AN ANALYSIS OF GLOBAL DEBRIS-FLOW FATALITIES AND RELATED SOCIOECONOMIC FACTORS FROM 1950 TO 2011

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geological Engineering).

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ABSTRACT

Debris flows cause significant damage and fatalities throughout the world. However, some debris flows only take a few victims, while others kill hundreds, and the differences between these events is not well understood. This study addresses the overall impacts of debris flows on a global scale from 1950 to 2011. Two hundred thirteen events with 77,779 fatalities were recorded from academic publications, newspapers, and personal correspondence. Spatial, temporal, and physical characteristics were documented and evaluated. In addition, multiple socioeconomic indicators were reviewed and statistically analyzed to evaluate if vulnerable populations are disproportionately affected by debris flows. This research provides evidence that populations with lower social, political, or economical standing are more at risk for debris–flow related fatality. Specifically, higher levels of fatalities tend to occur in developing countries, characterized by less wealth, more corrupt governments, and weaker healthcare systems. The median number of deaths per flow in developing countries is 23, but only 6 in advanced countries. The analysis also indicates that debris flow occurrence and deadliness is affected by seasonal precipitation patterns, as the most common trigger for fatal events has been found to be extreme precipitation, particularly in the form of large seasonal events like cyclones and monsoon storms. Rainfall caused or triggered 144 of the 213 fatal debris flows within the database. However, it is the more uncommon and catastrophic triggers, such as earthquakes, and landslide dam bursts that tend to create more deadly debris flows, with a median fatality count greater than 500 while rainfall induced debris flows have a median fatality rate of only 9 per event.

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CHAPTER 1

INTRODUCTION

Debris flows are a common hazard in mountainous regions around the world. They have long been considered a particularly devastating geologic hazard due to their rapid velocities and ability to travel great distances. Debris flows are responsible for some of the largest landslide disasters in modern times (Jakob and Hungr, 2005), capable of burying entire cities and killing tens of thousands in a single event. While these large events are especially destructive, the cumulative effects of smaller debris flows over a wet season also can cause significant losses. Furthermore, population growth has driven development farther into debris-flow prone areas, causing increased risk from this hazard (Jakob and Hungr, 2005).

As geoscientists have become increasingly aware of the risk of debris flows, a large amount of research has been conducted to better understand the hazard. Many of these studies have focused on the physical characteristics and processes of debris flows. These include geologic settings, triggering mechanisms, transport processes, deposition characteristics and mitigation options. However across the research, there is a key piece of analysis missing. Presently, there are no publications which directly compile and analyze the losses of human life caused by debris flows.

Disregarding particularly devastating incidents, (e.g., Venezuela 1999, Taiwan 1996) debris-flow fatalities often have been lumped into the death tolls of large scale regional disasters such as earthquakes, volcanic eruptions, and hurricanes (Santi et al., 2010). This occurs because debris flows often are a secondary process of these larger calamities (Jakob and Hungr, 2005). This practice undermines recognition of the impact of debris flows related to these events. While triggered by the overall disaster, damage from debris flows differs from that caused by flooding or extreme ground shaking and may be unexpected. If authorities are not aware of the potential impact of debris flows, funds for prevention or hazard response may be wrongly allocated; allowing debris flows to significantly increase the overall death toll (Santi et al. 2010). As Santi and others (2010) indicate, regional disasters cannot be prevented, but to some degree debris-flow hazards can be mitigated.

In addition to increased fatalities, it is also becoming evident that debris flows disproportionally affect those with social disadvantages. A "disaster of social vulnerability" as defined by Hewitt (1997) is one which has particularly devastating effects on populations with resource limitations, such as economic, space, and influence/power constraints. The perception of debris flows as a "disaster of social vulnerability" has been alluded to in recent publications (Santi et al. 2010), but has not been supported by quantitative data.

This thesis provides a debris-flow fatality database to address the above needs within the field of debris-flow research. It provides quantitative data to evaluate certain physical and socioeconomic indicators, which may be indicative of a location's risk to fatal debris flows. This evaluation tests the hypothesis that debris flows are in fact "disasters of social vulnerability." Finally, by providing quantitative data on debris-flow fatalities, the database can be used to validate further research on debris flows such as effectiveness of debris-flow warning systems and mitigation techniques.

CHAPTER 2

PRIOR RESEARCH

Substantial amounts of research have been performed in the field of landslides, with increasing focus on debris flows in recent years. As researchers have delved into the physical mechanics of debris flows, significant human losses across the globe have been attributed to the phenomenon. However, this understanding is often over-generalized, with no specific details or quantitative information. Jakob and Hungr's introduction to their compilation on debris-flow hazards (Jakob and Hungr, 2005) recognizes the need for more specific data and states "direct debris flow damage…is difficult to quantify." Many large debris flow disasters have been studied in great detail (e.g., Garcia-Martinez and Lopez, 2005; Jan and Chen, 2005; Sanchez et al., 2009) and some publications contain inventories of events for particularly famous locales (Guadagno and Revellino, 2005; Kanji et al., 2003), or for the broader topic of landslide fatalities (Petley et al., 2005), but there is currently no global database specific to debris flows.

The first attempt at a quantitative loss database for the all-encompassing hazard of landslides is that of Petley and others (2005). It was found that while some local and national databases had been created, there was no global landslide loss database. Prior to this study, landslide loss figures tended to be over-generalized, making it difficult to illustrate just how destructive landslides could be (Petley et al., 2005). In September of 2003, Petley and others began compiling a database of landslide incidents on a global scale. In the database, landslides are defined as "all soil/rock failures, including slides, flows and falls" (Petley et al., 2005). Debris flows were included only when they could be "clearly differentiated from a flood" (Petley et al., 2005). Within the database, only landslides that caused fatalities were recorded, because fatalities are a universal currency with an identical value around the globe. Petley and others note that fatalities are the worst case scenario, representing the greatest loss occurring from a landslide, and they are one of the few things reliably reported around the globe no matter the level of development or remoteness of a setting. Data was gathered from a variety of sources including professional papers, media articles, government data, and aid agency reports (Petley et al., 2005).

Petley (2012) examined the trends in landslide fatalities from the landslide database covering the period between January 1, 2004 and December 31, 2010, excluding seismically triggered events. From this subset, he showed that locations of landslide fatalities were clustered in particular locations across the globe. Typically these locations had a combination of four characteristics: high relief, high rates of tectonic processes, intense precipitation, and dense human populations. He observed that, in general, regions with substantial amounts of research such as Italy and Hong Kong, had far fewer fatalities than those with limited landslide research. This occurred even though all four previously mentioned conditions existed. Japan was an exception; even though the country had intense research and mitigation, many landslides still caused fatalities. Petley (2012) found that the top fifteen countries with the most landslide fatalities during the period between 2004 and 2010 were all developing nations, supporting the hypothesis that landslides may disproportionately affect vulnerable populations.

While Petley's (2012) research focused on landslides of all types, similar trends for debris flow fatality data collected in the database for this research are expected. This project differs from the work of Petley and others (2005) and Petley (2012) as it focuses only on debris flows and reviews data over a much longer period of time. This study also performs a statistical analysis to identify trends between specific socioeconomic indicators and the severity of debris-flow impacts.

Jakob and others (2011) was one of the first quantitative risk assessments of debris-flow losses, based on building damage from 68 incidents around the world. They used a quantitative risk assessment to calculate the risk to a population from a hazard based on the probability of an event, the spatial and temporal probability, vulnerability, and the number of people at risk. Since the study was focused on the vulnerability of structures, a database was created to record the damage done to buildings from debris flows of varying sizes, depths, and velocities. Fatalities caused by the events were not recorded.

Rather than structural damage, the work of Santi and others (2010) focused on the socioeconomic factors which may influence the number of fatalities caused by debris flows. Santi and others (2010) is the first publication to suggest that debris flows are "disasters of social vulnerability," in the same way that Hewitt (1997) describes earthquakes. These types of disasters preferentially cause more fatalities in populations with various resource limitations, such as economic, space, and influence/power restrictions. Economic and space restrictions force these vulnerable populations to live in high hazard areas where the risk for debris flows is great and the topography may confine the population in times of disaster (Santi et al., 2010). Political power limitations prevent these populations from receiving the resources necessary to address the risk of debris flows (Santi et al., 2010). The paper included six case studies of fatal debris flows from around the world in which socioeconomic restrictions played a major role. Qualitative information from the case studies showed the victims were typically found to be living in high hazard areas, with no place to evacuate in the short time following the initiation of the debris flow (Santi et al., 2010). The authors speculate socioeconomic indicators may be useful in measuring the vulnerability of populations; however, no quantitative measures were made for the six case studies.

CHAPTER 3

METHODOLOGY

This thesis aims to examine debris flow losses through the creation and analysis of a fatality database. To accomplish this task, fatal debris flow events were found through a variety of different sources with different levels of technical expertise. This involved differentiating debris flows from flooding and other forms of landslides. Furthermore, statistical analysis has been performed on the data to evaluate physical and socioeconomic trends common amongst fatal debris flows.

3.1 Debris Flow Event Collection

Over two hundred fatal debris flows have been recorded between the years 1950 and 2011. The term “debris flow” includes both debris and earth flows as defined by Cruden and Varnes (1996). This leads to the inclusion of flow-type failures which are both predominantly coarse-grained (debris) and predominantly fine-grained (earth) (Varnes, 1978). The volcanic counterpart of debris flows, lahars, have also been included in the database as these events cause similar damage to debris flows and fit the definition of debris and earth flows under Varnes’ (1978) classification. The database does not include flood fatalities. For each event, the database contains information on a variety of factors which address both the physical and socioeconomic conditions that may influence the number of fatalities caused by a debris flow. Information recorded in the database is provided in Table 3.1.

Table 3.1: Information recorded in the Debris Flow Fatality Database.

Topic	Item
Spatial/ temporal information	Country, location, date, time of day
Flow information and effects	Volume, number of fatalities
Short term warning	High rainfall, local debris flows within 1-2 days, earthquake, hurricane rainfall, monsoon rainfall, wildfire within last 3 years, shaking of ground, roaring noises, observation of landslide
Long term warning	Recent history of debris flows, annual debris flows in region, prehistoric debris flow deposits, construction of debris flow mitigation, debris flow landforms, massive boulders on adjacent land
Cause/ trigger	Landslide mobilization, glacial lake outburst flood, volcano flank collapse, landslide dam burst, glacial melt lahar, earthquake, rainfall (tropical cyclone rainfall, monsoon rainfall, winter storm rainfall, summer storm rainfall, rain following fire, rain on ash lahar, rain after land clearing, rain on snow)
Mitigation	None, check dam, sabo dam, debris fence, debris basin, deflection walls
Economic indicators	Technical journal articles per capita (research investment surrogate), gross domestic product (GDP) per capita (indicator of economic development and wealth for country)
Healthcare indicators	Maternal mortality rate (MMR) (indicator of development of a country's healthcare system), number of hospital beds per capita (indicator of a country's ability to provide emergency services), life expectancy at birth (indicator of development of a country's healthcare system)
Political indicators	Government corruption index (GCI) (indicator of a government's ability to respond to emergencies)

Information for the database has been collected from a variety of published resources including: technical literature, newspaper articles, government documents, and aid organization filings. Technical literature was found online, through academic resources, and in library records. Journalism sources were found online, in newspapers, and through journalism databases. Government and international aid documents were obtained through respective government, World Bank, and United Nations websites.

While technical literature correctly classified the type of slope movement, incorrect terminology often appeared in non-technical literature such as news media, government, and international aid documents. When an event was not classified specifically as a debris flow, the following system was utilized to evaluate whether the event belonged in the database. The terms “landslide” or “mudslide” are common phrases used when describing debris-flow events in non-technical articles. If only the term “landslide” was provided, article photographs were used to classify the type of slope movement, where evidence of flow movement indicated debris flows. If no photographs were available, the article’s description of the event was utilized. If keywords such as “flow” or “torrent” were used in the article, the event was recorded in the database, as these terms are indicative of the type of movement associated with debris flows. The term “mudslide” also alludes to rapid flow type behavior, but is often used for both earth and debris flow type slope movements in nontechnical sources. As it was not physically possible to evaluate grain size distribution and make a proper classification, it was reasonable in the scope of this study to include both earth and debris flows in the database, thus allowing events termed as “mudslides” to be included. Debris flows were separated from floods by reviewing the mechanisms of death. Death by burial or trauma from debris was assumed to be a debris-flow fatality while death from drowning was assumed to be caused by flooding.

Non-technical sources also tend to lump debris-flow fatalities with other fatalities occurring during regional disasters such as flooding from heavy rain or structural damage from earthquakes. The lumped number provided in these counts was not used in the database, as the fatality count would have been inflated from deaths not caused specifically from debris flows. Care was taken to include only fatality counts from articles that specifically provided the count for the debris-flow event. Multiple debris flows caused by the same regional event were broken out when possible. If the regional count could not be broken into its individual events, the fatality number was still recorded in the database as a single event.

Immediately following disasters, media articles typically report preliminary information with rough figures for fatalities and missing persons. The fatality number will often increase over time as missing persons are found to have deceased (Petley et al., 2005). Unfortunately, media sources do not always cover events for long enough periods to report final death tolls. If an official toll could not be found from other sources, only the reported death count was recorded, not the combined death and missing count.

Personal correspondence with professional earth scientists was utilized to find information on smaller events not published in professional papers or media articles. A survey was created to collect information from these individuals using the website Surveymonkey.com. The link to the survey was sent to the Geologic Society of America, the Association of Environmental and Engineering Geologists, and was posted on David Petley's Landslide Blog (Petley, 2012). The survey consisted of multiple choice and short response questions and addressed the information provided in Table 3.1. Contact information was provided in case respondents would rather respond directly than complete the survey.

Once event-specific data were collected, socioeconomic data were gathered on a national scale from a variety of readily available internet resources. GDP per capita, literacy rates, hospital beds per capita, and the number of technical journal articles published were found at the

World Bank website. The Corruption Perception Index (CPI) was attained from the Transparency International website. Maternal mortality data was collected from the United Nations website. When possible, socioeconomic data were recorded for the year the event occurred. If data were not available, data for the closest time period were utilized. If data were not found within 5 years of the event, the debris flow was not included in that specific analysis.

