences the upper kilometre of the ocean whereas the thermohaline circulation reaches the sea floor in some regions and is associated with ocean overturning. Wind driven circulation can be in the range of tens to hundreds of centimetres per second while ocean overturning can take up to 1000 years for a full exchange of water (NOAA, 2013b).

The principle behind thermohaline circulation is the density difference of water masses as a result of changes in temperature and salinity. For instance, heat removal in the upper layers in polar region induces a vertical movement as the denser surface water descends to lower layers and then moves to lower latitudes, driving the ocean conveyor belt. (Levinton, 2011: 26-32)

On the other hand, the oceanic surface currents are controlled by the interaction of the planetary wind system and the earth's rotation. While wind exerts drag on the surface water and induces movement of the upper layer, the Coriolis effect, as a consequence of the earth's rotation, causes water to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The combination of winds and the Coriolis effect move tremendous volumes of surface waters in large circular patterns, known as gyres, which move clockwise in the Northern Hemisphere and anti-clockwise in the Southern Hemisphere (Eriksen et al., 2013). The wind-driven deflection in the surface layer is passed on throughout the water column, a motion known as Ekman transport, with a net deflection of 90º (Lebreton et al., 2012). The Ekman transport is responsible for upwellings, where divergence of water masses is compensated by an upward movement of nutrient-rich deeper water, and for downwellings in the case of convergent water masses (sinking surface water) (Lebreton et al., 2012). The difference in sea surface height due to this sinking and upwelling can be of up to 1.5 meters, and thus sufficient to induce horizontal pressure gradients, which are counterbalanced by the Coriolis force.

The convergent zones are being fed by major oceanic currents and are highly influenced by the global down-stream effects, such as runoff from rivers (Avery-Gomm et al., 2012). The five gyres, which are subject to this thesis, are defined as major cyclonic surface current systems with a convergent zone (NOAA, 2013b). They are zones of accumulation of flows and have been shown to concentrate a higher abundance of debris (Avery-Gomm et al., 2012; IPRC, 2008; Law et al., 2010). Divergent current systems on the other hand are zones with upwelling of the water and separation of the flows (IPRC, 2008).

In terms of surface currents, there is little exchange between the northern and southern hemisphere. Only in the coastal areas around the equator does an exchange of material happen. Concerning the plastic in the gyres, this underlines the relative importance of intra-gyral inputs and thus the importance of reducing garbage dumping at sea (Wilber, 1987).

