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A Targeted Health Risk Assessment Following the *Deep Water Horizon* Oil Spill: Polycyclic Aromatic Hydrocarbon Exposure in Vietnamese-American Shrimp Consumers

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Competing financial interests: Daniel Nguyen and Tap Bui are members of the Vietnamese-American community under study and are employees of Mary Queen of Vietnam Community Development Corporation (MQVNCDC), a non-profit organization, that was involved in assisting the short-term and long-term needs of fisherfolk affected by the Deep Water Horizon oil spill. No fees were charged by MQVNCDC to any person seeking assistance and MQVNCDC had no vested financial interest based on the total number of claims from the community. The other authors declare they have no actual or potential competing financial interests.

Abstract

Background: The *Deep Water Horizon* oil spill of 2010, prompted concern about health risks among seafood consumers exposed to polycyclic aromatic hydrocarbons (PAHs) via consumption of contaminated seafood.

Objective: To conduct population-specific probabilistic health risk assessments based on consumption of locally harvested white shrimp (*Litopenaeus setiferus*) among Vietnamese-Americans in Southeast Louisiana.

Methods: We conducted a survey of Vietnamese-Americans in Southeast Louisiana, to measure shrimp consumption, preparation methods, and bodyweight among shrimp consumers in the disaster-impacted region. We also collected and chemically analyzed locally harvested white shrimp for 81 individual PAHs. We combined the PAH levels (with accepted reference doses) found in the shrimp with the survey data to conduct Monte Carlo simulations for probabilistic non-cancer health risk assessments. We also conducted probabilistic cancer risk assessments using relative potency factors (RPFs) to estimate cancer risks from the intake of PAHs from white shrimp.

Results: Monte Carlo simulations were used to generate hazard quotient distributions for non-cancer health risks, reported as mean ± standard deviation, for naphthalene ($1.8 \times 10^{-4} \pm 3.3 \times 10^{-4}$), fluorene ($2.4 \times 10^{-5} \pm 3.3 \times 10^{-5}$), anthracene ($3.9 \times 10^{-6} \pm 5.4 \times 10^{-6}$), pyrene ($3.2 \times 10^{-5} \pm 4.3 \times 10^{-5}$), and fluoranthene ($1.8 \times 10^{-4} \pm 3.3 \times 10^{-4}$). A cancer risk distribution, based on RPF-adjusted PAH intake, was also generated ($2.4 \times 10^{-7} \pm 3.9 \times 10^{-7}$).

Conclusions: The risk assessment results show no acute health risks or excess cancer risk associated with consumption of shrimp containing levels of PAHs detected in our study, even among frequent shrimp consumers.

Introduction

On April 20, 2010, a large explosion on the *Deep Water Horizon* (DWH) drilling rig initiated nearly three months of continuous petroleum and chemical contamination flow into the waters of the Gulf of Mexico. By July 15, 2010, approximately 205 million gallons of crude oil had entered the northern Gulf of Mexico (Griffiths 2012; McNutt et al. 2012; USCG 2011). Efforts to dissipate the oil resulted in the environmental application of approximately 2 million gallons of chemical dispersants (USCG 2011). The catastrophe spurred widespread concern about health risks associated with consumption of spill-related contaminated seafood. Concern was driven by many factors including the state and federal closure of fisheries from May through late August 2010 in the areas under study due to the actual or anticipated presence of oil, extensive media coverage coupled with high levels of scientific uncertainty, and potential impacts on marine ecosystems, the coastal economy, and human health. Additionally, public worry regarding the ecological and human health impacts of the spill was often exacerbated due to conjecture, biased information, and misinformation, as well as a lack of information and debate among experts. Knowledge gaps were often reinforced or erroneously filled by commercial and social media. (Alexander-Bloch 2012; Dhar 2012) Within impacted Gulf coastal communities, such dynamics contributed to a substantial lack of trust in information from industry and government agencies. This distrust fed claims from various quarters that the risk assessment process employed by federal and state regulatory agencies in the Gulf oil spill disaster was neither transparent nor inclusive of specific community concerns.

Many members of the Vietnamese-American communities in the Gulf coast region are directly involved in the seafood industry. Many, if not most members of this community have historically been or are now actively engaged in commercial shrimping or fishing as their primary source of income. Vietnamese-Americans comprise 1.9%, 4.4%, 1.1%, 1.4%, and 3.0% of the total populations of Louisiana, Texas, Mississippi, Alabama, and Florida respectively (Hoeffel et al. 2012). Shrimp are not only of great economic importance to Gulf coast Vietnamese-Americans, but they are also the principal seafood type consumed by this group as well as many other coastal populations. Thus, the DWH oil spill greatly impacted the Vietnamese-American community by affecting their economic stability and potentially increasing health risks associated with consuming petroleum-contaminated shrimp.

Federal government agencies including the U.S. Food and Drug Administration (FDA) and the National Oceanic and Atmospheric Association (NOAA) were lead organizations tasked with reopening commercial fisheries in the oil-affected areas (FDA 2010). This process involved a stepwise screening of finfish, shrimp, crab, and oysters in order to determine when a fishery would be deemed safe to reopen. The first step, organoleptic testing, required the expertise of trained chemosensory testers. Organoleptic testing identified, through scent, any residual petroleum taint in seafood that may render it unsafe for human consumption. Failure to pass organoleptic screening resulted in continued fishery closures. If no petroleum scent was detected, the seafood was subjected to further testing by chemical analysis for specific oil toxicants including polycyclic aromatic hydrocarbons (PAHs). PAHs are assumed to be the primary toxicants in crude oil that may contaminate seafood which might then pose a health risk when consumed. If the levels of 13 of the 16 priority PAHs used in health risk assessments did not reach or exceed FDA-determined consumption levels of concern (LOCs), the fisheries were reopened (FDA 2010).

LOCs for anthracene, phenanthrene, fluoranthene, fluorene, naphthalene and pyrene, PAHs which are not considered carcinogens, were calculated using a safety threshold known as a reference dose (FDA 2010). A reference dose is based on an assumed daily exposure that does not pose a significant non-cancer risk to health over an entire lifetime. LOCs for the remaining 7 priority PAHs that are considered carcinogens were calculated by using a relative potency factor (RPF) approach as described by the U.S. Environmental Protection Agency (EPA) (USEPA 1993b). Under this protocol, shrimp consumption was assumed to be 13 grams of shrimp per day, which was taken from the 90^{th} percentile of the National Health and Nutrition Examination Survey (CDC 2003), and bodyweight was assumed to be 80 kilograms. An acceptable risk level of 1×10^{-5} was used as the basis for the FDA and NOAA cancer risk LOC calculation (FDA 2010). Lifespan, or the cancer risk averaging time was assumed to be 78 years, and the exposure duration was assumed to be 5 years (FDA 2010). The 90^{th} percentile NHANES seafood consumption rate and standard bodyweight assumptions used in the FDA health risk advisory and reopening guidelines are likely protective for the vast majority of Americans but by definition they exclude the highest 10% of seafood consumers. Because this sub-population has the highest exposure potential, some argue that it should be the primary target for risk assessments (Rotkin-Ellman et al. 2012).