3.2 Data Analysis

Data were analyzed to evaluate trends and characteristics for multiple aspects of fatal debris flows. Descriptive statistics were found for the entire data set to evaluate the hazard over the time span of the database. Spatial data were reviewed to examine which countries are more at risk for fatal debris flows. A review of temporal data has been conducted to evaluate whether the number of debris-flow fatalities changes over the course of the year and if there may be a data discrepancy over the time frame of the database. Physical characteristics of the events were analyzed to assess whether certain aspects such as volume or trigger mechanisms may impact the number of fatalities. Finally, socioeconomic indicators were examined to review whether the magnitude of debris-flow tragedies may be influenced by social, economic, or political factors within a country. Not all events contain the data required for all analyses. If certain information could not be found for a debris flow, that event was not included in the specific analysis.

3.2.1 Descriptive Statistics

Descriptive statistics for the database were calculated to evaluate the overall impact of debris flows on society. The central tendency of the database has been analyzed by finding the mean and median fatalities per event and per annum. It was expected that a small number of fatal debris flows with high casualty rates would greatly increase the mean value per event.

Hence the median has been used to measure central tendency as the high end values do not impact this statistic to the same degree as they do the mean. The standard deviation and skewness were used to further evaluate the distribution of the data. These analyses were carried out using the computer program Minitab.

For some analyses, it was necessary to calculate a threshold that denoted outliers, which are events that had fatality counts that were far larger than typical values in the database. To calculate this value, the Interquartile Range (IQR) was utilized. A value was considered an outlier if it fell outside of a multiple of the IQR ranging from 1.5 to 3 times the IQR (Tukey, 1977). For this study the threshold selected was 3 times the IQR, as shown by Equation 3.1 below.

$$\mathrm{OL} > 3 * (\mathrm{Q}_3 - \mathrm{Q}_1) + \mathrm{Q}_3 \tag{3.1}$$

Where:

OL = Outlier

Q_1 = Quartile 1

Q_3 = Quartile 3

3.2.2 Spatial Analysis

To illustrate the spatial distribution of fatal debris flows in the database, multiple maps were created. One map provides data on the number of events occurring in each country. Another map illustrates the severity of debris flows in each country by providing the median number of fatalities per debris flow for that country. The maps illustrate this data by using bubbles that are proportional in size to the numerical value they are representing. Maps were created using Geographical Information System (GIS) files and the computer program ArcGIS.

3.2.3 Temporal Analysis

Debris flows were analyzed based on the year and month they occurred to evaluate temporal trends. Fatal debris flows were assessed based on the year they occurred to examine whether the number of recorded debris flows has changed over the time span of the database. Changes in the number of debris flows recorded could be due either to an actual change in the number of fatal debris flows occurring or a change in the documentation of flows. To investigate trends, the central tendency of the data was evaluated by decade. If the number of fatal debris flows was truly changing, the median value of fatalities per event would not be expected to change over the time span of the database. A decrease in the median fatalities per event over the timespan of the database would indicate that a greater number of smaller debris flows were being recorded over time. This is indicative of a change in documentation, rather than a change in the actual number of debris flows occurring. It is likely that new technology and increased research is leading to a greater number of smaller events being recorded.

Furthermore, it was desired to examine whether the country's development status, as defined by the International Monetary Fund (IMF), would affect the number and size of recorded debris flows recorded over the timespan of the database. The data was analyzed in similar manner as described above except that it was subdivided into two groups, "developing" and "advanced," as identified by the IMF. The IMF classification is based on per capita income, export diversification, and the degree of integration into the global financial system (IMF, 2011). Graphs of the number of recorded debris flows and boxplots of fatalities per debris flow over the timespan of the database were created and the trends were compared. Changes in the median number of one group, but not the other, would indicate the documentation within that particular group had changed over the timeframe of the database.

Seasonal trends in debris-flow fatalities were analyzed by dividing debris-flow events by the month in which they occurred. Graphs of the number of debris flows and the mean number of fatalities per month were created for both the entire database and specific regions. Regional graphs could be utilized to see the trends in fatal debris flows and trends in the severity of debris flows on a regional basis. Regions were assigned based on geographic locations as follows:

- North America
- Central America
- South America
- Europe
- Africa
- Asia
- Southeast Asia
- Oceania

As this analysis was performed to observe seasonal trends, large fatality debris flows caused by non-seasonal events were omitted. These large events were classified as outliers utilizing Equation 3.1 as described in section 3.2.1. Any trends were compared to seasonal weather patterns for the corresponding region to analyze whether specific seasonal events played a role in fatal debris-flow occurrence.

3.2.4 Physical Characteristics

Physical characteristics of fatal debris flows were analyzed to evaluate whether certain attributes were commonplace and whether any played a role in the severity of the flow. The physical characteristics included short and long term warning signs, trigger and cause mechanisms, and volume. Short and long term warnings were tallied and evaluated to assess whether certain warning signs are more common for fatal debris flows. The various warning signs included in the analysis are provided in Table 3.1. These warning signs are not mutually exclusive as many events had multiple warning signs.

Like the analysis of warning signs, analysis for trigger and cause mechanisms (Table 3.1) consisted of tallying the number of debris flows initiated by each mechanism and evaluating which are the most common. This analysis also included tallying the median number of fatalities for each mechanism in order to assess which triggers or causes may cause more severe debris flows. It was desired to analyze rainfall events separately, as such a large number of fatal debris flows occur due to this specific mechanism. Hence a graph was created in which all rainfall events are combined and compared to non-rainfall induced mechanisms. Many debris flows are the result of multiple causes and triggers and a mutually exclusive analysis was not possible for all events.

Information on debris-flow mitigation was recorded and tallied to evaluate how common debris-flow mitigation is and whether mitigation failure was common during fatal debris flows. The type, or lack of, mitigation was recorded only if it was specifically mentioned (see Table 3.1 for possible mitigation types). While it was desired to compare whether the presence of debris-flow mitigation affected the severity of fatal flows, the lack of mitigation information prohibited reliable statistical comparisons.

The effect of debris-flow volume on the number of fatalities was analyzed through regression analysis, where fatalities in each event were plotted against the volume of the event. The effect of the population size in the area of the debris flow and the relationship between volume and fatalities has also been analyzed. Events were grouped into four population classes, and a regression was then calculated for each class. The size of the population classes are defined in Table 3.2.

Table 3.2: Population Classes

Population Class	Size of Population
City	10000+
Town	1000-10000
Village	10-1000
Rural	0-10

3.2.5 Socioeconomic Analysis

Various socioeconomic indicators (provided in Table 3.1) were analyzed to evaluate whether debris flows are "disasters of social vulnerability." Essentially, it was desired to see whether social, economic, or political standing of the affected population may influence the number of fatalities in debris flows, as indicated by the strength of linear regression plots of socioeconomic data and the number of fatalities.

Quantitative socioeconomic data included economic, healthcare, education, and political indicators, which were assigned numerical score values by global organizations, such as the World Bank, United Nations, or IMF. The fatality counts of debris flows were plotted against the numerical value of the indicator and the computer program, Minitab, was utilized to produce a regression. Socioeconomic indicators that have undergone regression analysis include the following:

- Fatalities and GDP per Capita

- Fatalities and Number of Hospital Beds Per Capita
- Fatalities and Government Corruption Index
- Fatalities and Maternal Mortality Rate
- Fatalities and Life Expectancy at Birth
- Fatalities and Number of General Technical Journal Articles per Capita

To further investigate whether debris flows disproportionately affect the developing world, it was useful to compare the distribution of debris-flow fatalities of advanced and developing nations. As in the temporal analysis, this involved splitting the data into two populations (advanced and developing) based on the IMF's development status for the country in which the event occurred. Descriptive statistics and histograms of debris-flow fatality size in these two populations were plotted to compare the distribution of the data. In particular, the median fatality count per debris flow has been compared to evaluate whether the severity of debris flows differs between groups.

3.2.6 Regression Analysis

Regression analysis was performed by a combination of hypothesis testing, evaluating the coefficient of determination, and the residuals versus fit plot. All analysis was done using the computer program Minitab. First, a relationship was evaluated to examine if a correlation existed between fatalities and a particular numerical indicator, by hypothesis testing using the F test. The null hypothesis was that no significant correlation existed between the indicator in question and the number of fatalities in a debris flow. The level of significance for the null hypothesis was set at 0.05. The F value was calculated in Minitab to find the corresponding P value. This was then compared to the level of significance. If the P value was less than the level of significance, the null hypothesis was rejected, indicating the existence of a correlation.

If a correlation did exist, the strength of the correlation was further analyzed using the coefficient of determination (R^2). R^2 is a useful parameter as it measures the amount of variation accounted for in the regression. The range of R^2 is from 0 to 1 with 0 indicating no variation is accounted for and a value of 1 indicating all variation is accounted for. Thus regressions with high R^2 values indicate that the regression accounts for a large amount of variation, and a strong correlation exists.

The residual versus fits plot provides a check on whether the regression is statistically strong. Residuals should be evenly distributed about the regression and no patterns should be present. If these conditions are not met, the regression may not be appropriate for the relationship between the indicator and the number of debris-flow fatalities.

The importance of various socioeconomic indicators was compared by ranking them in accordance to the strength of the regression. This was done by closely evaluating the P value, the R^2 value, and the residual versus fits plot. The initial ranking was based on the P value. This is because the F test, used to obtain the P value, is dependent not only on the R^2 value but also the degrees of freedom. The P value thus allows regressions with different degrees of freedom to be directly compared. The lower the P value, the higher the probability that the independent variables influence the dependent variable. Hence a lower P value indicates better correlation. For regressions with the same P values, the R^2 values were compared. Those closer to 1 were considered stronger regressions. If both the P and R^2 values are the same or similar, the ranking was based on the residuals versus fit plot. Regressions with a better residual plot were given a higher rank.

CHAPTER 4

RESULTS

This chapter contains the results from the debris flow fatality database. The subsections are divided by the type of analysis performed. These are as follows: Descriptive Statistics, Spatial Results, Temporal Results, Physical Attribute Results, and Socioeconomic Results.

4.1 Descriptive Statistics

Two hundred thirteen fatal debris flows were recorded in the database between the years 1950 and 2011. These recorded debris flows have caused 77,779 fatalities. Table 4.1 provides descriptive statistics for the database while Figure 4.1 provides the histogram of the fatalities per debris flow.

Table 4.1: Descriptive Statistics for the Debris Flow Fatality Database

Statistic	Value
Total Fatalities	77,779
Total Debris Flows	213
Mean Fatalities per Event	365
Median Fatalities per Event	11
Lower Quartile	4
Upper Quartile	71
Median Fatalities per Year	165
Lower Quartile	14
Upper Quartile	546
Outlier Threshold	269
Number of Events < Outlier	185
Number of Events > Outlier	28

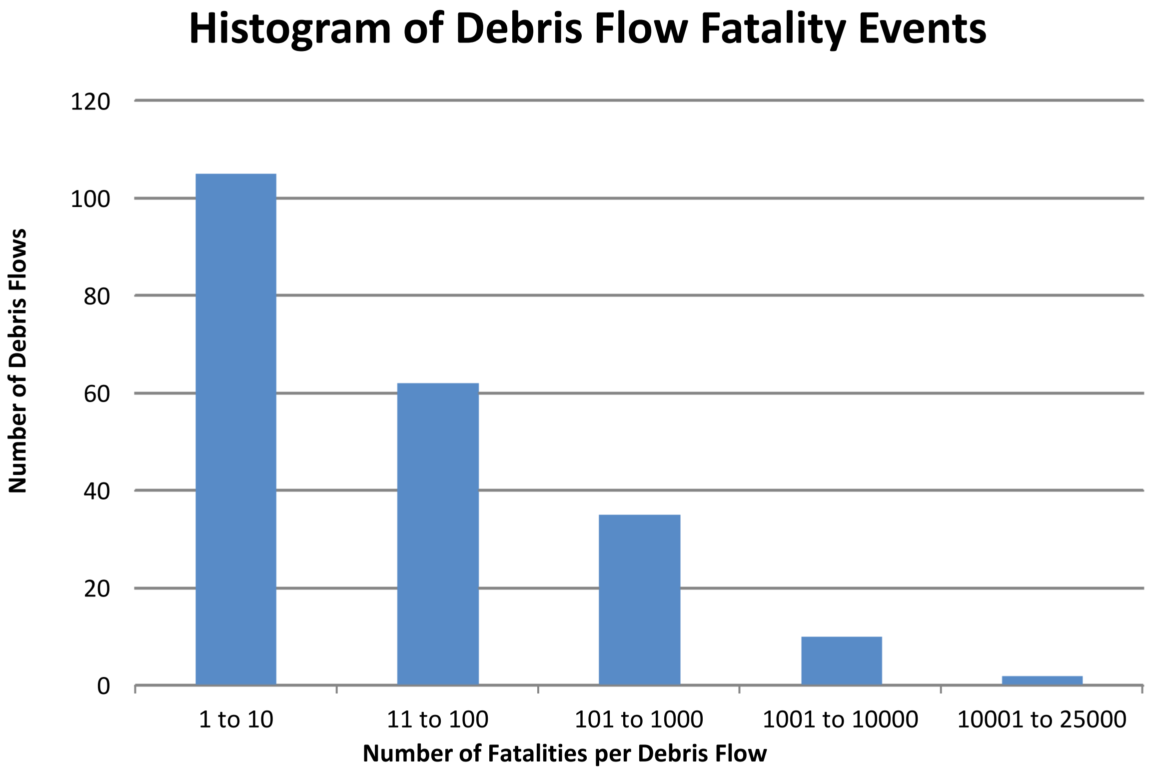

Figure 4.1: Histogram of fatalities per debris flow recorded in the database.

4.2 Spatial Results

The spatial debris flow data are displayed by country on the following maps. Figure 4.2 provides the number of fatal debris flows recorded in each country. Figure 4.3 indicates the median fatality count per debris flow by country.

4.3 Temporal Results

Temporal Results are subdivided into two categories: Database Overview and Monthly Results. The database overview results display data over the entire timeframe of the database. The monthly data results provide data on a monthly basis for the entire database as well as for specific regions.