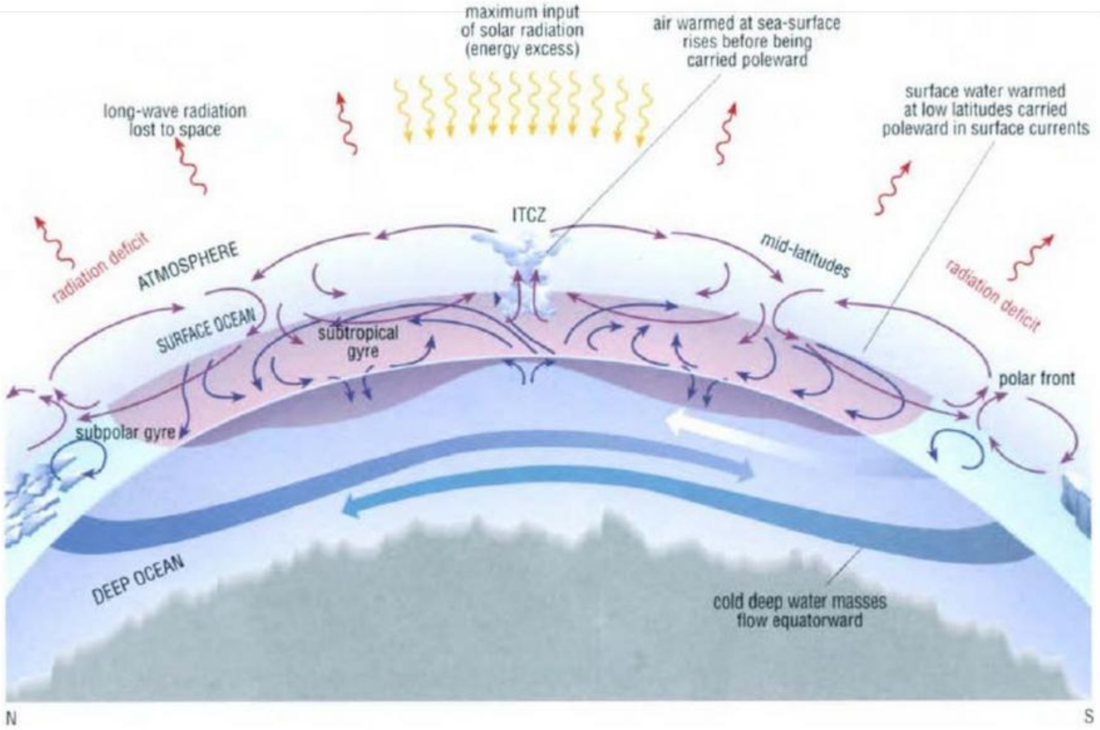

Figure IV.1: Schematic diagram of the three interacting components of the Earth's heat-redistribution system: the wind system, the surface current system and the thermohaline circulation (Colling et al., 2004: 190)

Annex V: Effects of plastic pollution on the marine ecosystem

> "The last fallen mahogany would lie perceptibly on the landscape, and the last black rhino would be obvious in its loneliness, but a marine species may disappear beneath the waves unobserved and the sea would seem to roll on the same as always." (Ray, 1988: 45)

In 1974, W.C. Fergusson, Council of British Plastics, is commonly quoted as having said, "plastic litter […] causes no harm to the environment except as an eyesore" (Derraik, 2002: 2). This view has long been proven to be incorrect, most recently at the discovery of the Great Pacific Garbage Patch in the North Pacific by Charles Moore in the late 1990s. Since Moore's documentation of the vast plastic soup in the ocean, proof for the impact on marine flora and fauna from floating plastic debris has been accumulating. Although it is not the goal of this thesis to evaluate the damage caused by plastic debris in the marine wildlife, it is of merit to give a short summary of the different problems associated with plastic debris and the extent documented thus far. Therefore, the following will briefly present the direct and indirect effects to outline the research made in this area.

The first category of environmental impact is the mechanical threat to wildlife (Derraik, 2002). It is the most widely documented threat in the media: seabirds with stomachs full of plastic items and turtles entangled in fishing nets that got lost at sea. The threat posed by entanglement is straightforward and includes injuries and death due to drowning or not being able to feed. Ingestion, on the other hand, is more complex. Several studies have shown that the ingested plastics are comparable to in size and colouring to the diet of the species as well as their foraging techniques (Derraik, 2002; Ryan et al., 1988). The ingested plastics fill up the stomach and induce a lack of appetite meaning that the animal starves itself (Derraik, 2002). Lack of food in animals does not only induce a lower fat deposition and body weight, but it also influences the ability to travel the long distances to the feeding grounds. Plastic ingestion thus implicitly impacts the fertility of a species (Derraik, 2002)

One of the main uncertainties remaining with assessing the effect of plastics on wildlife lies with the level of exposure to the plastics themselves, the chemicals within and the potentially attracted contaminants and hydrophobic POPs (Science for Environment Policy, 2011; Derraik, 2002). The additives inside the plastics may also be released due to digestion processes inside the stomach (Derraik, 2002). It is estimated that the bioaccumulation through the food chain exposes humans to the highest dose of chemicals, but the degradation process of plastic inside the stomach of the animals needs to be further studied to give proper assumptions on how high the exposure is (Science for Environment Policy, 2011). The extent and potential exponential increase of the problem should, however, not be underestimated as 40% of seabird species and 43% of marine mammal species are documented to be affected by entanglement and ingestion potentially leading to morbidity, mortality and/or population-level effects (Williams et al., 2011).