There has been ongoing debate in the scientific literature and media regarding the FDA’s parameter assumptions for seafood consumers and apparent exclusion of sensitive subgroups (Rotkin-Ellman et al. 2012). Our data confirms that the Vietnamese-American population in eastern New Orleans, LA, represents a particularly vulnerable subgroup that not only eats substantially more shrimp than the NHANES estimates, but their average bodyweight is also significantly less than the average standard bodyweight of 80 kilograms.

To address these possible shortcomings, we estimated health risks following both deterministic and probabilistic approaches using chemical analysis of locally harvested shrimp and household survey data collected from a random sample of adult Vietnamese-Americans who work in the local seafood industry. The research design for our study embedded members of this community in the entire process - from problem formulation to sample collection and communication of risk assessment results following a Community-based Participatory Research (CBPR) model (Brown et al. 2012). It is the only DWH-related study published to date to use community-specific data including shrimp consumption habits and body weights to parameterize the risk models along with chemical analyses of white shrimp (*Litopenaeus setiferus*) collected from sites that commercial shrimpers in this community traditionally use. Probabilistic risk modeling using Monte-Carlo simulations of community-specific data also allows us to address issues of uncertainty and variability not discussed in previous risk-related studies regarding the DWH event. Using this probabilistic framework, we also explored modeled consumption health risks with increasing numbers of PAH analytes to more fully explore and account for where and under what circumstances unacceptable risks may exist (Wickliffe et al. 2014). Some of our assumptions, especially those regarding multiple PAH carcinogenicity, have not yet been scientifically investigated, but we speculate that concerns regarding health risks from the increasing numbers of PAH compounds examined will be raised in future work especially considering research and regulation of oil spills in marine environments and seafood safety (Wickliffe et al. 2014). We discuss this in more detail below and present the results of our community-specific risk analysis and characterization and details of our CBPR-designed approach.

Methods

Our study design was tailored around a community-based approach, which began with a series of discussions with community organizers, shrimpers, and the larger Vietnamese community. These meetings were ongoing through the summer and early fall of 2010 and were used to determine the objective of our study, comparative research design, methods for harvesting and sample preparation, and to identify and involve the assistance of six community investigators. The decision to focus on Gulf white shrimp – the primary type of seafood consumed in this community - emerged from a large community meeting with over 50 residents in attendance. Sites for sample collection were worked out among a smaller core group involving Wickliffe, Frickel, and six community investigators. These sites were chosen specifically because they are where shrimpers from this community have traditionally harvested shrimp. This was deemed important because the locally caught shrimp was the most likely to be consumed by these community members.

Sample collection

White shrimp were collected from two areas. Samples from 2 nettings were collected inshore in an area that was not oil impacted (not closed) on 11-November-2010, along a 2 km transect (29.988096, -89.931829; 29.996385, -89.917538) on a commercial shrimping vessel equipped with a skimmer. Samples were also collected offshore in an area in the Chandeleur Sound that was oil impacted and closed. The samples from the offshore location were collected after the fishery had been officially reopened. Samples from 6 nettings were collected in this area on 17-November-2010, along a 25 km transect (30.044133, -89.077835 to 29.833496, -89.125214) on a commercial shrimp trawler. Randomly selected shrimp (n = 5-10) from each netting were batched, immediately wrapped in aluminum foil, placed inside a plastic freezer bag, and iced. Five to ten batches were collected from each netting. Shrimp were returned to the laboratory within 12-24 hour of collection and transferred to a -80°C freezer for storage until analysis. Shrimp tissue samples consisting of tail muscle (abdomen) without shell were composited to yield a minimum of 20 g of material for chemical analysis. Multiple composites (n = 3) from each netting were sent for analysis.

Chemical analysis

Quantitative PAH analysis was used to determine the quantities of 81 individual PAHs in extracts of shrimp abdominal tissue (see Supplemental Material, "List of all PAH analytes included in chemical analysis"). PAH analysis was performed using gas chromatography/mass spectrometry (GC/MS) in selected ion monitoring (SIM) mode. Method detection limits for PAHs using this method were extremely low (< 10 ng/wet g for tissue).

The GC was temperature programmed, operated in splitless mode, and carrier flow was by electronic pressure control. The capillary column was a J&W DB-5MS© (60 m long by 0.25 mm ID and 0.25 mm film thickness) or equivalent. The data acquisition system allowed for continuous acquisition and storage of all data during analysis and was capable of displaying ion abundance versus time or scan number. A sample batch was analyzed as an analytical set including samples along with the following specified quality control samples: method-blank, matrix-spike, duplicate, matrix-spike duplicate, and standard reference material. A calibration curve was established by analyzing five individual calibration standards (analyte concentrations ranging from 0.02 to 1 mg/mL). An individual relative response factor (RRF) for each analyte of interest was determined at all five calibration levels. A mean RRF was calculated as the average of each of the five calibration level RRFs. Calibration check standards were interspersed throughout an analytical batch in order to insure the instrument's integrity. A diluted oil standard was used as a retention index solution for compounds not found in the calibration solution. Analyte concentrations were determined using the internal standard method and analyte concentrations were corrected for surrogate recovery. Analyses were performed by TDI-Brooks International (College Station, TX, USA).

Community survey

To better understand how the DHW impacted shrimp consumption patterns and potential health risks among shrimp consumers in southeastern Louisiana, we surveyed Vietnamese-American adults working in the seafood industry, primarily in the shrimping sector. The Vietnamese Community Seafood Consumption Survey is a telephone and online survey designed by the research team (including community participants) in collaboration with staff from the Social and Economic Sciences Research Center (SESRC) at Washington State University. Washington State University Office of Research Assurances determined that the study design satisfied the criteria for Exempt

Research at 45 CFR 46.101(b)(2) and SESRC implemented the survey in April – June 2012.

The sampling frame consisted of 375 Vietnamese adult men and women, including members in the same households, who had sought assistance from the Mary Queen of the Vietnam Community Development Corporation (MQVN-CDC) in filing claims for economic losses in the weeks and months following the DWH. MQVN-CDC provided our research team with a list of names and contact information for these assistance-seekers, who were most likely to have direct economic ties to the seafood industry, for example as fishermen, shrimpers, deck hands, or dock workers. This is not, therefore, a general population survey of the affected community, but rather a targeted survey of the most economically vulnerable segment of the affected community.

Personalized letters of notification describing the survey were printed in Vietnamese and English and sent to all potential respondents. These letters were followed by a telephone survey conducted in Vietnamese by Vietnamese-speaking interviewers conversant in the local dialect or in English as preferred by respondents. Respondents could also opt to complete the survey online in Vietnamese or English. The data collection process utilized Tailored Design Method (TDM) principles to maximize respondent comprehension and ease navigation with the interview (Dillman et al. 2009). All respondents gave prior informed consent in accordance with Institutional Review Board (IRB) regulations. Respondents were not compensated for their participation.