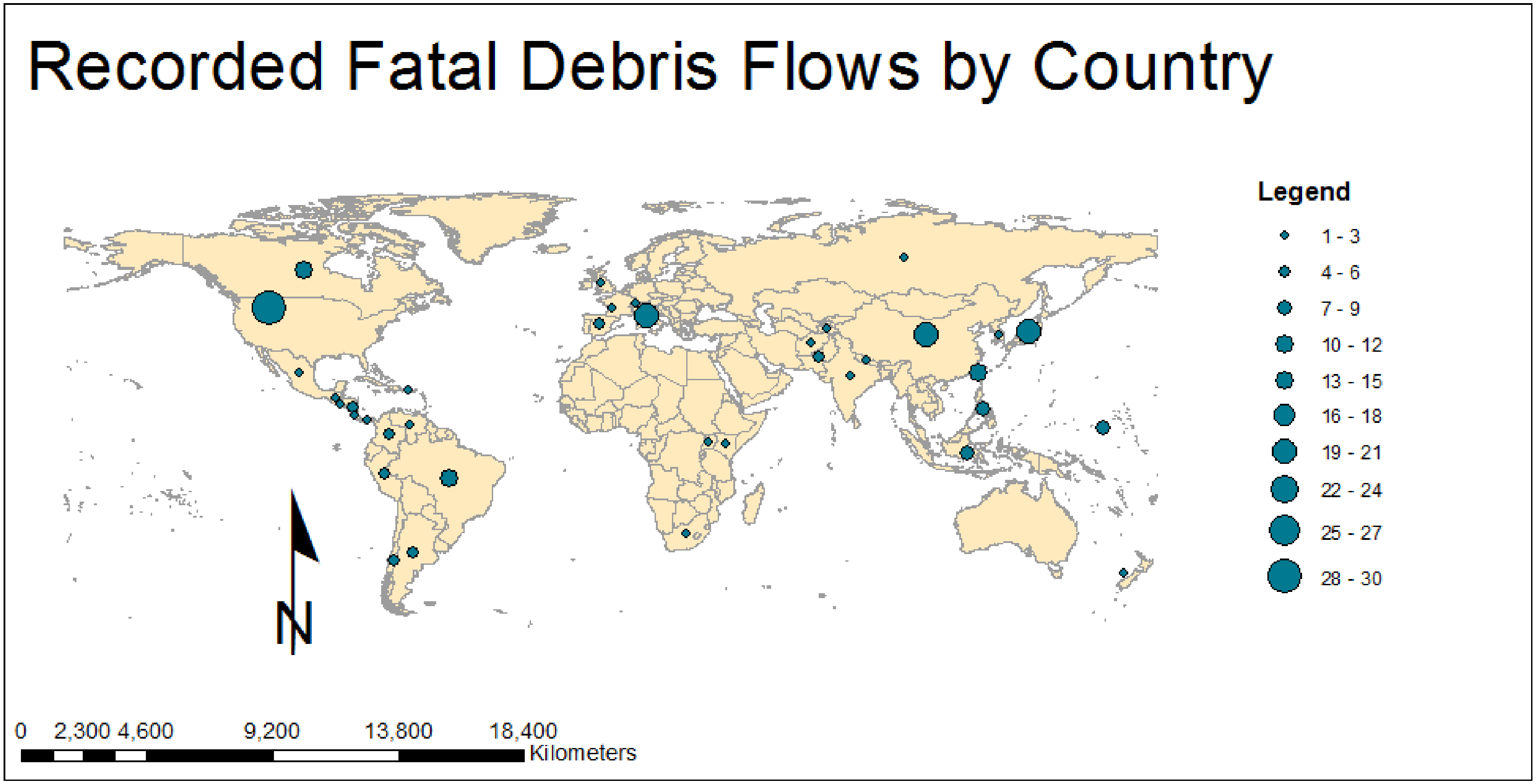

Figure 4.2: Map showing distribution of recorded fatal debris flow within countries in the database. Dot size represents the number of fatal debris flows per country.

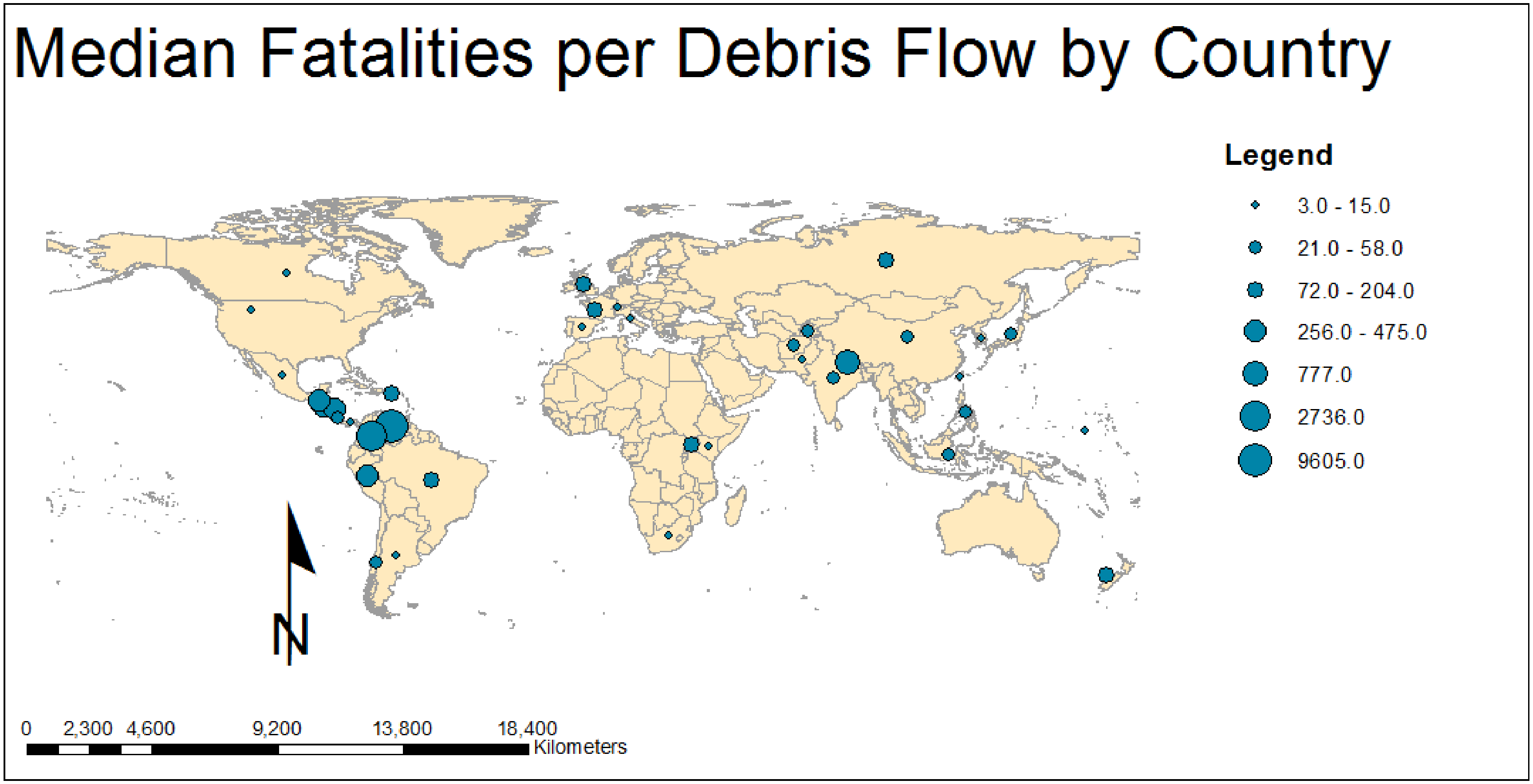

Figure 4.3: Map showing distribution of median debris-flow fatalities within countries recorded in the database. Dot size represents the mean debris-flow fatalities per event in each country.

4.3.1 Database Overview

Figure 4.4 provides data on the number of fatal debris flows by decade. Figure 4.5 contains boxplots of the number of fatalities per event by decade. Figure 4.6 through Figure 4.8 provide these same results but broken down by IMF classification.

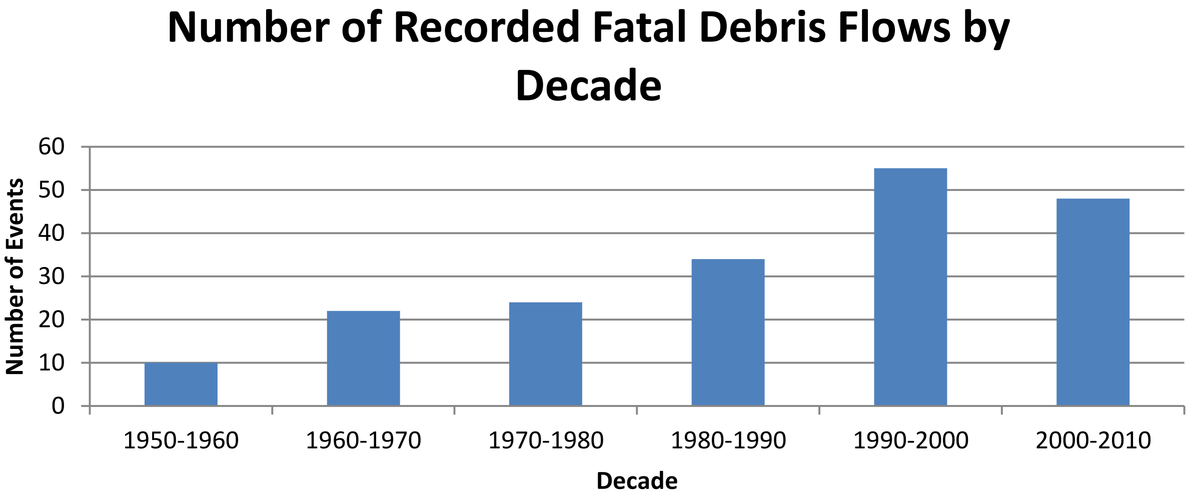

Figure 4.4: Bar graph showing the number of recorded fatal debris flows in the database by decade.

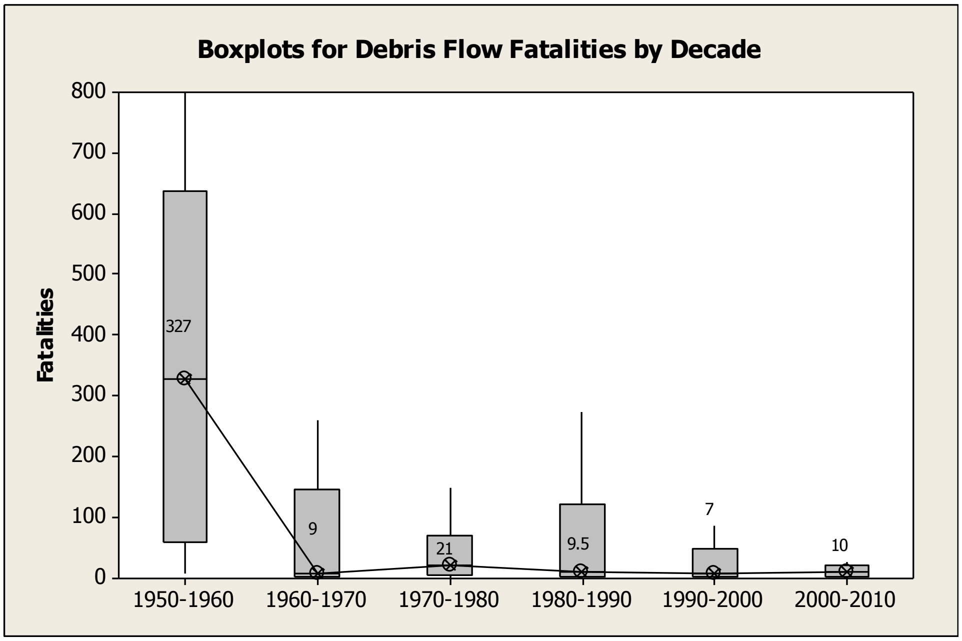

Figure 4.5: Boxplot of fatalities per debris flow by decade. The median value and its trend line are displayed.

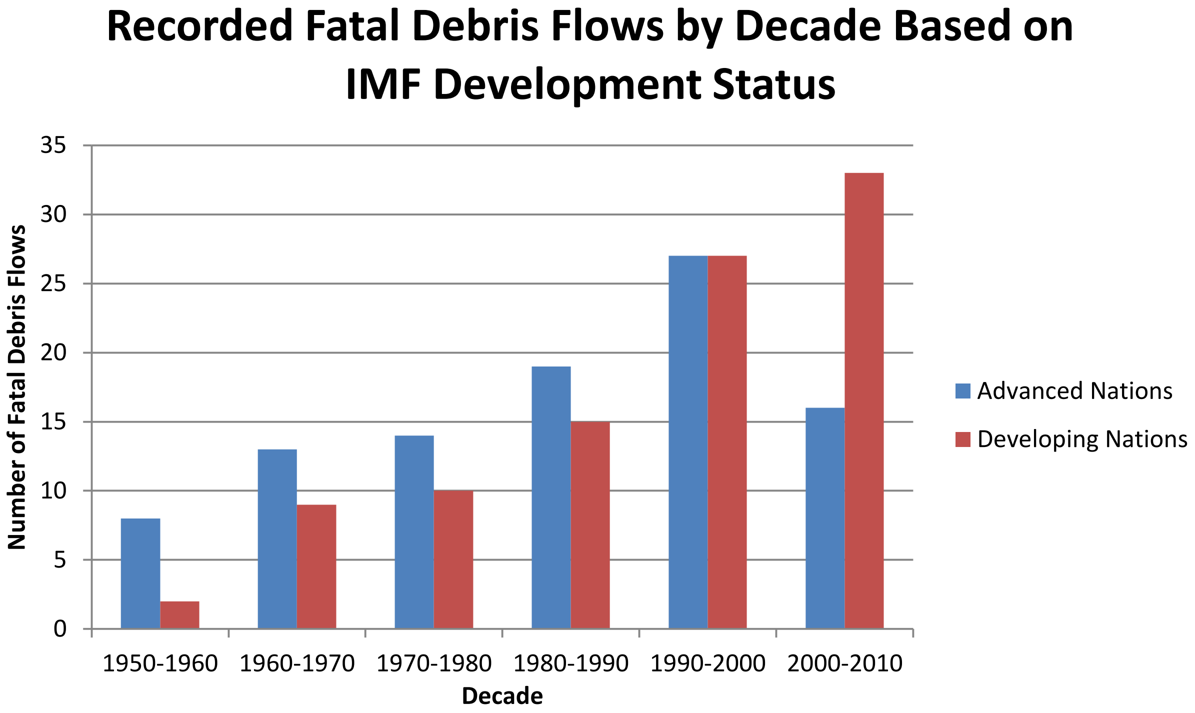

Figure 4.6: Bar graph showing the number of recorded debris flows per decade subdivided by IMF development status.