An indirect effect of plastic in the marine environment is the plastics' ability to attract contaminants, such as hydrophobic POPs, due to the large surface to volume ratio of plastics (Science for Environment Policy, 2011). Concentration of contaminants such as PCBs, DDTs and PAH has been reported to be much higher on the sea surface than in lower levels of the water due to being attached to plastic waste (Teuten et al., 2007). In fact, the concentration of POPs in plastic debris in the Northern Pacific Gyre seems to be of similar extent than in marine sediments (Rios et al., 2010; Rios et al., 2007). Plastic acts both as a sink and as storage of POPs: it lessens the availability of pollutants in the environment, but it also increases the residence time as it inhibits the natural process, making the fate of the pollutants dependent on that of the plastics (Teuten et al., 2007). However, in contrast to POPs in the sediments, the concentration of POPs of a few part per billion (ppb) to thousands of ppb in plastics can be and has been directly taken up by wildlife (Rios et al., 2010). The study further showed that 50% of the plastic debris in the Northern Pacific Gyre contained PCBs, 40% contained pesticides and nearly 80% contained PAHs. Some of the pollutants, such as PCBs, are known to affect the reproductive system of the animals (Derraik, 2002). When analysing plastics on beaches and in stranded albatrosses along the coasts of California, Hawaii and Mexico, Rios et al. (2007) found that polyethylene and polypropylene were the most common types of plastics. This enforces the assumption that thermoplastic resins most commonly used in packaging accumulate more organic contaminants than other plastics (Teuten et al., 2007).

Although the level of toxicity caused by this accumulation is still unknown, several studies have been conducted to determine the dose-response relationship for each type of microplastics. Such experiments in the laboratory can only give limited insight as the impact in real-life will differ with each marine species considering that both bioaccumulation and metabolic degradation patterns vary from species to species (Science for Environment Policy, 2011). Nevertheless, in the long run, the transportation of hydrophobic contaminants by plastic on the sea surface will induce irreversible impacts of which the extent is yet unknown but will involve not only the primary food chain but also shoreline sediments and consequently will continue to be in the food chain long-term (Rios et al., 2007; Teuten et al., 2007; Science for Environment Policy, 2011).

However, drifting plastics do not only attract contaminants, they also act as settling space for marine organisms such as bacteria and algae (Derraik, 2002). The problem associated with this is twofold. First, the plastic is again ingested by species, which do not recognise the threat below their natural hunting ground. Second, plastics act as transportation mode via rafting and introduce alien species to environments where they could potentially destroy the existing ecosystem. This induces a change in the natural habitat due to introduction of alien species (Science for Environment Policy, 2011).

Probably the least researched impact category involves the accumulation of plastics on the sea floor (Science for Environment Policy, 2011; Derraik, 2002). Not all types of plastic are floating and even those who are can sink to the bottom due to fouling mechanisms or ingestion by later on decaying organisms. This potentially releases toxins and other substances to the marine environment to an amount as of yet unknown and little researched. In this case, leaching of plasticizing chemicals is considered one of the main threats to the marine biota (Derraik, 2002). However, plastic accumulation on the sea floor will also inhibit the gas exchange necessary for the sediments to develop. The resulting hypoxia or anoxia in the benthos would disrupt the normal ecosystem functioning at its very basis (Derraik, 2002).

All in all, the negative impacts on the marine ecosystem are by now well documented and the unknowns can only increase the incentive to reduce the inflow to and increase the removal of plastics from the marine environment.

Annex VI: International Legal Framework

The societal awareness of open-ocean and coastal pollution is reflected in the national and international agreements aiming at improving the understanding and regulation of the marine environment. In general, pollution of the marine environment is defined in legal documents according to Art.1(4) of the United Nations Convention on the Law of the Sea (hitherto referred to as UNCLOS) as follows:

> "pollution of the marine environment" means the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities;
> UNCLOS Art.1 (4)

In other words, marine pollution occurs when any substance is introduced in the marine environment, which harms living resources and impairs marine activity. Since human knowledge is limited, the Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) additionally stresses the need for caution in regards to the probability that an act may cause harm to the environment (Molenaar, 1998). The substances and energy are laid down in Art. 1(4) of UNCLOS are further elaborated in the 1974 UN Convention on the Safety of the Life at Sea (hitherto referred to as SOLAS 74) as well as in the International Convention for the Prevention of Pollution from Ships 1973 and its 1978 Protocol (hitherto referred to as MARPOL 73/78). The latter is also the most important convention in terms of plastic pollution and was the starting point of many other national and international acts and regulations (Baztan et al., 2014-in press).