The survey consisted of 32 items. The questions were designed to collect information about respondents' and their families' consumption of shrimp before, during, and after the DWH. Respondents were asked how often they and their families ate locally harvested shrimp, whether the consumed shrimp were subsistence-caught or store-bought. The survey also included questions about portion size, preparation methods, perceived risks associated with eating shrimp, and demographic information on respondents' gender, age, weight, and ages of other family members. Health risk related to shrimp consumption was explored due to shrimp being the primary seafood our study population consumed. Furthermore the study population expressed concern over whether or not gulf shrimp was contaminated or unhealthy following the DWH event. Overall, 115 respondents fully completed the interview and 2 respondents partially completed it. This completion resulted in a response rate of 38.9%.

Interview response data was entered directly into a database by a computer assisted telephone interviewing program (VOXCO Interviewer, Montréal Canada). SESRC staff then checked the data for record accuracy and imported it into Statistical package for the social sciences (SPSS) for generation of summary statistics for each question.

Risk assessment model input parameter distributions

The Microsoft® Excel Add-In @Risk version 6.01 (Palisade Corporation, Ithaca, NY) was used for distribution fitting, fit testing, probabilistic risk assessments, and sensitivity analyses.

Bodyweight

The distribution of bodyweight among the respondents was modeled using normal, log-normal, and Pearson 5 distributions. Goodness-of-fit testing and fit ranking were carried out using a log-likelihood approach and Bayesian Information Criteria.

Intake rate

The shrimp intake rate (grams shrimp consumed per day) was calculated for each respondent (Equation 1):

g. shrimp consumed/day = (#shrimp/shrimp meal)(g. shrimp/#shrimp)(#shrimp meals/week)(1 week/7 days) [1]

The number of shrimp consumed per meal and the number of shrimp meals per week were taken directly from the survey responses. This approach allows for the calculation of individual intake rates that take into account the consumption patterns of each individual respondent. The mass (grams) of shrimp consumed was based on the survey responses for both the number and size of shrimp consumed per meal. Commercial size classifications for shrimp were used to generate a conversion factor to determine the number of shrimp per gram of shrimp. The frequency of shrimp consumption or intake rate was converted into shrimp consumed per day in grams using the information in Supplemental Material, Tables S1 and S2.

The distribution of shrimp intake rate was based on the individual survey responses and was modeled using Weibull, log-normal, and Pearson 6 distributions. These were compared and ranked in the same manner as bodyweight distributions.

PAH concentrations in shrimp tissue

The concentration of individual PAHs in the shrimp samples was assumed to be log-normally distributed. Log-normal distributions, based on detected mean and standard deviation values for each individual PAH, were used to model PAH concentrations. All

PAHs that were below the method limit of detection (MDL) were conservatively assumed to be present at the limit of detection/$\sqrt{2}$ (LOD/$\sqrt{2}$).

Exposure duration

The exposure duration was assigned a uniform distribution with a range from 5-10 years. This distribution was used as a parameter in the probabilistic cancer health risk assessments. The non-cancer health risk assessment process does not include the 5-10 year exposure duration; rather it assumes a continuous exposure over a lifetime (78 years).

Risk assessment

Non-cancer health risk

First a non-cancer risk assessment using the reference dose method was carried out using the chemical analysis data and consumption and bodyweight parameters from the survey.

These data were used to generate the average daily PAH intake from shrimp consumption:

$$\text{Average daily intake} = (PAH_i \times IR) / (BW \times CF), \quad [2]$$

where PAH_i is the concentration in ppm (mg of an individual PAH per kg shrimp), IR is the average shrimp intake rate from the survey data, BW is the average bodyweight from the survey data, and CF is a conversion factor (1000 g shrimp/kg shrimp).

Non-cancer health risk was expressed as a hazard quotient (HQ):

$$HQ = \text{Daily intake} / RfD. \quad [3]$$

Hazard quotients exceeding 1 indicate the specific PAH or PAHs for the same non-cancer effect may pose an unreasonable health risk. Hazard quotients were calculated as the mean and the 95th percentile of the daily intake distribution generated by running a Monte Carlo analysis based on the distributions of the input variables for 10,000 iterations. PAHs with accepted USEPA RfDs were included in the non-cancer risk assessment. These were Naphthalene, Flourene, Anthracene/Phenanthrene, Pyrene, and Flouranthene (USEPA 1990a, b, 1991, 1993a, 1998). Alkylated homologues were assumed to have the same toxicity as the parent PAH and were included in the total PAH concentration.

Cancer health risk

<u>Relative potency factor (RPF) adjusted B[a]P equivalents</u>

A value of LOD/√2 was assigned to each carcinogenic PAH (cPAH) with an accepted RPF to provide a conservative, quantitative measure for estimating cancer health risks due to PAH exposure.

USEPA RPFs were used to calculate the B[a]P equivalent adjusted cPAH concentrations in the shrimp samples (see Supplemental Material, Table S3).

The total B[a]P equivalent concentration was calculated as the sum of the RPF-adjusted concentrations of each cPAH in μg /kg shrimp. No cPAHs were detected in any of our shrimp samples (Method Detection Limit (MDL) for each cPAH < 10 ng/g shrimp). The calculated B[a]P equivalent value was based on the assumption that these PAHs were present at LOD/√2. For the 7 cPAHs the calculated value is 0.668 μg B[a]P equivalents/kg shrimp.

Monte Carlo simulations were performed using the distributions generated from the survey data as model parameters and the B[a]P equivalent concentrations assumed to be present in our shrimp. Cancer risk over a 78-year lifespan (28,470 days) was calculated using equation 4 as a basis:

$$\text{Risk} = [\{(\text{mg B[a]P}_{eq}/\text{Kg shrimp}) \times (\text{kg shrimp consumed/day}) \times (365 \text{ days/year}) \times \text{years exposed}\} / (\text{kg body weight} \times 28{,}470 \text{ days})] \times \text{oral slope factor} \quad [4]$$

A conservative assumption of daily (365 days per year) exposure was used.

Exposure duration was modeled as a uniform distribution ranging from 5-10 years. Bodyweight was modeled using a truncated normal distribution to avoid unrealistically low (e.g. ≤ 0 kg) or high (e.g. ≥ 250 kg) values based on the survey data. A 78-year life span was assumed for all calculations. The standard EPA oral slope factor for B[a]P of 7.3 $(\text{mg/kg-day})^{-1}$ was used (USEPA 1994). A total 10,000 simulations was used to generate the cancer risk output distributions. Three iterations of risk distributions were calculated using the LOD/$\sqrt{2}$ value of the seven cPAHs followed by the addition of RPF adjusted unalkylated and finally alkylated PAHs as a basis.