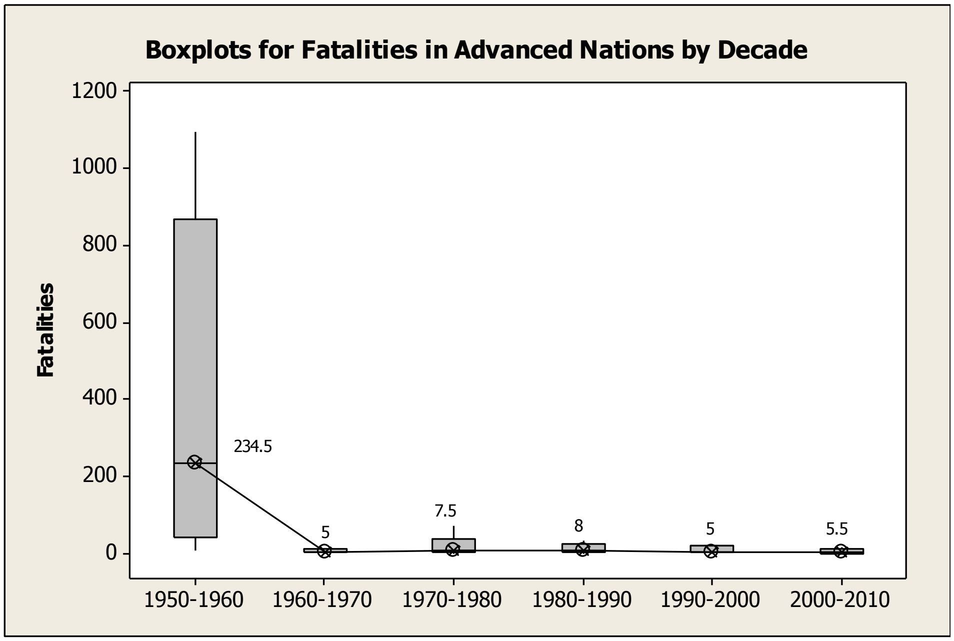

Figure 4.7: Boxplot of fatalities per debris flow in advanced nations divided by decades. The median value and its trend line are displayed.

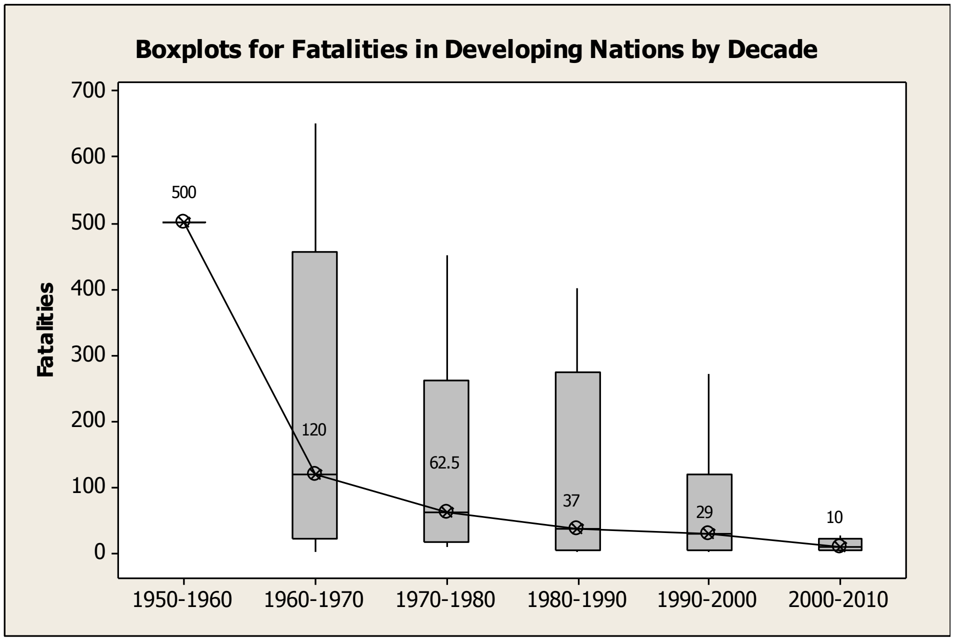

Figure 4.8: Boxplot of fatalities per debris flow in developing nations divided by decades. The median value and its trend line are displayed.

4.3.2 Monthly Analysis

The monthly analysis includes results for the number of fatal debris flows and the mean number of fatalities on a monthly basis for the database as a whole (Figure 4.9) as well as subdivided by specific regions (Figure 4.10 through Figure 4.17).

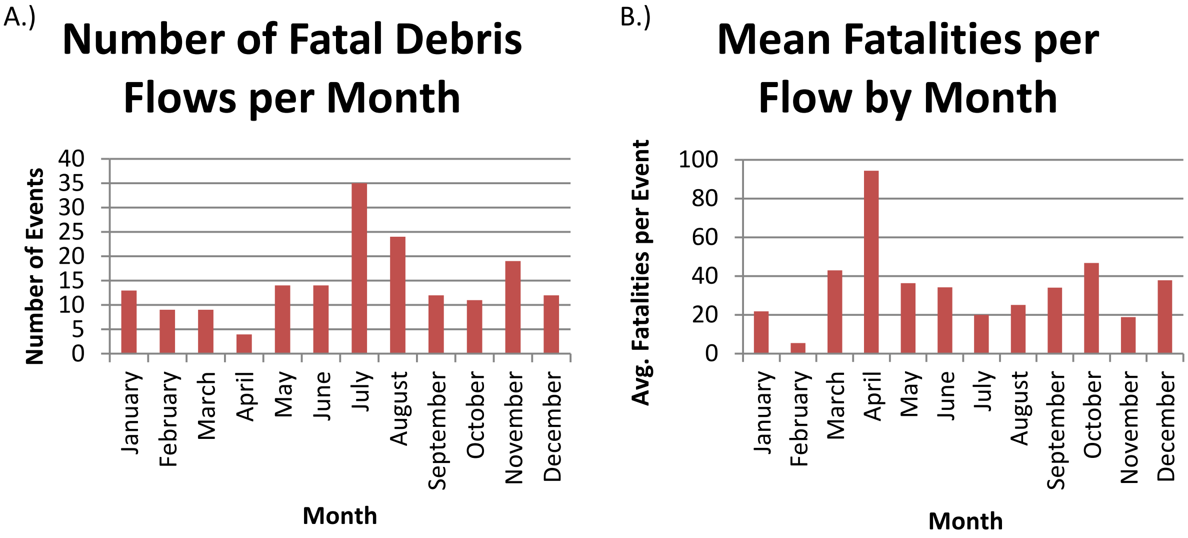

Figure 4.9: A.) Number of fatal debris flow per month for the database. B.) Mean fatalities per debris flow by month for the database.

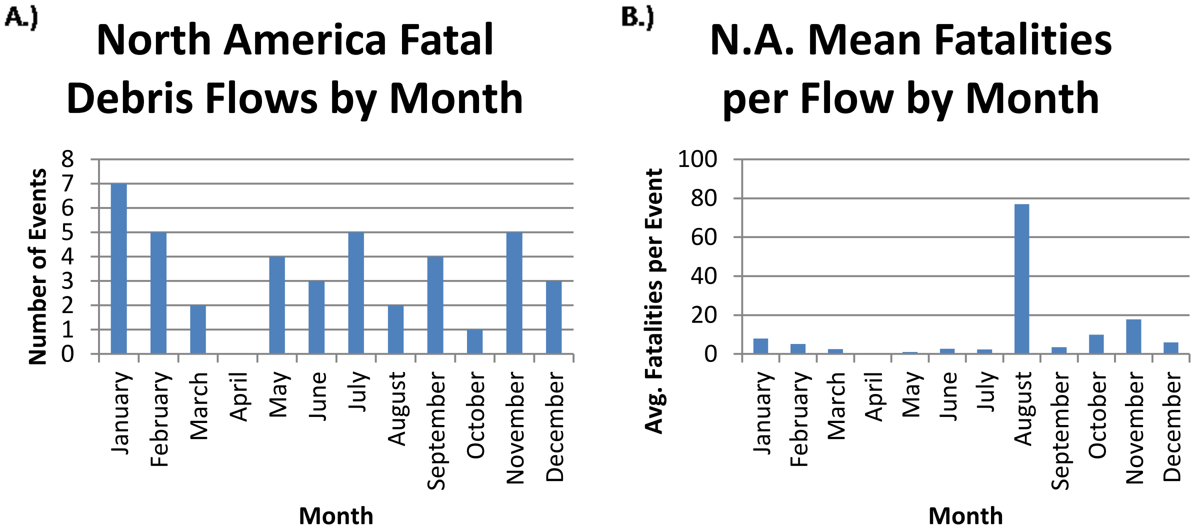

Figure 4.10: A.) Number of fatal debris flow per month in North America. B.) Average fatalities per debris flow by month in North America.

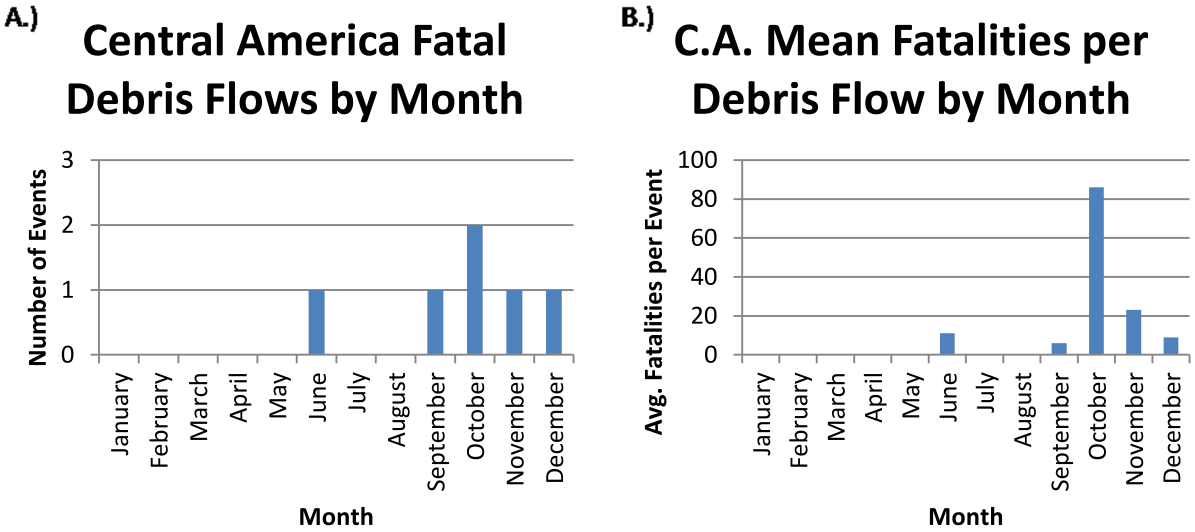

Figure 4.11: A.) Number of fatal debris flow per month in Central America. B.) Average fatalities per debris flow by month in Central America.

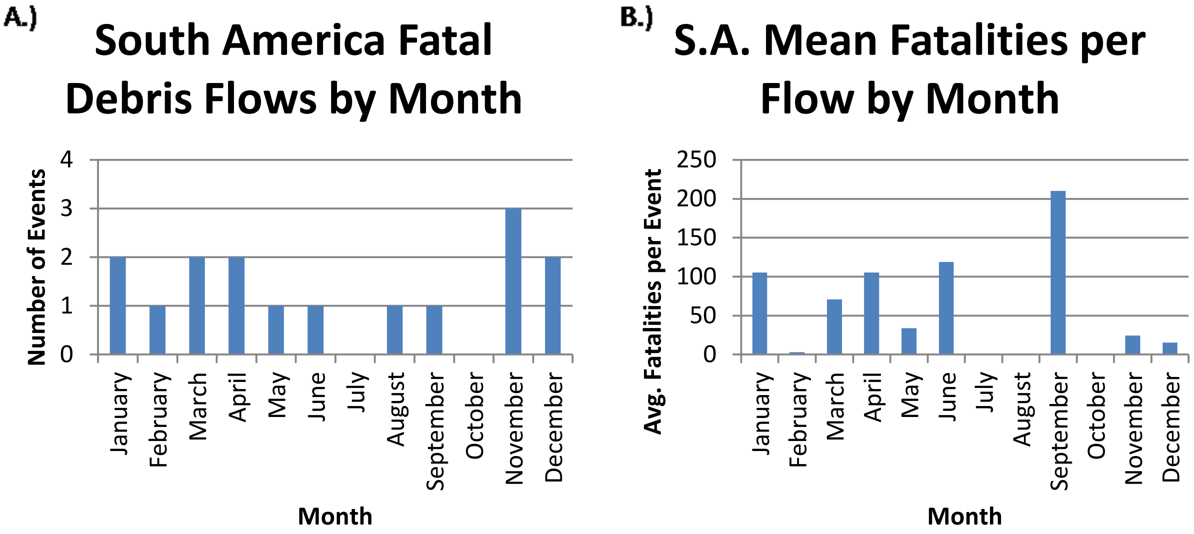

Figure 4.12: A.) Number of fatal debris flow per month in South America. B.) Average fatalities per debris flow by month in South America.

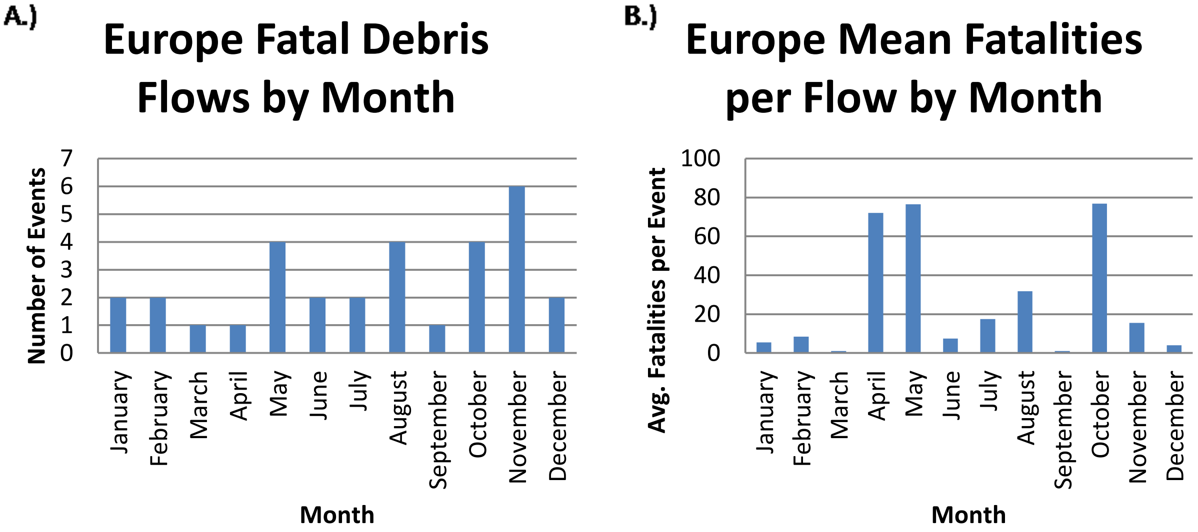

Figure 4.13: A.) Number of fatal debris flow per month in Europe. B.) Average fatalities per debris flow by month in Europe.

