ARTICLE IN PRESS

Marine Pollution Bulletin xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

# The influx of marine debris from the Great Japan Tsunami of 2011 to North American shorelines☆

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ARTICLE INFO

*Keywords:*
Marine debris
Japanese tsunami
Shoreline monitoring
Ocean drift model
North Pacific

ABSTRACT

Marine debris is one of the leading threats to the ocean and the Great East Japan Earthquake and tsunami on March 11, 2011 washed away an estimated 5 million tons of debris in a single, tragic event. Here we used shoreline surveys, disaster debris reports and ocean drift models to investigate the temporal and spatial trends in the arrival of tsunami marine debris. The increase in debris influx to surveyed North American and Hawaiian shorelines was substantial and significant, representing a 10 time increase over the baseline in northern Washington State where a long term dataset was available. The tsunami event brought different types of debris along the coast, with high-windage items dominant in Alaska and British Columbia and large, medium-windage items in Washington State and Oregon. Recorded cumulative debris landings to North America were close to 100,000 items in the four year study period. The temporal peaks in measured shoreline debris and debris reports match the ocean drift model solutions. Mitigation and monitoring activities, such as shoreline surveys, provide crucial data and monitoring for potential impacts should be continued in the future.

## 1. Introduction

Marine debris is an important threat to ocean diversity and health (Sutherland et al., 2010). It is a global problem that can have intense local impacts on wildlife, human health, aesthetic values, and the economy (Coe and Rogers, 1997; Criddle et al., 2009; Derraik, 2002; Gall and Thompson, 2015). The emergence and persistence of plastic as marine debris has increasing risks from entanglement, ingestion, provision of new surfaces for colonization, rafting, effects of microplastics and associated chemical contamination (Gregory, 2009; Gall and Thompson, 2015). The source of marine debris is generally difficult to trace making it challenging to mitigate and control (Ryan et al., 2009).

The Tohoku Earthquake in Japan and resulting tsunami washed an estimated 5 million tons of debris into the Pacific Ocean (Ministry of the Environment, Japan, 2012). This single event delivered an amount in the range of the global debris input to the ocean each year and more than any single country, other than China, was estimated to produce in a whole year (Jambeck et al., 2015). Marine debris associated with this unique natural history event differs from general marine debris because the source and date of dislodgment or entry into the ocean are both known and fixed. While general artificial marine debris is dominated by relatively small plastic items (fishing nets are an exception), tsunami debris included large items, such as lumber and other construction materials from broken homes as well as large objects, as ships and floating docks. Additionally, the predominant drift in the North Pacific is eastward toward the Pacific coast of North America and the Hawaiian Islands (Howell et al., 2012) and drift can be modeled to estimate the spatial and temporal trends in shoreline interception (Bagulayan et al., 2012). The first confirmed tsunami debris item to be found on shore, a soccer ball, landed in Alaska in March 2012 (NOAA Marine Debris Program, 2015). Anecdotal reports and documented sightings suggest that the influx of marine debris in the years after the tsunami was substantial and unprecedented but there have been no attempts to measure and analyze the amount of incoming debris. Large debris items (e.g. vessels, floating docks) present a hazard to navigation and may act as floating islands that carry fouling and hitchhiking organisms that

☆ This is one of the papers from the special issue of Marine Pollution Bulletin on "The effect of marine debris caused by the Great Tsunami of 2011." The special issue was supported by funding provided by the Ministry of the Environment of Japan (MOE) through the North Pacific Marine Science Organization (PICES).

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https://doi.org/10.1016/j.marpolbul.2018.01.004
Received 20 April 2017; Received in revised form 5 December 2017; Accepted 2 January 2018

pose a risk to native ecosystems. Smaller debris items (e.g. lumber and building material) are more difficult to trace but the type of debris from the tsunami is generally different than baseline marine debris.

Monitoring and removal of shoreline debris in North America has been ongoing since the 1990s (Ribic et al., 2012; Morishige et al., 2007). After the tsunami occurred, sightings of debris were recorded and if possible, traced to the original owner and confirmed as lost during the tsunami. In the wake of the 2011 tsunami, this ongoing research provides an opportunity to analyze the landing and trends in amount of marine debris. Quantifying and categorizing the influx of tsunami-associated debris will assist in the prioritization of research on marine debris impacts, document impacts to wildlife and ecosystems, optimize clean ups and removal activities and investigate the potential for the introduction of invasive species.

Here we analyze available data on the landings of debris on North American and Hawaiian shorelines in order to 1) quantify the amount, distribution and timing of debris landfall, 2) estimate debris landfall attributable to the 2011 tsunami and 3) compare to oceanographic modeling predictions. In short, we ask whether we can we detect the signal of the tsunami debris against the background of ongoing marine debris and generalize sparse observational reports into a bigger picture of the event.