Results

Chemical analysis

Eight PAHs, including alkylated and unalkylated forms, were present at or above the method limit of detection (quantitation limit 1-10 ng of specific PAH/g of shrimp tissue). Six detected PAHs (Figure 1), Naphthalene, Biphenyl, Dibenzofuran, Phenanthrene, Pyrene, Perylene, are classified as suggestive evidence of carcinogenic potential, USEPA

Class D carcinogens, IARC Group 3 carcinogens, or as USEPA class C, or IARC Group 2B carcinogens(IARC 1987, 2002; USEPA 1990c, d, 1991, 2013). Two specific alkylated PAHs (Figure 1), 2-methylNaphthalene and 1-methylPhenanthrene, were found at or above the MDL. No currently accepted RPFs are available for these chemicals.

There was no statistically significant main effect of inland vs. offshore location by 2 way ANOVA ($p > 0.5$). Further analysis by Bonferoni post hoc tests revealed small but significant differences among the individual PAHs. Naphthalene ($p < 0.01$) and 2-Methylnapthalene ($p < 0.001$) were significantly higher in the inland samples. Biphenyl, Dibenzofuran, Phenanthrene and 1-Methylphenanthrene were not significantly different between the two locations ($p > 0.05$). Pyrene ($p < 0.001$) and Perylene ($p < 0.001$) were significantly higher in the offshore samples. The magnitude of all detected PAHs was very small, less than 2 ppb, so care must be taken when ascribing biological meaning to these very small but statistically significant differences. We chose to combine the inland and offshore data to represent not only the shrimp that could be potentially consumed by our study population but also in order to include more detected PAHs in our health risk assessments.

Findings from the community survey

The overall survey response rate was 38.9% (n=115 completed surveys). Data from The Vietnamese Community Seafood Consumption Survey reveal the average bodyweight in the survey population to be 63 kg (67.5 kg for males, 58.9 kg for females) (Supplemental Material, Figure S1). The estimated average shrimp intake rate is 45.2 g/day (95% CI +/- 12.32 g/day). Shrimp are most frequently boiled (Supplemental Material, Figure S2). Medium to large shrimp are the preferred size range (Supplemental Material, Figure S3).

Ten to fifteen shrimp per meal is the most frequently consumed meal size (Supplemental Material, Figure S4) and shrimp meal frequency is several times per week (Figure 2).

Non-cancer risk assessment

Hazard quotients were calculated using the arithmetic mean and 95th percentile consumption rates (Table 1). No levels of PAHs in the shrimp samples are anticipated to correspond to increased health risk after consumption, even at the 95th percentile estimate of consumption.

Cancer risk assessment

The modeled mean cancer risk levels from both deterministic and probabilistic models for the seven canonical cPAHs were an order of magnitude below a risk level of 1 x 10^{-6} including risk levels from the probabilistic risk distribution out to the 95th percentile (Figure 3A). However, when the remaining unsubstituted PAHs from the list of analytes are conservatively assigned an RPF of 1 and included in the analysis the mean and 95th percentile risk levels meet or exceed 1 x 10^{-5} (Figure 3B). The addition of the alkylated PAHs, again with an assumed RPF of 1, increased the calculated mean and 95th percentile risk level by a factor of approximately 1.5 (Figure 3C). This demonstrates that the cancer risk estimates must increase as the list of PAH analytes used as the basis for the risk calculation is expanded to include unalkylated and alkylated PAHs (Table 2).

Discussion

Following the DWH oil spill event questions arose from diverse sources regarding how inclusive, and ultimately protective, the health risk assessment process used by FDA and NOAA actually was (Rotkin-Ellman et al. 2012; Ylitalo et al. 2012). A primary concern centered on the exposure metrics used by these agencies which some felt did not account for the substantial quantities of seafood consumed by Gulf coast residents who live in areas and/or work in occupations directly affected by the oil spill (e.g. commercial shrimpers) (Rotkin-Ellman et al. 2012). The Vietnamese community in eastern New Orleans, LA, exemplifies one such community. These residents' comparatively low body weights and high levels of seafood consumption, especially shrimp consumption, make this community particularly vulnerable. We believe that we have collected what is to date the most detailed information on DWH-related changes in shrimp consumption patterns among Vietnamese-Americans in southeast Louisiana, a population whose economic and cultural ties to commercial shrimping and geographic proximity to the DHW makes them particularly vulnerable to potential hazards posed by consumption of oil-impacted shrimp.

The relatively low survey response rate (38.9%) was actually higher than expected given the specific characteristics of this "hard-to-reach" population and the unique circumstances of this community in the aftermath of the DWH event. Factors such as minority and immigrant status, lower household income and education levels, and lower English literacy can negatively impact participation in telephone surveys. (Dillman et al. 2009) Indeed 23% of the sample refused to participate, likely indicating moderate to high levels of mistrust and/or cultural insularity. Another 19% did not answer their phones despite repeated attempts to reach them, suggesting our sample included disconnected or non-working lines or wrong numbers – all indicative of the highly dynamic levels of change this community was experiencing in the aftermath of the DWH even. A concern with low response rates in surveys is nonresponse error, which "occurs when the people selected for the survey who do not respond are different from those who do respond in a way that is important to the study". (Dillman et al. 2009) Based on our knowledge of the target population, it is highly unlikely that responders and non-responders are significantly different from one another in terms of shrimp preparation and consumption habits. Recall bias is another concern with survey-based data and a limitation of our study is that it was conducted 2 years after the DWH event. However, based on the reported frequency of shrimp consumption (i.e. several times per week) within our study population it is unlikely that recall bias would be significant. Consumption of shrimp as part of their diet is normal and any changes from normal behavior are likely to be remembered accurately.

The seafood consumption rates used as the basis of FDA's LOC derivation were abstracted from the NHANES data set and do not accurately represent either the types or amounts of seafood consumed by Gulf-coast communities which may be considered vulnerable (Dickey 2012; Rotkin-Ellman et al. 2012). Our findings indicate that this population consumes *over three times* more shrimp when compared to the FDA's NHANES 90th percentile consumption rate (44 grams per day vs. 13 grams per day) and that average bodyweight is 63 kg which is *17 kg lower* than the 80 kg standard used as the basis for the FDA risk assessment method. Although these differences in shrimp consumption rates and body weight do in fact exist our analyses did not detect excess health risk within this Vietnamese-American community. The very low levels of PAHs detected in our cross-sectional sample of shrimp did not result in excess risk from dietary PAH exposure within our study population. Our data reflects sampling at two distinct locations on two different days following fishery openings approximately 6 months after the DWH event. Therefore we cannot generalize these findings longitudinally for other dates or locations. However, the lack of risk among shrimp consumers included in our study is informative for the risk assessment process going forward.