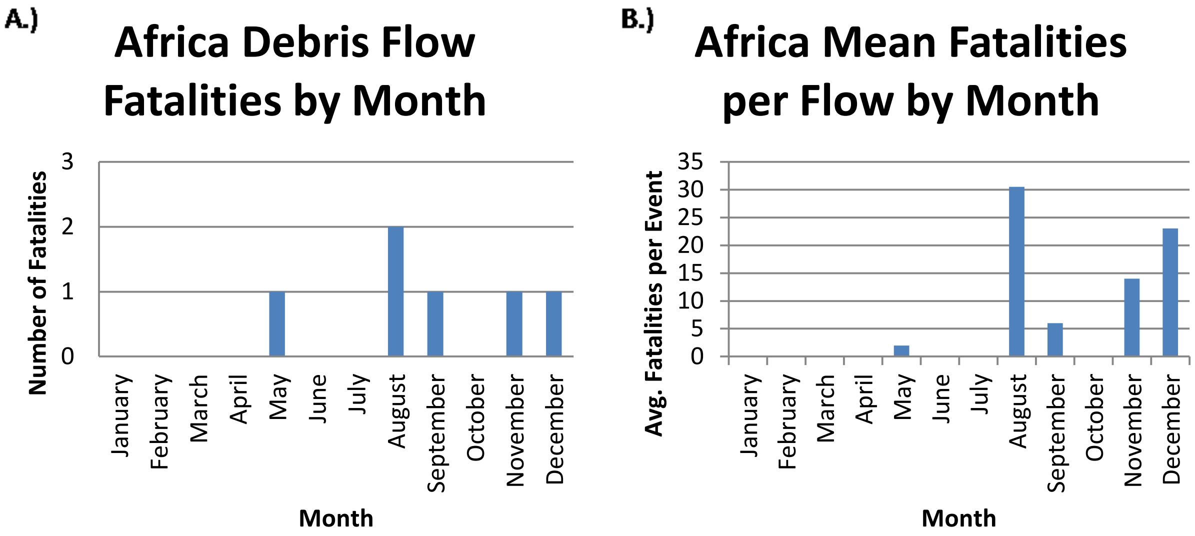

Figure 4.14: A.) Number of fatal debris flow per month in Africa. B.) Average fatalities per debris flow by month in Africa.

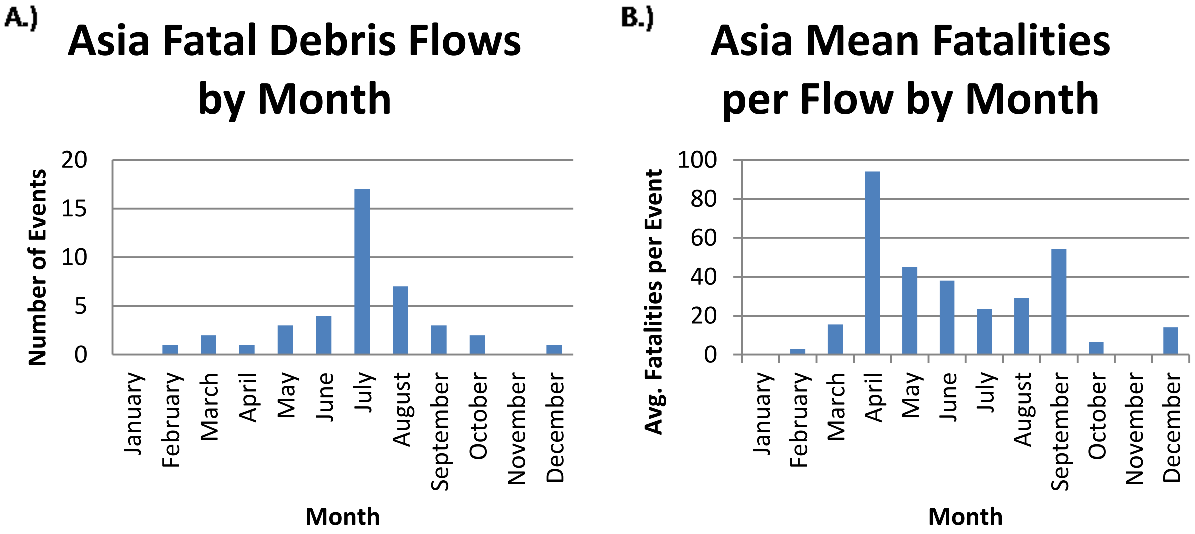

Figure 4.15: A.) Number of fatal debris flow per month in Asia. B.) Average fatalities per debris flow by month in Asia.

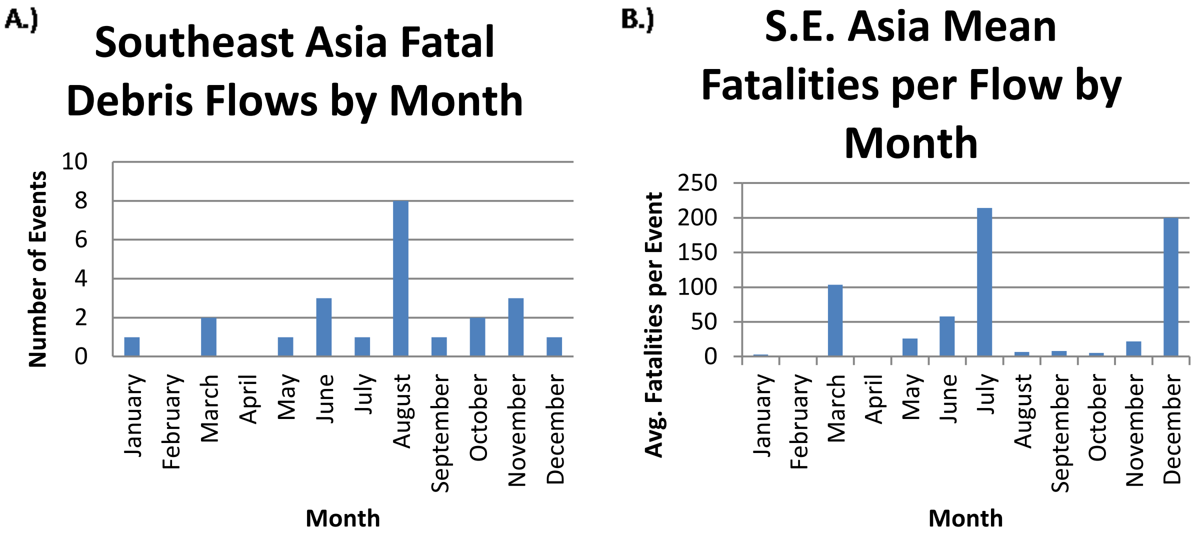

Figure 4.16: A.) Number of fatal debris flow per month in Southeast Asia. B.) Average fatalities per debris flow by month in Southeast Asia.

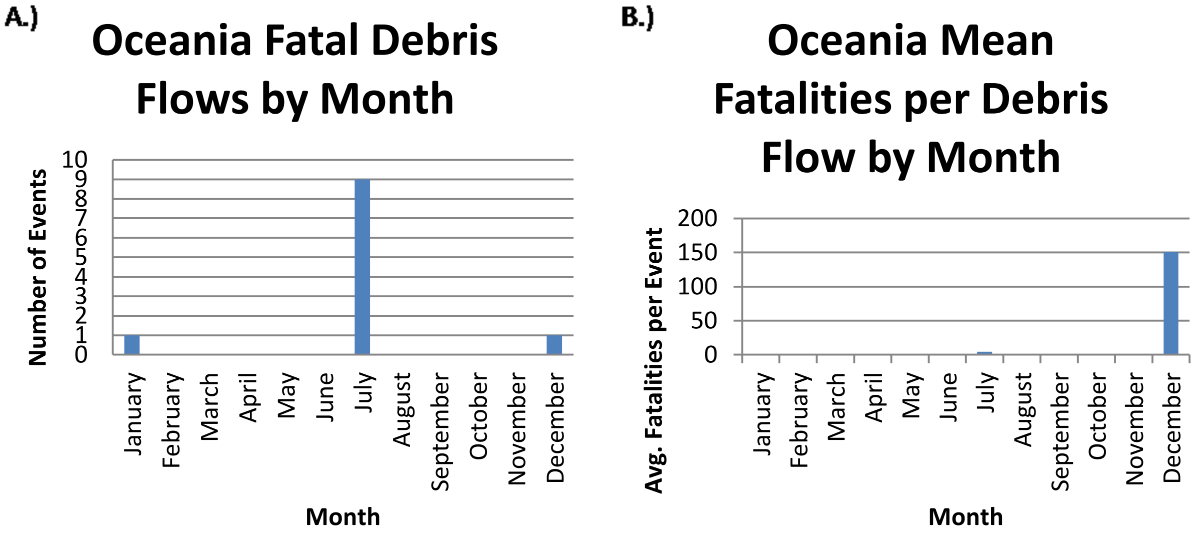

Figure 4.17: A.) Number of fatal debris flow per month in Oceania. B.) Average fatalities per debris flow by month in Oceania.

4.4 Physical Attribute Results

The results of the physical aspects of debris flows are provided below. They are subdivided into the following sections: Warning Signs, Mitigation, Triggers and Causes, and Debris-Flow Volume.

4.4.1 Warning Signs

This section contains the results for both the long and short term warning signs for debris flows. Long term warning signs, provided in Figure 4.18, were recorded for 101 events. These warning signs are those which exist days and months prior to a debris-flow triggering event. Short term warning signs, shown in Figure 4.19 were recorded for 158 events. These warning signs are those that immediately precede or occur during a debris flow.

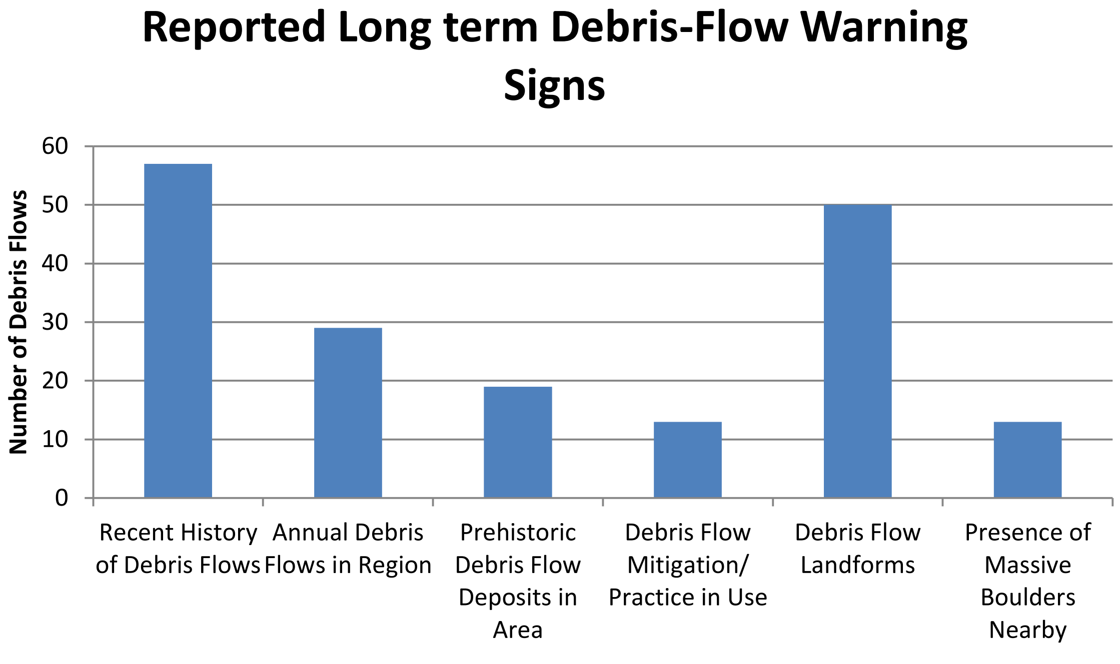

Figure 4.18: Graph of the long term warning signs for debris flows in the locations of fatal debris flows. These values reflect the long term warning signs reported and do not necessarily represent the true frequency of warning signs, which are often omitted from news and literature reports. Categories are not mutually exclusive.