The most general and underlying rule for the protection of the marine environment from said pollution is set out in Part XII of UNCLOS which states that „States have the obligation to protect and preserve the marine environment." (Art. 192 UNCLOS) This general obligation is established as customary international law and supplemented by other duties under environmental law, e.g. prohibition of transboundary harm and the prohibition to transfer pollution from one area to another (Art.195 UNCLOS).

Further, UNCLOS Part XII distinguishes six different sources of marine pollution starting with pollution from land-based sources in Art. 207 and ending with pollution from or through the atmosphere in Art. 212. In the following, the most relevant articles in terms of plastic pollution to the marine environment from ocean-based sources as well as land-based sources will be briefly elaborated.

VI.1 Ocean-based sources

Ocean-based sources in the international conventions usually refer to vessel-sourced pollution. This is due to the fact that ships constitute a specific target at which improvements can be aimed. However, each regulation of ships also includes the issues of territorial limits of the sovereignty and flag state issues.

Pollution from vessels is laid down in Art. 211(1) UNCLOS and includes an obligation for states to "establish international rules and standards to prevent, reduce and control pollution of the marine environment from vessels" (UNCLOS Art. 211 (1)). Further, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the London Convention), adopted in 1972, and its 1996 Protocols, contain the key international rules and standards dealing with dumping. The International Maritime Organisation (IMO) oversees pollution by ships, but, as mentioned above, the enforcement regime is defined for each convention and is limited in its implementation due to issues of state sovereignty as well as economic and technological development of the signatory countries. While UNCLOS differentiates between the different sources of marine pollution in terms of enforcement, MARPOL 73/78 assigns the most rights to the flag state and ship owners (Griffin, 1994). Enforcement regime under MARPOL 73/78 is little comprehensive and mostly provides for flag states to inspect vessels to control that they meet the technical standards set out under the Convention and to monitor discharge standards of ships (Griffin, 1994). The flag state further has the right to punish the violators after investigation and legal proceeding judging the matter and the evidence presented. In regards to the punishment, MARPOL 73/78 clarifies that the punishment has to be made in a justified, adequate and non-discriminatory way (Griffin, 1994). Although the enforcement is under the responsibility of the contracting state in its own territories and in regard to its own nationals and vessels, the enforcement measures can still be rejected by a 2/3 majority or consensus in conservation matters by the Commission (Molenaar, 1998). Despite this weakness, MARPOL and UNCLOS are in a way customary law, since the principle of "no more favourable treatment" allows parties to the treaty to enforce standards on ships of non-party countries once they enter the jurisdiction of the State party.

This question of flag, coastal and port state jurisdiction has been covered in several studies of marine legislation and simultaneously reflects the compromise between environment and trade, between freedom of navigation versus freedom of exploitation and pollution (Tan 2006). In order to find a balance between the interests of maritime trade (flag state) and the marine environment (coastal state), both UNCLOS (Art. 218 and 220) and MARPOL (Art. 6) provide for port-state jurisdiction in terms of inspection rights. The Memoranda of Understanding on Port State Control provides for further monitoring and controlling mechanisms applicable by the port state.

However, the jurisdiction and inspection right is still very limited. Foreign flagged ships are only subject to coastal or port state jurisdiction if the polluting discharge is being made on the territory of the state, within its exclusive economic zone (200 miles offshore). Beyond this zone, the coastal and port states can only report violations to the flag state. This induces two main issues. First, the port and coastal states need evidence of the reported violation when demanding a prosecution by the flag state (Tan, 2006). In order to gain this evidence, they need technical equipment and monitoring devices, which especially the developing countries cannot afford (Tan, 2006). Second, there are no specific guidelines for standards or for the punishment of violations. This means that states wishing to attract a bigger number of vessels might lower their standards. Flags of such low- standard states are usually known as flags of convenience. (Griffin, 1994)