The FDA reopening guidelines were designed to be protective of 90% of the general population, while the remaining 10% of the population (the highest consumers of seafood) were specifically excluded. Therefore, the responsibility of protecting the excluded high-end seafood (i.e. 90th percentile and above shrimp consumers) fell directly to state and local regulatory agencies (FDA 2010). We do consider this approach as reasonable considering FDA is tasked with protecting the health of the entire US population. However, it is not unreasonable to speculate that one of the many driving factors in taking this approach was the lack of relevant metrics (i.e. seafood consumption rates) among populations who fall into the upper 10% of seafood consumers.

There are limitations and assumptions in both our risk assessment methods and analysis of our survey data. In our study, we only tested the edible tail meat from locally harvested shrimp samples. Our reasoning, informed by members in the community that participated in the research, was that shrimp was the primary seafood type consumed by our study population and we should test the parts of the animal they actually consume. PAH content in foods can be influenced by the method used to prepare the food (Phillips 1999). Broiling, chargrilling, smoking, and blackening are all methods that increase the amount of pyrogenic, and consequently often carcinogenic PAHs in foods. Boiling in water has little effect on PAH content, and we did determine that the majority of our study population primarily consumes boiled shrimp (FEHD 2004). Therefore, different cooking methods are not likely to confound our results regarding PAH content in prepared foods within our study group.

While our study population was well balanced in terms of gender, our primary female respondents were older (see Supplemental Material, Table S4). We were therefore unable to make any type of informed statements regarding any effect the DWH spill had on the shrimp consumption patterns among women of childbearing age due to small sample size (N=15). Also our study did not capture demographic and shrimp consumption behaviors regarding children. We found that primary survey respondents were likely to give information only about themselves.

The PAH levels in the seafood samples we collected and analyzed were comparable to the results of seafood analyses conducted by several regulatory agencies, academic institutions, and environmental organizations (Gohlke et al. 2011; Lubchenco et al. 2012; Rotkin-Ellman et al. 2012; Xia et al. 2012; Ylitalo et al. 2012). None of the data in the literature indicates that PAH contamination of seafood, particularly shrimp, was a serious health concern following the DWH oil spill and reopening of the fisheries. We did find that 81% of our survey respondents reduced the amount of shrimp they consumed for at least 5 months following the DWH oil spill. Furthermore, 43% of our survey respondents reduced shrimp consumption for at least 12 months. This indicates that a majority of the respondents essentially conducted their own risk assessments and decided to reduce the amount of seafood they consumed without any sort of guidance from local, state, or federal regulatory agencies. We do not know what types of foods were substituted for shrimp during this period of reduced consumption or what health impacts the substitution might have had.

Many of the compounds included in the chemical analysis do not have any type of regulatory limits or toxicity data available. This is an emerging problem for the risk assessment process (Wickliffe et al. 2014). Some of the detected chemicals lack RPFs for even the “parent” class of chemicals. This raises the question of how to conduct health risk assessments for chemicals without regulatory guidance and/or toxicity data. Assumptions regarding a chemical’s potency or toxicity must be made for chemicals that lack regulatory standards. When assumptions are applied to compounds without adequate toxicological data in risk assessment calculations, estimates of risk will ultimately exceed acceptable risk levels. This is especially true for large classes of compounds such as PAHs. Furthermore, using an RPF approach assumes additivity across the PAHs. Thus, risk can only increase as individual PAHs are added to the risk dose model. To highlight this emerging issue, we conducted a health risk assessment where we assigned a value of LOD/√2 to all chemicals that were not detected. While this is a conservative but reasonable assumption, this approach is problematic because many of these PAHs lack toxicity data and do not have RPF values. Therefore, we conservatively assigned an RPF of 1, equal to B[a]P, for all chemicals that lacked accepted RPFs. By doing so, the levels of B[a]P-equivalents was substantially increased in our seafood samples. Consequently, as we included greater numbers of PAHs in our probabilistic analyses, risk estimates increased to what most would consider unacceptable levels. This example demonstrates the problem inherent in using an additive model to calculate health risks based on an ever-increasing list of analytes. While this approach is clearly not ideal, the other end of the spectrum is to ignore all chemicals that do not have adequate toxicological data and accepted RPFs for risk assessment purposes, which could then lead to actual unacceptable health risks from exposure to such unstudied PAHs.

Conclusions

Ultimately, there is an association between people with direct ties to commercial shrimping and comparatively high rates of shrimp consumption. This group represents stakeholders who are most likely to have the highest dietary exposures and suffer the greatest economic loss because of fishery closures and market loss due to the general public's consumption concerns and changes in their dietary behaviors. The fact that these somewhat marginalized coastal communities are the most likely to experience both potential health and economic impacts of risk assessment and management policy illustrate why they should be targeted for inclusion in the risk assessment process. A more inclusive approach to risk assessment might begin with a focus on sensitive subpopulations (such as greater than average shrimp consumers in this instance). Finding no unacceptable risk within these groups would suggest that the rest of the general population will also have no unacceptable health risks. Such an approach protects not only the general population but also would mitigate the criticism that federal policy-based risk assessment practices ignore the safety of sensitive subpopulations. Our data demonstrate that the standard exposure assumptions used as the basis for policy-based health risk assessment and the development of LOCs is not representative of shrimp consumption along the US Gulf coast. However, given that actual data from these populations was not available, it is unreasonable to hold the regulatory risk assessment process accountable for ignoring potential health effects within this vulnerable demographic.

How then is it possible to navigate the risk assessment and subsequent risk communication process within a community who is concerned about the safety of their food supply and both wants and deserves access to chemical analysis data from their food sources? We would argue that it is inappropriate to inform affected communities that in the absence of regulatory information about these chemicals they are simply excluded from the health risk assessment process. As currently practiced in the risk assessment process, intentional exclusion of 90th percentile seafood consumers presents further difficulties in the arena of effective risk communication among coastal communities.

Through communication with community liaisons we were able to conduct a tailored risk assessment within a “sensitive subpopulation” that served to demonstrate the safety of shrimp harvested from the Gulf of Mexico and addressed concerns that were meaningful to the community as a whole. Our study demonstrates the need to actively collect relevant data regarding the most affected populations living in disaster prone areas such as the US Gulf coast. We acknowledge that it is not reasonable to expect federal regulatory agencies to gather this type of primary data. They are tasked with protecting the entire population and the approach FDA took in their risk assessment achieved that goal. Our data demonstrates that the NHANES shrimp consumption data and standard body weight assumptions do not accurately represent the Vietnamese-Americans in our study population. The responsibility for the collection of the primary data sets needed to encapsulate the experience of this, and other “sensitive sub-populations” therefore falls directly on academic institutions, local and state health agencies, and environmental advocacy groups.

References

Alexander-Bloch B. 2012. 2 years after Gulf oil spill, Louisiana seafood still battling negative perception. Available: http://www.nola.com/news/gulf-oil-spill/index.ssf/2012/04/2_years_after_gulf_oil_spill_1_1.html [accessed 5 October, 2014].