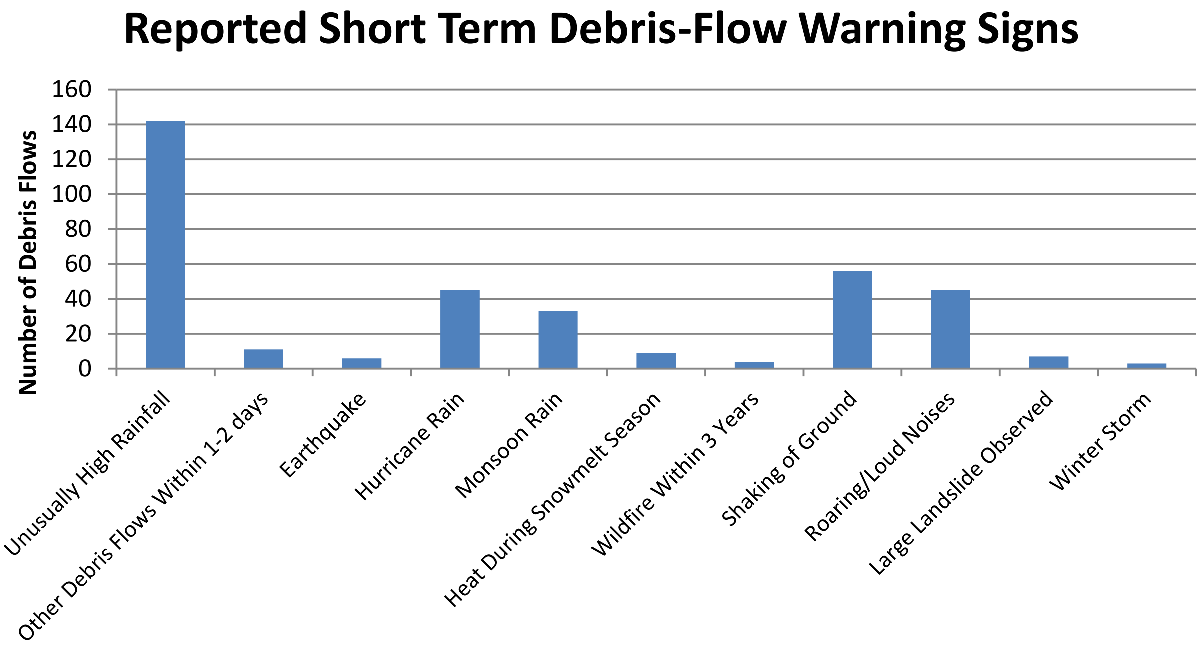

Figure 4.19: Graph of the short term warning signs for debris flows in the locations of fatal debris flows. These values reflect the short term warning signs reported and do not necessarily represent the true frequency of warning signs, which are often omitted from news and literature reports. Categories are not mutually exclusive.

4.4.2 Mitigation

The results for debris-flow mitigation are presented in Figure 4.20. Fifty seven events contain information on presence or absence of debris-flow mitigation.

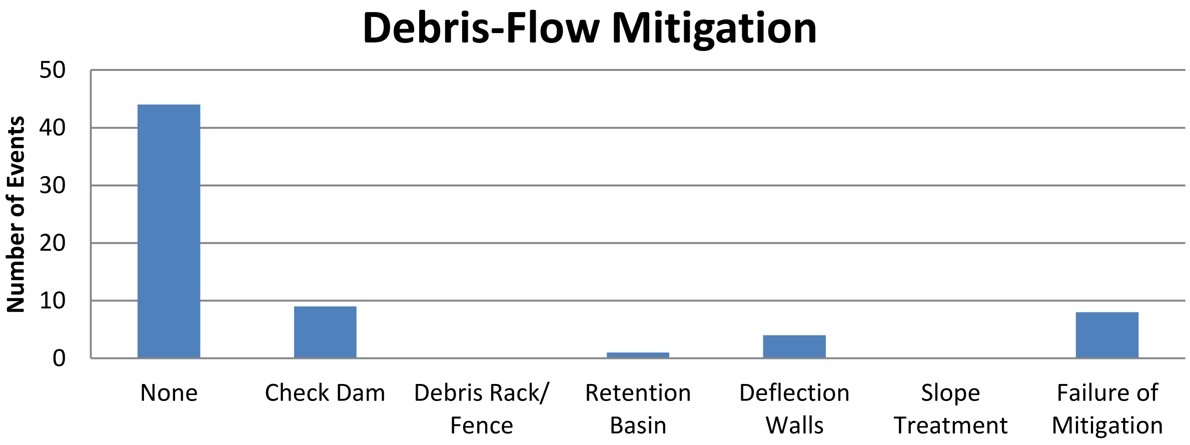

Figure 4.20: Graph of debris-flow mitigation present in the locations of fatal debris flows.

4.4.3 Triggers and Causes

The following graphs present the results on triggers and causes of fatal debris flows. Figure 4.21and Figure 4.22 compare the overall causes and triggers, while Figure 4.23 and Figure 4.24 compare triggers and causes specifically from rainfall. One hundred sixty five events from the database contain information on the trigger and cause of fatal debris flows.

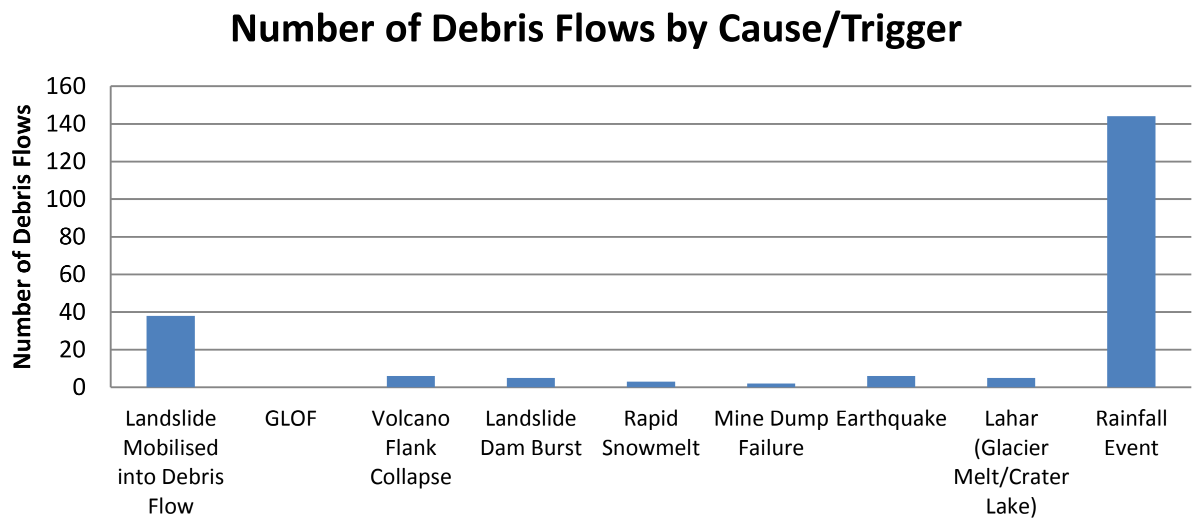

Figure 4.21: Graph of the number of fatal debris flows by the cause/trigger.

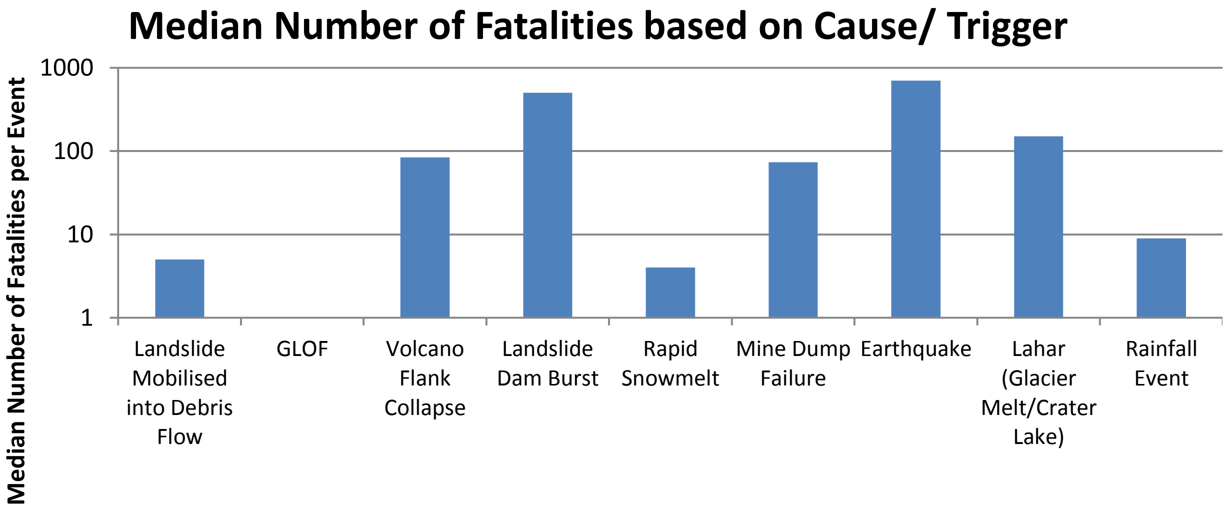

Figure 4.22: Graph of the median number of fatalities per debris flow by cause/trigger.

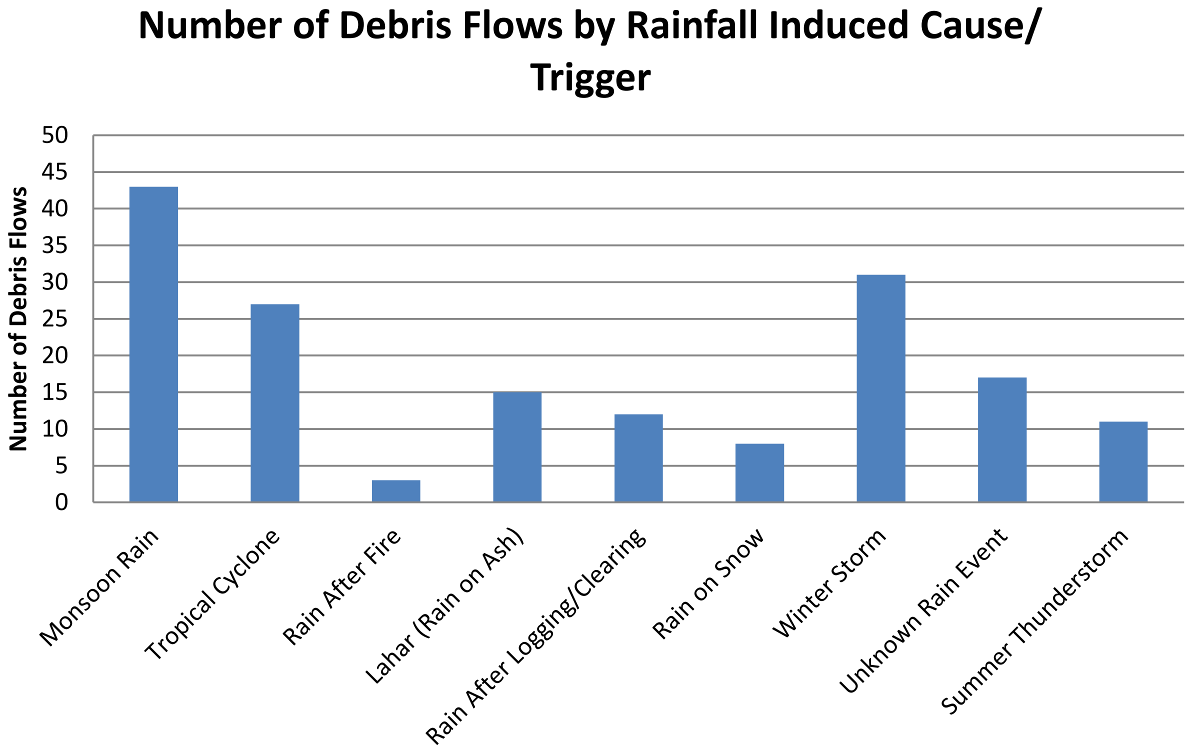

Figure 4.23: Graph of the number of fatal debris flows triggered/caused by rainfall induced events.

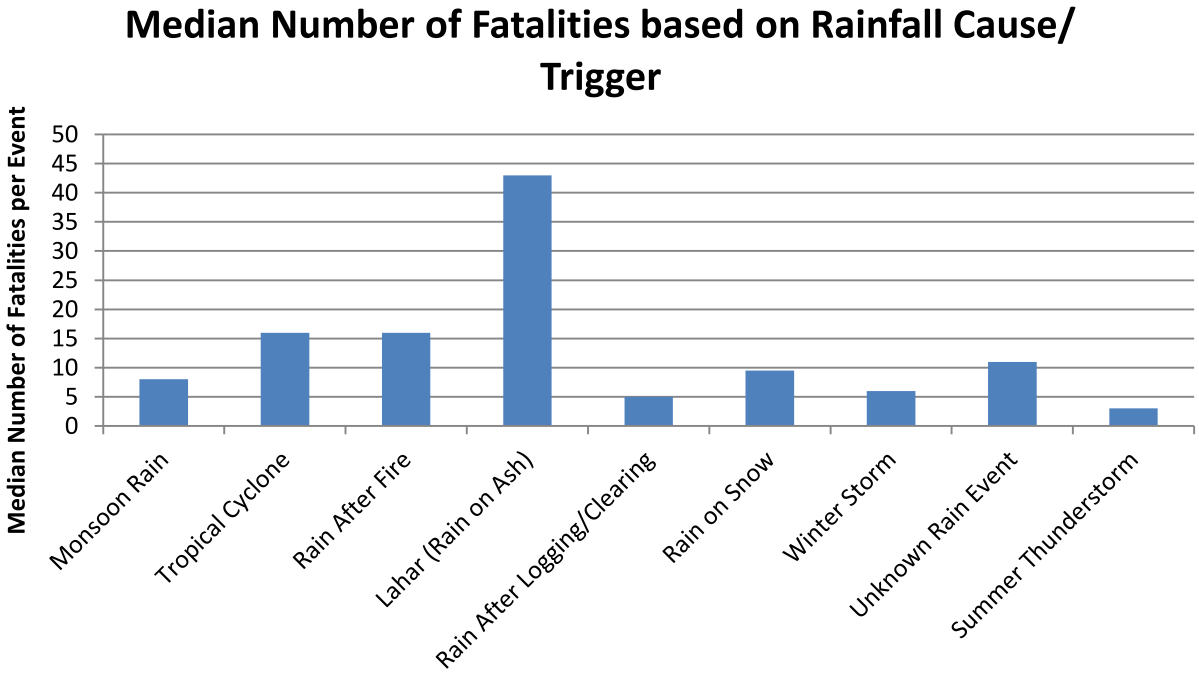

Figure 4.24: Graph of the median number of debris-flow fatalities by rainfall induced cause/trigger.

4.4.4 Debris-Flow Volume

This section contains the results of the regression analysis for the relationship between debris-flow volume and fatalities. Table 4.2 provides data from the F test while Figure 4.25 and Figure 4.26 contain the results for the regression analysis. Figure 4.27 provides four regressions, one for each population class as defined in Table 3.2. Volume data was collected for 66 debris flows.