Furthermore, the pollution outside of the exclusive economic zone usually still damages the coastal state. Therefore, the coastal states claimed environmental jurisdiction beyond the usual economic jurisdiction. Flag states, however, were worried to lose their sovereignty if their ships were subject to another nation's jurisdiction. The question really was where to draw the line between a valid environmental reason to break the flag state hegemony and a claim of jurisdiction of a richer or more developed state for political reasons. The compromise in the end was to stipulate (under Art.4 of MARPOL 73/78) that, if international law – and in this case UNCLOS III – would ever change, so would the jurisdiction of the coastal state (Griffin, 1994).

All in all, mitigating marine debris stemming from ships has been comprehensively regulated and is constantly being addressed. Nevertheless, only a small fraction of estimated 20% of marine debris comes from ships (Williams et al., 2011) and it is thus important to see which regulations are in place for land-based activities.

VI.2 Land-based source

On the occasion of the 20th Anniversary of the UNCLOS (UN; Law of the Sea, 2002), the Global Environmental Facility identified pollution from land-based sources as one of the three greatest threats to the world's oceans. This is based on the fact that land-based sources are first of all responsible for vast majority of the pollution and secondly affect the most productive areas thus having the biggest impact all in all. The Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (GPA) covers land-based activities. As land-based sources are under national sovereignties and considered to be more or less a localised issue, the main legal instruments are regional and specific marine environment relating ones rather than global conventions. For example, the main legal instruments governing pollution of the Mediterranean Sea by land-based discharges are the Barcelona Convention for the Protection of the Mediterranean Environment and the Coastal Region of the Mediterranean 1976, amended in 1995, and the Protocol for the Protection of the Mediterranean Sea against Pollution for Land-Based Sources and Activities 1980, amended in 1996.

The only international convention implicitly covering marine pollution from land-based activities is the Basel Convention on the Control of Transboundary Movement of Hazardous Waste and their Disposal 1989, hitherto referred to as the Basel Convention, and the London Convention 1972. The former prohibits disposal and transport of waste from one country to another and specifically from developed to developing. The impact in terms of plastic pollution of the Basel Convention lies mainly in the order of secondary wastes. If plastic is not transferred to countries with less efficient waste management systems, then the extent of plastics reaching the ocean may be reduced. The London Convention, on the other hand, prohibits dumping of waste at sea except for a small group of wastes such as sea-based fishing activities (Johnson, 2007). In fact, the London Convention was first based on the premise that dumping is permitted unless explicitly forbidden, which reflected a need to prove negative impact of the dumped substance. Nowadays, the prove needs to be given that the waste will not have an impact, which is a big step forward

(Johnson, 2007). All in all, there Is little legislation governing land-based pollution and waste especially as the international custom of State sovereignty is the main applicable law and is only restricted by often ignored precautionary principle (Johnson, 2007).

VI.3 The Conventions

United Nations Convention on the Law of the Sea, 1982
Entry into force: 16 November 1994

International Convention for the Safety of Life at Sea, 1974, as amended (SOLAS (amended) 1974)
Entry into force: 25 May 1980

International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL (amended) 73/78)
Entry into force: 2 October 1983
Annex I 2 October 1983
Annex II 6 April 1987
Annex III 1 July 1992
Annex IV 27 September 2003
Annex V 31 December 1988

Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL PROT 1997)
Annex VI on the Prevention of Air Pollution from Ships
Entry into force: 19 May 2005

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972
Entry into force: 30 August 1975

Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter, 1996
Entry into force: 24 March 2006

Barcelona Convention for the Protection of the Mediterranean Environment and the Coastal Region of the Mediterranean 1976, amended June 1995
Entry into force: 12 February 1978

Protocol for the Protection of the Mediterranean Sea against Pollution for Land-Based Sources and Activities 1980, amended March 1996
Entry into force: 17 June 1983

Basel Convention on the Control of Transboundary Movement of Hazardous Waste and their Disposal, 1989
Entry into force: 5 May 1992