Brown P, Brody JG, Morello-Frosch R, Tovar J, Zota AR, Rudel RA. 2012. Measuring the success of community science: the northern California Household Exposure Study. Environ Health Perspect 120:326-331.

CDC. 2003. National Health and Nutrition Examination Survey Homepage. Available: http://www.cdc.gov/nchs/nhanes.htm [accessed 5 October, 2014].

Dhar J. 2012. Gulf seafood deformities alarm scientists. Available: http://www.aljazeera.com/indepth/features/2012/04/201241682318260912.html [accessed 5 October, 2014].

Dickey RW. 2012. FDA Risk Assessment of Seafood Contamination after the BP Oil Spill. Environ Health Perspect 120:a54-55; author reply a55-56. doi: http://10.1289/ehp.1104539

Dillman DA, Smyth JD, Christian LM. 2009. Internet, mail, and mixed-mode surveys : the tailored design method. 3rd ed. Hoboken, N.J.:Wiley & Sons.

FDA. 2010. Protocol for Interpretation and Use of Sensory Testing and Analytical Chemistry Results for Re-Opening Oil-Impacted Areas Closed to Seafood Harvesting Due to The *Deep Water Horizon* Oil Spill. Available: http://www.fda.gov/food/ucm217601.htm [accessed 5 October 2014].

FEHD (Food and Environment Hygiene Department). 2004. Chemical Hazard Evaluation: Polycyclic Aromatic Hydrocarbons in Barbecued Meat. Available: http://www.cfs.gov.hk/english/programme/programme_rafs/files/ra_pah.pdf [accessed 2 October 2014].

Gohlke JM, Doke D, Tipre M, Leader M, Fitzgerald T. 2011. A review of seafood safety after the *Deep Water Horizon* blowout. Environ Health Perspect 119:1062-1069.

Griffiths SK. 2012. Oil release from Macondo well MC252 following the *Deep Water Horizon* accident. Environ Sci Technol 46:5616-5622.

Hoeffel R, Kim, Shahid. 2012. The Asian Population: 2010, 2010 Census Briefs. Available: http://www.census.gov/prod/cen2010/briefs/c2010br-11.pdf [accessed 7/18 2014].

IARC. 1987. Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Man: Polynuclear Aromatic Compounds, Part 1: Chemical, Environmental and Experimental Data. Available: http://monographs.iarc.fr/ENG/Monographs/vol1-42/mono32.pdf [accessed 5 October 2014].

IARC. 2002. Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Man: Some Traditional Herbal Medicines, Some Mycotoxins, Naphthalene, and Styrene. Available: http://monographs.iarc.fr/ENG/Monographs/vol82/mono82.pdf [accessed 5 October 2014].

Lubchenco J, McNutt MK, Dreyfus G, Murawski SA, Kennedy DM, Anastas PT, et al. 2012. Science in support of the *Deep Water Horizon* response. Proc Natl Acad Sci U S A 109:20212-20221.

McNutt MK, Camilli R, Crone TJ, Guthrie GD, Hsieh PA, Ryerson TB, et al. 2012. Review of flow rate estimates of the *Deep Water Horizon* oil spill. Proc Natl Acad Sci U S A 109:20260-20267.

Phillips DH. 1999. Polycyclic aromatic hydrocarbons in the diet. Mutation Research/Genetic Toxicology and Environmental Mutagenesis 443:139-147.

Rotkin-Ellman M, Wong KK, Solomon GM. 2012. Seafood Contamination after the BP Gulf Oil Spill and Risks to Vulnerable Populations: A Critique of the FDA Risk Assessment. Environ Health Perspect 120:157-161.

USCG (United States Coast Guard). 2011. On scene coordinator report : *Deep Water Horizon* oil spill. Washington, D.C. : U.S. Dept. of Homeland Security, U.S. Coast Guard. Available: http://noaa.ntis.gov/view.php?pid=NOAA:ocn760102831 [accessed 5 October, 2014].

USEPA (United States Environmental Protection Agency). 1990a. Flourene: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0435.htm [accessed 5 October 2014].

USEPA (United States Environmental Protection Agency). 1990b. Anthracene: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0434.htm [accessed 5 October 2014].

USEPA (United States Environmental Protection Agency). 1990c. Phenanthrene: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0459.htm [accessed 5 October 2014].

USEPA (United States Environmental Protection Agency). 1990d. Dibenzofuran: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0429.htm [accessed 5 October 2014].

USEPA (United States Environmental Protection Agency). 1991. Pyrene: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0445.htm [accessed 5 October 2014].

USEPA (United States Environmental Protection Agency). 1993a. Flouranthene: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0444.htm [accessed 5 October 2014].

USEPA (United States Environmental Protection Agency). 1993b. Provisional Guidance for Quantative Risk Assessment of Polycyclic Aromatic Hydrocarbons. Washington D.C.

USEPA (United States Environmental Protection Agency). 1994. Benzo[a]Pyrene: Integraged Risk Information System. Available: http://www.epa.gov/iris/subst/0136.htm [accessed 2 October 2014].

USEPA (United States Environmental Protection Agency). 1998. Napthalene: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0436.htm [accessed 5 October 2014].

USEPA (United States Environmental Protection Agency). 2013. Biphenyl: Integrated Risk Information System. Available: http://www.epa.gov/iris/subst/0013.htm [accessed 5 October 2014].

Wickliffe J, Overton E, Frickel S, Howard J, Wilson M, Simon B, et al. 2014. Evaluation of polycyclic aromatic hydrocarbons using analytical methods, toxicology, and risk assessment research: seafood safety after a petroleum spill as an example. Environ Health Perspect 122:6-9.

Xia K, Hagood G, Childers C, Atkins J, Rogers B, Ware L, et al. 2012. Polycyclic aromatic hydrocarbons (PAHs) in Mississippi seafood from areas affected by the *Deep Water Horizon* Oil Spill. Environ Sci Technol 46:5310-5318.

Ylitalo GM, Krahn MM, Dickhoff WW, Stein JE, Walker CC, Lassitter CL, et al. 2012. Federal seafood safety response to the *Deep Water Horizon* oil spill. Proc Natl Acad Sci U S A 109:20274-20279.

Table 1. Non-cancer health risk hazard quotients for mean and 95th %tile consumers.

Chemical	RfD (mg/kg-day)	Level detected (ppm)	Mean consumption HQ	95th %tile consumption HQ
Naphthalene	0.02[a]	4.9×10^{-3}	1.7×10^{-4}	2.2×10^{-4}
Fluorene	0.04[b]	1.3×10^{-3}	2.3×10^{-5}	2.9×10^{-5}
Anthracene/phenanthrene	0.3[c]	1.6×10^{-3}	3.8×10^{-6}	4.7×10^{-6}
Pyrene	0.03[d]	1.3×10^{-3}	3.1×10^{-5}	3.8×10^{-5}
Fluoranthene	0.04[e]	1.0×10^{-4}	1.8×10^{-6}	2.2×10^{-6}

[a]USEPA 1998, [b]USEPA 1990a, [c]USEPA 1990b, [d]USEPA 1991, [e]USEPA 1993a.