Table 4.2: Volume Regression F Test Results

Source	Degree of Freedom	Sum of Squares	Mean Squares	F Value	P Value
Regression	1	26.7763	26.7763	34.84	0.000
Error	64	49.1857	0.7685		
Total	65	75.9619			

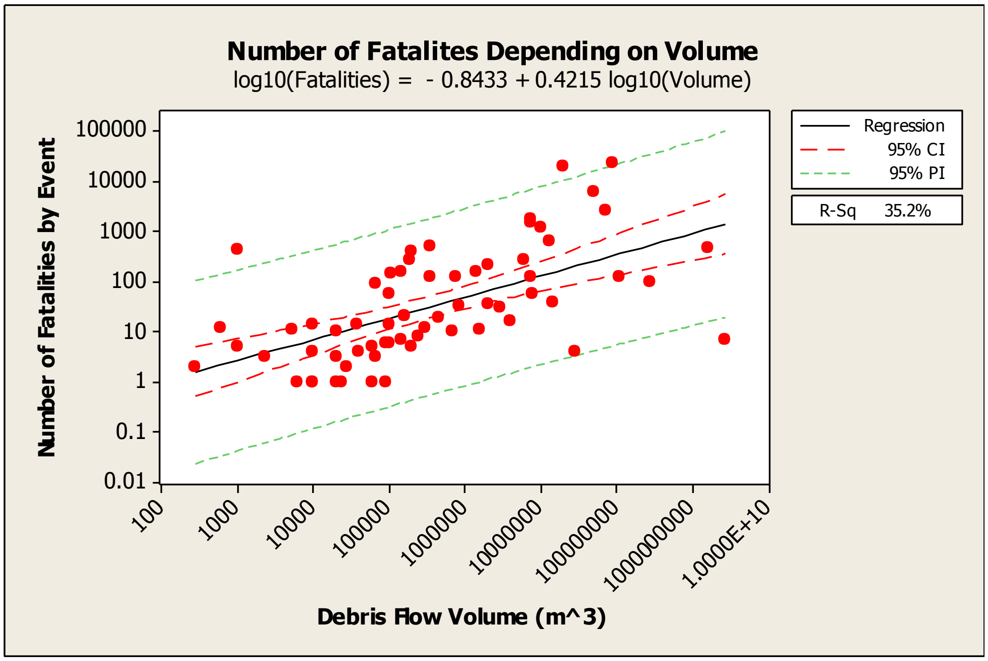

Figure 4.25: Graph of number of fatalities depending on volume. The regression equation, trend line with confidence and prediction intervals, as well as the R^2 value are provided.

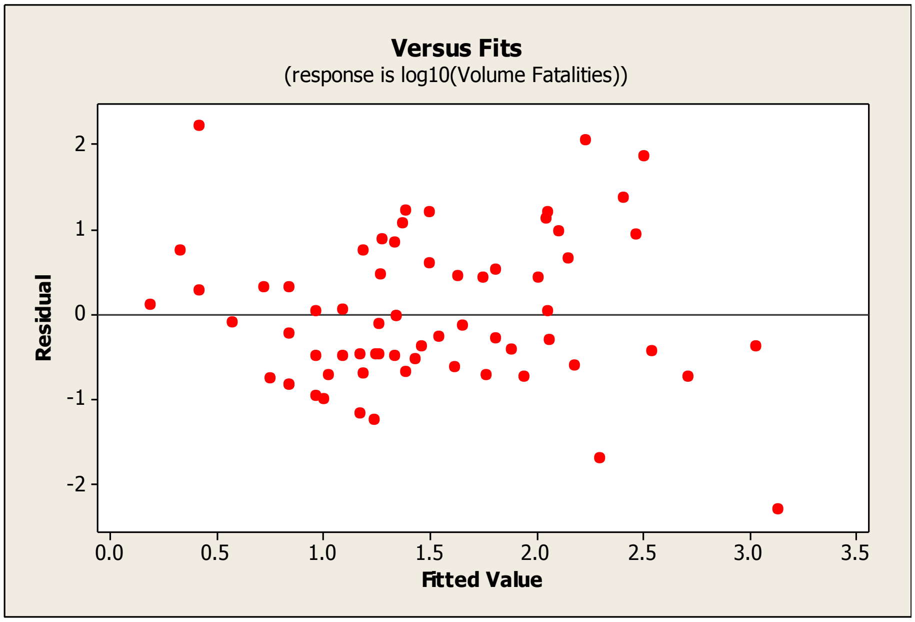

Figure 4.26: Residual versus fits plot for fatalities versus volume regression.

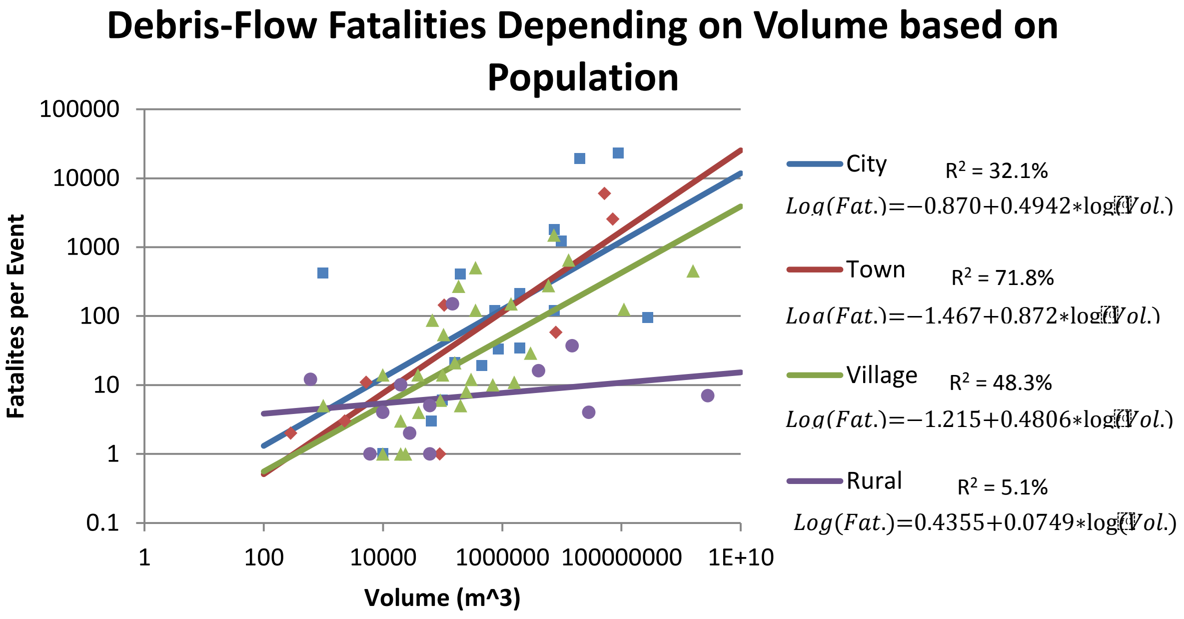

Figure 4.27: Line graphs of debris-flow fatalities depending on volume based on the population. The R^2 values and the regression found by Minitab are provided in the key for each population size.

4.5 Socioeconomic Results

The results of the socioeconomic analysis were subdivided by indicator. Each indicator includes a table of F Test results, a graph of the regression, and the residuals versus fit plot for the regression. The final subsection includes the histograms and descriptive statistics for developing and advanced countries as classified by the IMF.

4.5.1 GDP per Capita Regression

This subsection contains the results of the GDP per capita regression. Table 4.3 provides the results for the F Test, Figure 4.28 provides a graph of the regression, and Figure 4.29 provides the residuals versus fit plot.

Table 4.3: Gross Domestic Product per Capita Regression F Test Results

Source	Degree of Freedom	Sum of Squares	Mean Squares	F Value	P Value
Regression	1	21.233	21.2327	27.51	0.000
Error	210	162.058	0.7717		
Total	211	183.290			

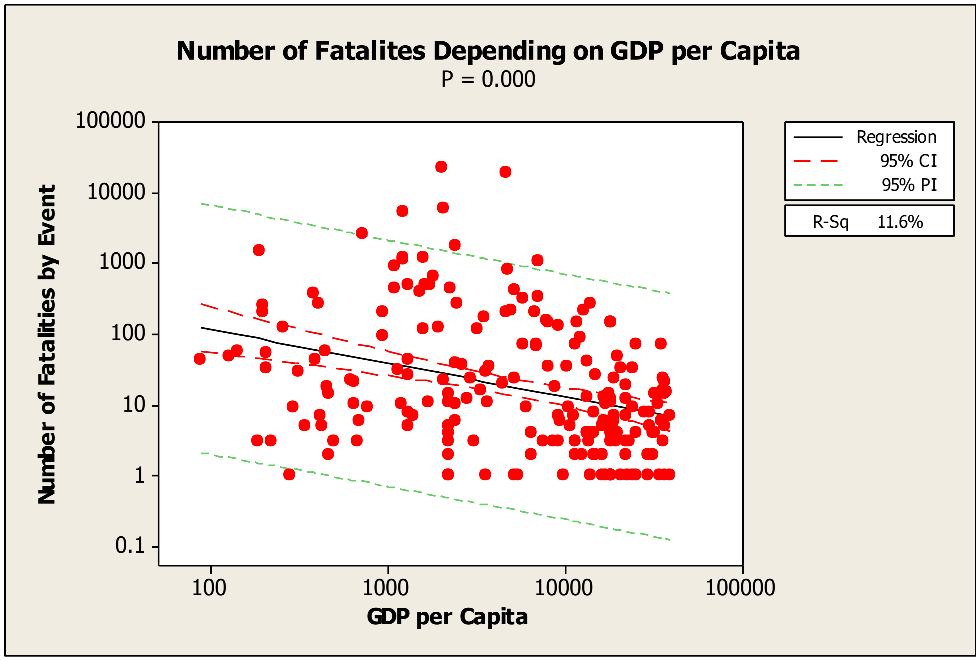

Figure 4.28: Graph of the relationship between fatalities per debris flow and GDP per capita. The P value, trend line with confidence and prediction intervals, as well as the R^2 value are provided.

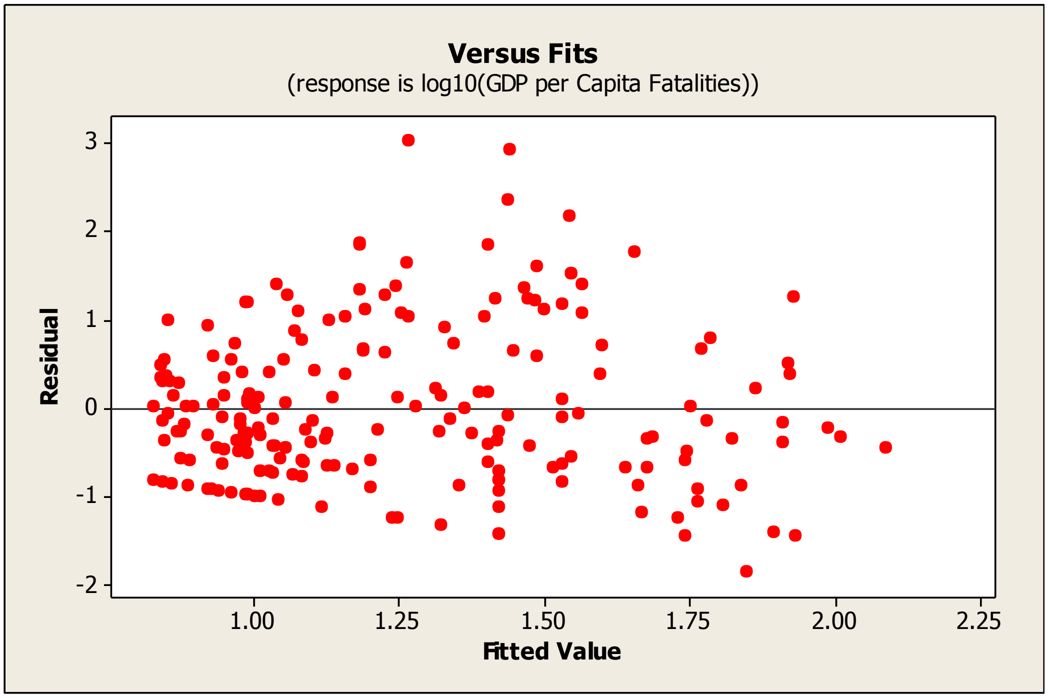

Figure 4.29: Residual versus fits plot for fatalities versus GDP per capita regression.

4.5.2 Hospital Beds per Capita Regression

This subsection contains the results of the hospital beds per capita regression. Table 4.4 provides the results for the F Test, Figure 4.30 provides a graph of the regression, and Figure 4.31 provides the residuals versus fit plot.

Table 4.4: Hospital Beds per Capita Regression F Test Results

Source	**Degree of Freedom**	**Sum of Squares**	**Mean Squares**	**F Value**	**P Value**
Regression	1	13.329	13.3294	17.73	0.000
Error	133	99.990	0.7518		
Total	134	113.320			

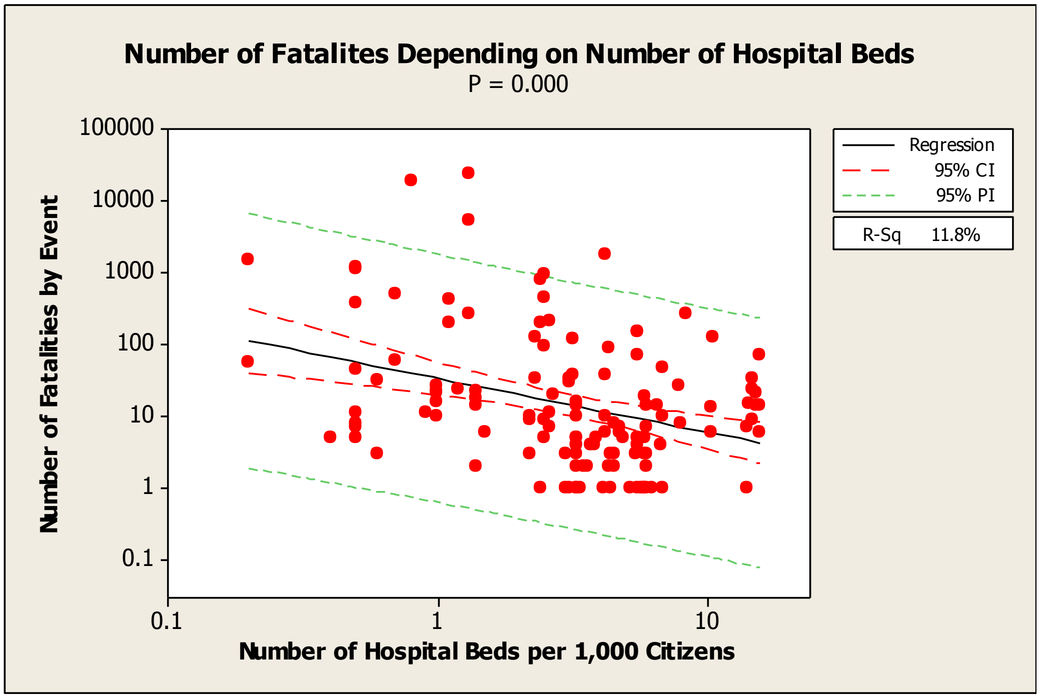

Figure 4.30: Graph of the relationship between fatalities per debris flow and the number of hospital beds per capita. The P value, trend line with confidence and prediction intervals, as well as the R^2 value are provided.