## 2. Materials and methods

### 2.1. Shoreline monitoring

The ongoing NOAA marine debris shoreline survey is a rapid, quantitative beach survey which uses trained community volunteer organizations to collect standardized and consistent data. NOAA's current shoreline Marine Debris Monitoring and Assessment Project (MDMAP) began in 2011 and continues through the present (Lippiatt et al., 2013). The MDMAP accumulation survey protocol measures the net accumulation of all types of marine debris items on a site's 100 m stretch of beach every 28 days. All debris items are recorded and removed from the shoreline. Surveys were conducted by citizen science groups or government staff and depending on weather and tides, the amount of beach and monthly schedule sometimes varied (Opfer et al., 2012). For each survey, the incidence of large items (> 30 cm) was specifically recorded and additional information and photos of the items were provided by surveyors. Between March 2012 and December 2015, over 1100 surveys have been conducted at > 120 sites in Alaska, British Columbia, Washington, Oregon, California and Hawaii. The NOAA dataset was analyzed for trends in distribution and abundance of debris influx and type over time and along the Pacific coast of North America and the islands of Hawaii.

Long-term spatially distributed marine debris monitoring datasets are rare so a dataset maintained by Olympic Coast National Marine Sanctuary (OCNMS) was used to establish a baseline of marine debris influx prior to the tsunami event. This survey protocol recorded marine debris indicator items at sites in northern Washington State from 2001 to 2011. All debris was removed from a 500 m stretch of beach at each site and the number of debris items in each of the 30 indicator categories was recorded (Supplementary Materials). Indicator items were chosen to represent different sources of debris (land, ocean and general source debris); the pre-2011 National Marine Debris Monitoring Program (NMDMP) protocol is described in more detail by Ribic et al. (2012).

In order to compare baseline debris influx with that after the tsunami event, we compared the two sets of debris categories and removed or combined categories and the data contained within as needed (see Supplementary Materials). The level of effort is consistent across both formal monitoring programs (MDMAP and NMDMP) as all items of interest from the survey area were recorded regardless of the number of surveyors. The NOAA MDMAP protocol records information on a more diverse set of debris items; only those fields that overlap with the NMDMP protocol were compared (Supplementary Table 1). We identified common sites between the two survey timelines, and then analyzed the spatial and temporal trends in marine debris influx. In total, 47 beaches were surveyed and 11 NMDMP sites continued to be surveyed with the new protocol (see Supplementary Materials). The mean number of debris items recorded per 100 m stretch of beach per day was analyzed and ANOVA with Tukey's b post-hoc statistical test used to test for differences between years and states or provinces. Spatial autocorrelation was investigated using Moran's $I$ in ArcMap 10.1 (Environmental Systems Research Institute, Inc., Redlands, CA: 2010).

After the 2011 tsunami occurred, NOAA established a reporting system for public sightings of suspected tsunami debris items. Reports were received by email and maintained in a database, hereafter referred to as “disaster debris reports”. Records as of April 13, 2016 were analyzed for temporal and spatial trends and compared to the shoreline monitoring results. Confirmed tsunami debris items were those with identifying marks that could be traced to items known to be lost during the tsunami event, through diplomatic channels.

### 2.2. Modeling tsunami debris

Simulations with the Surface Currents from a Diagnostic (SCUD; Maximenko and Hafner, 2010) model were used to study particle and tracer motions after release on March 11, 2011 along the east coast of Honshu, Japan. SCUD is an empirical, diagnostic model, developed at the International Pacific Research Center, University of Hawaii and forced with data from satellite altimetry (sea level anomaly) and scatterometry (vector wind). The model is calibrated on a 1/4-degree global so that it reproduces trajectories of historical satellite-tracked drifting buoys. To include into consideration various types of debris a fraction of wind velocity, described by the windage parameter, was added representing the direct effect of the wind on items floating on the ocean surface. Model experiments used 61 values of windage ranging between 0 and 6%. In this paper we compare the monthly model predictions to observations of debris influx during the shoreline surveys and the sightings reported using Spearman's rank correlations.

## 3. Results

### 3.1. Debris monitoring

The debris landings after 2013 were significantly different than 2012 and prior (One-way ANOVA, F = 3.992, df = 12, $p < 0.001$) (Fig. 1). There was a sharp increase in the influx of indicator debris items, from mean 0.03 items per 100 m of shoreline per day between 2003 and 2012 to mean 0.29 debris items per 100 m per day from 2013 to 2015. This is an almost ten-fold increase in debris influx to sites in northern Washington State over that recorded in the nine year period prior to the tsunami event. Prior to the peak in indicator debris items (May 2012), monthly mean debris influx ranged from 0.01 to 0.08 indicator debris items per 100 m per day and after the peak indicator debris influx ranged from 0 to 0.78 debris items per 100 m per day (Fig. 2).

Across the West Coast of the US (Washington State, Oregon and California), there were peaks in all debris items (not just indicator items) in June 2012, March 2013, and smaller peaks in May 2014 and late 2014 (Fig. 2). Across all North American study sites, the recorded mean debris influx peaked in July 2012 at 13.8 debris items per 100 m per day. Mean monthly debris influx for all debris items (2012–2015) was 2.7 debris items per 100 m per day (ranged from 0.5 to 13.8 debris items per 100 m per day).

Across all the states and provinces of study, Hawaii, USA received the highest mean debris items over the post-tsunami study period (2012–2015) (Fig. 3). British Columbia, Canada has the second highest mean debris influx in this time period, driven by a few surveys in the islands of Haida Gwaii (northern BC) with high numbers of large