Table 2. Mean, 95th %tile, and 99th %tile cancer risks with increasing number of PAH analytes.

PAH analytes	Mean cancer risk	95th%tile cancer risk	99th%tile cancer risk
7 cPAHs	2×10^{-7}	9×10^{-7}	2×10^{-6}
7 cPAHs and unsubstituted PAHs	1×10^{-5}	4×10^{-5}	8×10^{-5}
7 cPAHs, unsubstituted PAHs, and alkylated PAHs	2×10^{-5}	6×10^{-5}	1×10^{-4}

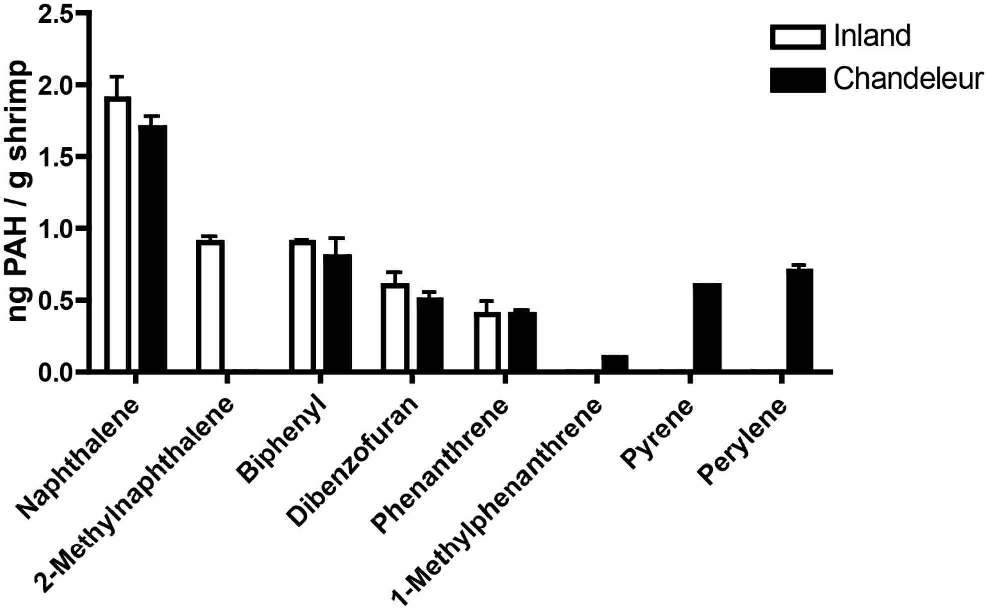
Figure Legends

Figure 1. Unsubstituted and alkylated PAHs detected in shrimp samples. Open bars depict levels found in shrimp collected from inland (bayou bienvenue) location and black bars depict levels found in shrimp collected offshore in the Chandeluer bay. Error bars represent 95% confidence interval of the mean for each analyte and location.

Figure 2. Shrimp consumption frequency among survey respondents.

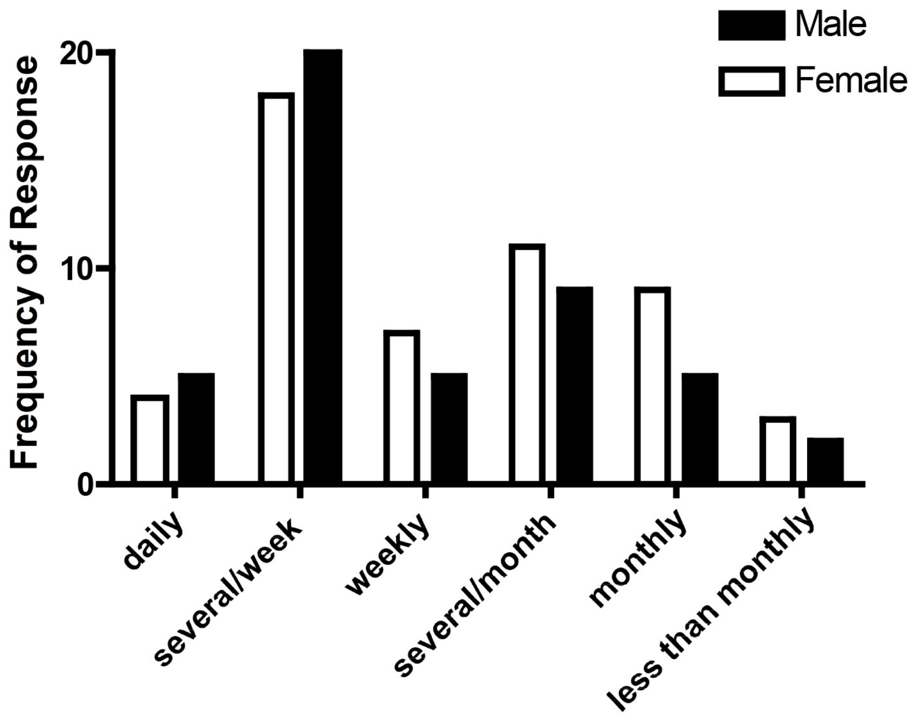
Figures 3A-3C. Monte-Carlo simulation cancer risk output distributions. (A) Cancer risk output distributions of respondents using 7 cPAH as a basis. (B) Cancer risk output distribution of respondents using 7 cPAH and detected unsubstituted PAHs as a basis. (C) Cancer risk output distribution of respondents using 7 cPAH and unsubstituted PAHs and alkylated PAHs as a basis. The bars represent a relative frequency histogram of calculated cancer risks. The y-axis is scaled so the total height of all the bars is equal to 1 (or 100%). The scale of the y-axis varies with the magnitude of the x-axis so the probability density function is equal to 1. The x-axis corresponds to increasing cancer risk levels. The mean, 95^{th} %tile, and 99^{th} %tile risk levels are indicated by callouts on the graphs. The relative frequency histogram was generated by first dividing the data into intervals, then counting the data points within each interval, followed by dividing the counts by the total number of data points.

Figure 1.



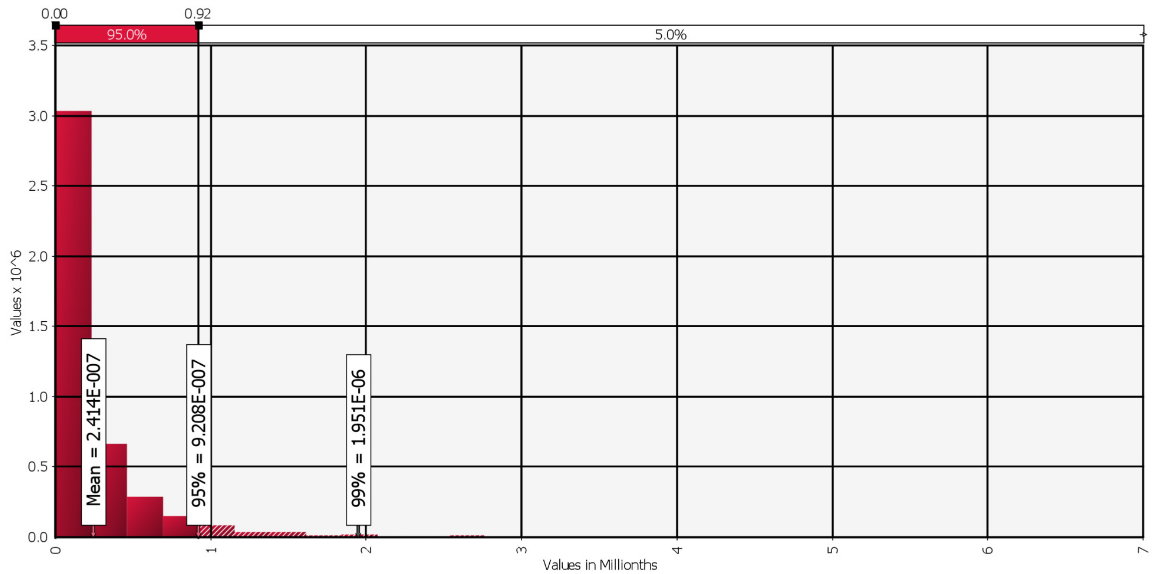
Inland
Chandeleur
ng PAH / g shrimp
2.5
2.0
1.5
1.0
0.5
0.0
Naphthalene
2-Methylnaphthalene
Biphenyl
Dibenzofuran
Phenanthrene
1-Methylphenanthrene
Pyrene
Perylene

Figure 2.

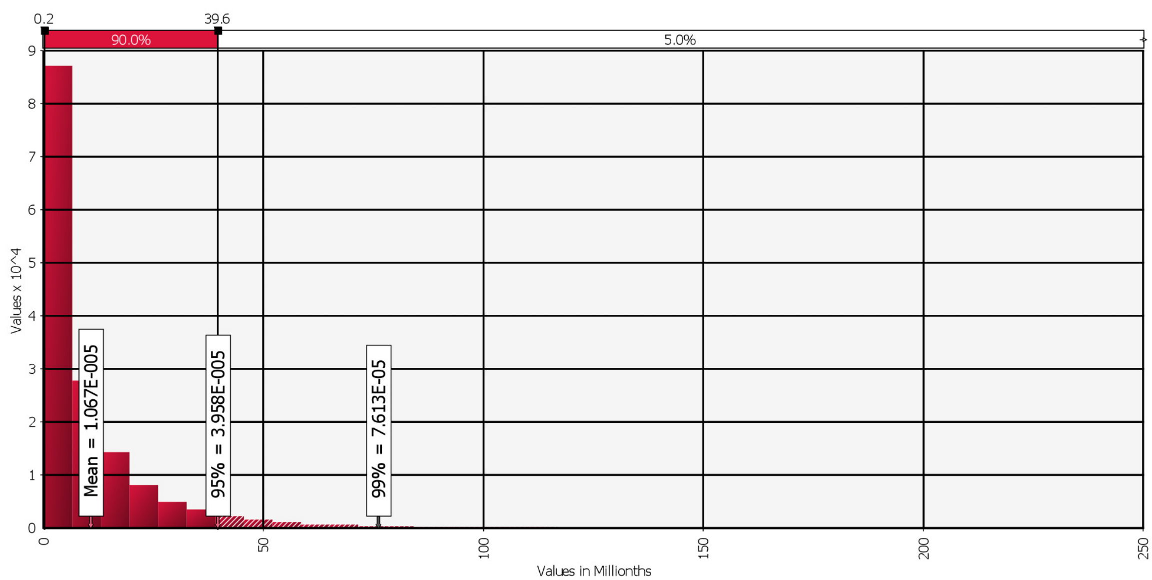

Male
Female
Frequency of Response
20
10
0
daily
several/week
weekly
several/month
monthly
less than monthly

Figue 3.

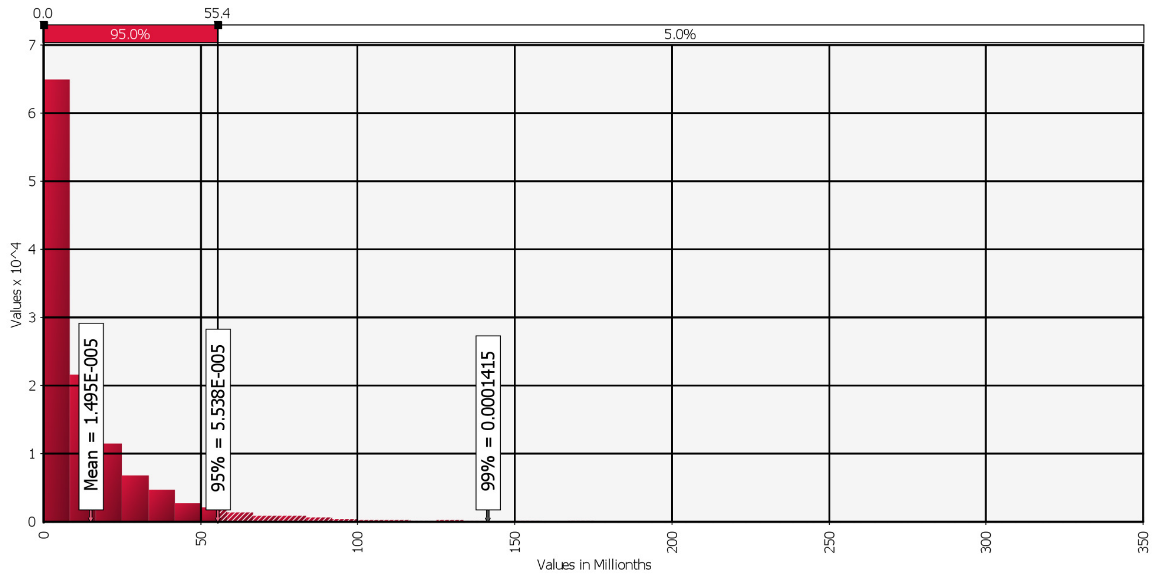
3A


0.00
0.92
95.0%
5.0%
Values x 10^6
Mean = 2.414E-007
95% = 9.208E-007
99% = 1.951E-06
Values in Millionths

3B


0.2
39.6
90.0%
5.0%
Values x 10^4
Mean = 1.067E-005
95% = 3.958E-005
99% = 7.613E-05
Values in Millionths

3C



0.0
55.4
95.0%
5.0%
Values x 10^4
Mean = 1.495E-005
95% = 5.538E-005
99% = 0.0001415
Values in Millionths