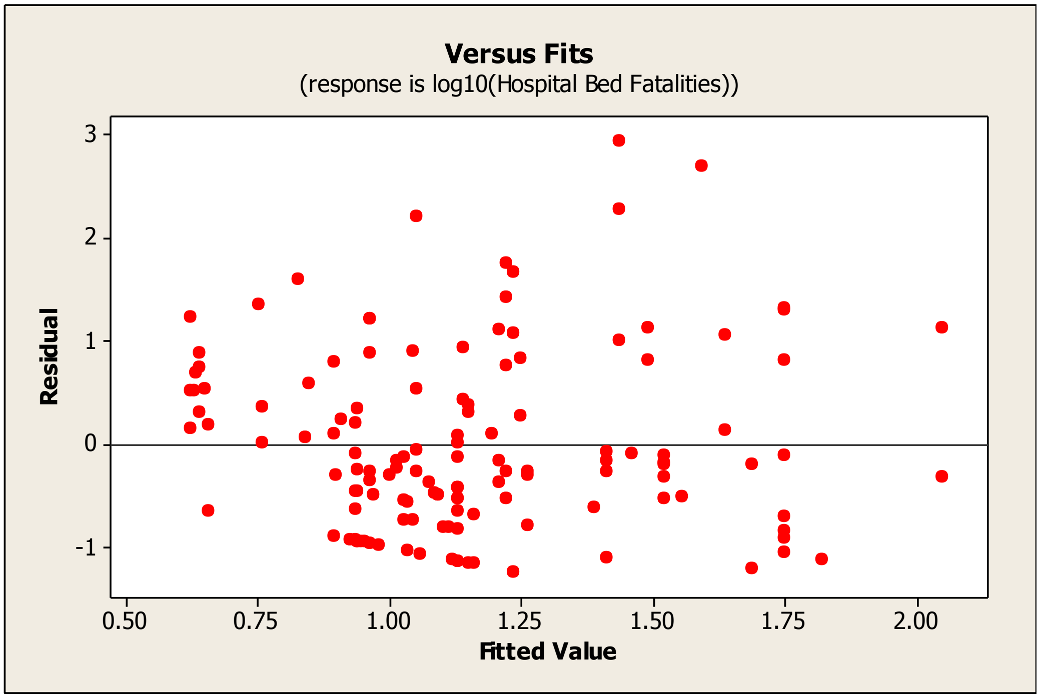

Figure 4.31: Residual versus fits plot for fatalities versus hospital beds per capita regression.

4.5.3 Maternal Mortality Rate Regression

This subsection contains the results of the Maternal Mortality Rate regression. Table 4.5 provides the results for the F Test, Figure 4.32 provides a graph of the regression, and Figure 4.33 provides the residuals versus fit plot.

Table 4.5: Maternal Mortality Rate Regression F Test Results

Source	Degree of Freedom	Sum of Squares	Mean Squares	F Value	P Value
Regression	1	8.6382	8.63818	11.70	0.001
Error	111	81.9504	0.73829		
Total	112	90.5886			

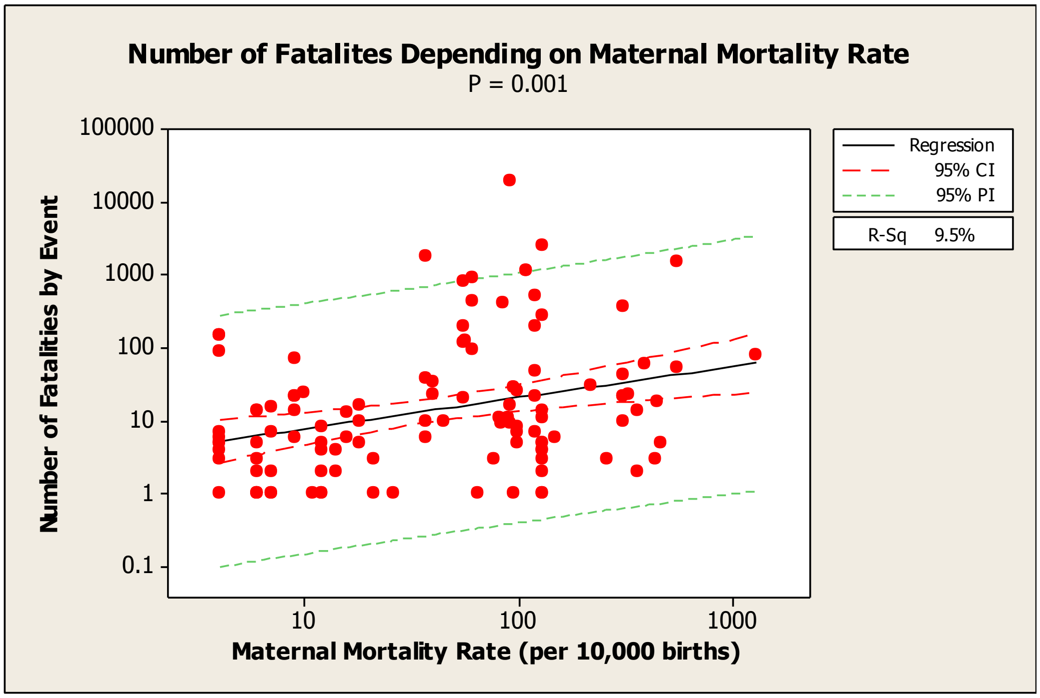

Figure 4.32: Graph of the relationship between fatalities per debris flow and MMR. The P value, trend line with confidence and prediction intervals, as well as the R^2 value are provided.

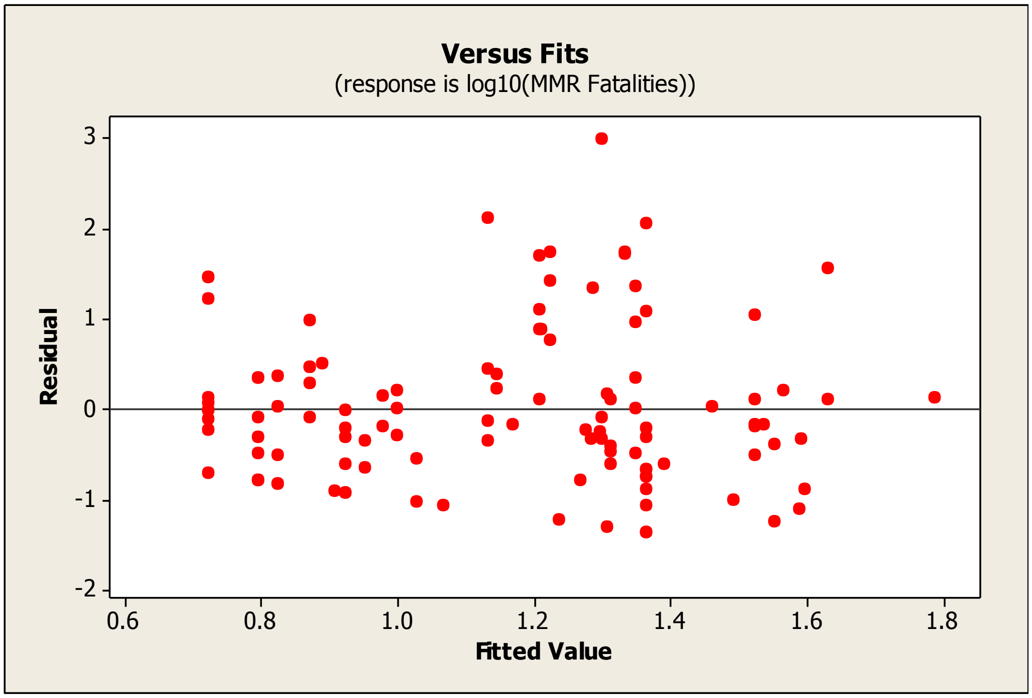

Figure 4.33: Residual versus fits plot for fatalities versus MMR regression.

4.5.4 Life Expectancy Regression

This subsection contains the results of the life expectancy at birth regression. Table 4.6 provides the results for the F Test, Figure 4.34 provides a graph of the regression, and Figure 4.35 provides the residuals versus fit plot.

Table 4.6: Life Expectancy Regression F Test Results

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F Value	P Value
Regression	1	8.522	8.52231	10.40	0.002
Error	145	118.871	0.81980		
Total	146	127.394			

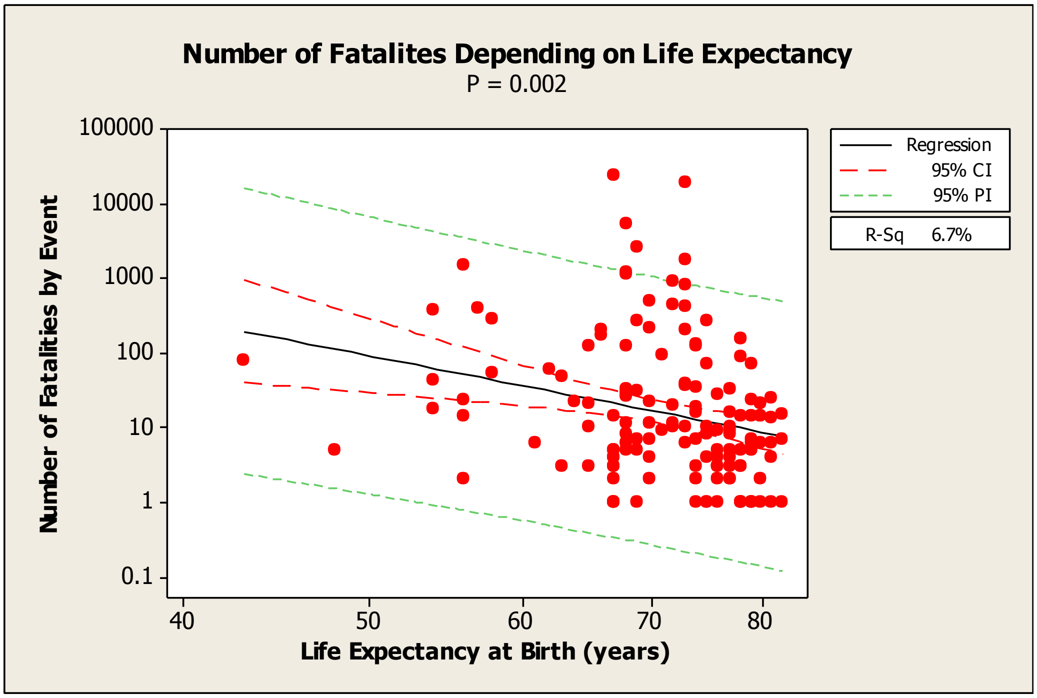

Figure 4.34: Graph of the relationship between fatalities per debris flow and life expectancy at birth. The P value, trend line with confidence and prediction intervals, as well as the R^2 value are provided.

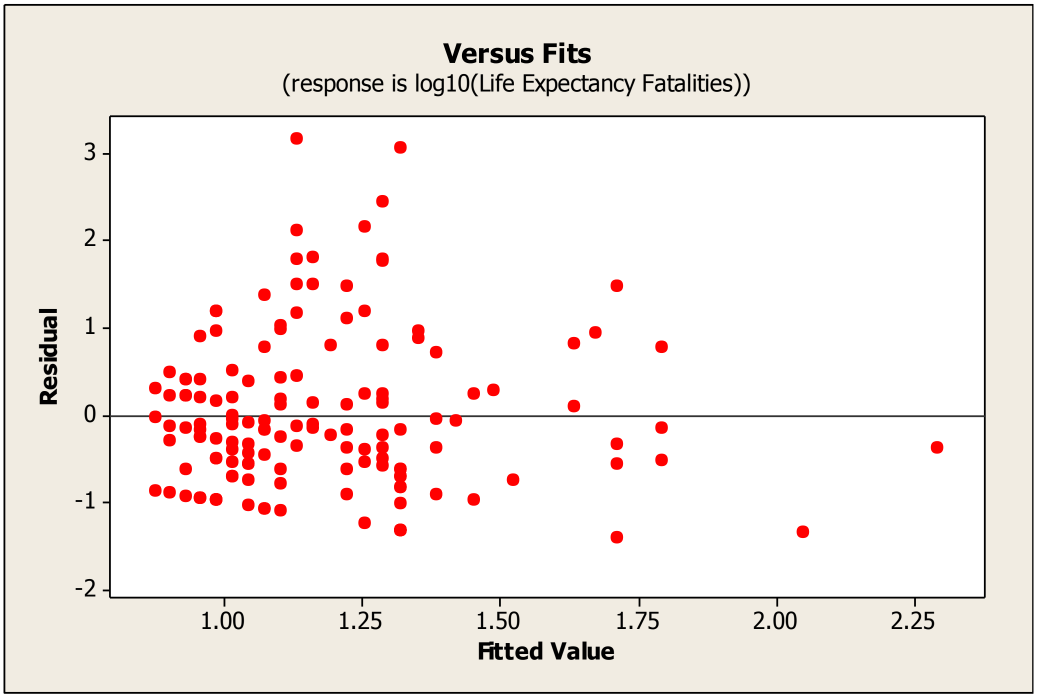

Figure 4.35: Residual versus fits plot for fatalities versus life expectancy at birth regression.

4.5.5 Corruption Perception Index Regression

This subsection contains the results of the Corruption Perception Index regression. Table 4.7 provides the results for the F Test, Figure 4.36 provides a graph of the regression, and Figure 4.37 provides the residuals versus fit plot.

Table 4.7: Corruption Perception Index Regression F Test Results

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F Value	P Value
Regression	1	12.1498	12.1498	17.35	0.000
Error	94	65.8331	0.7004		
Total	95	77.9829			

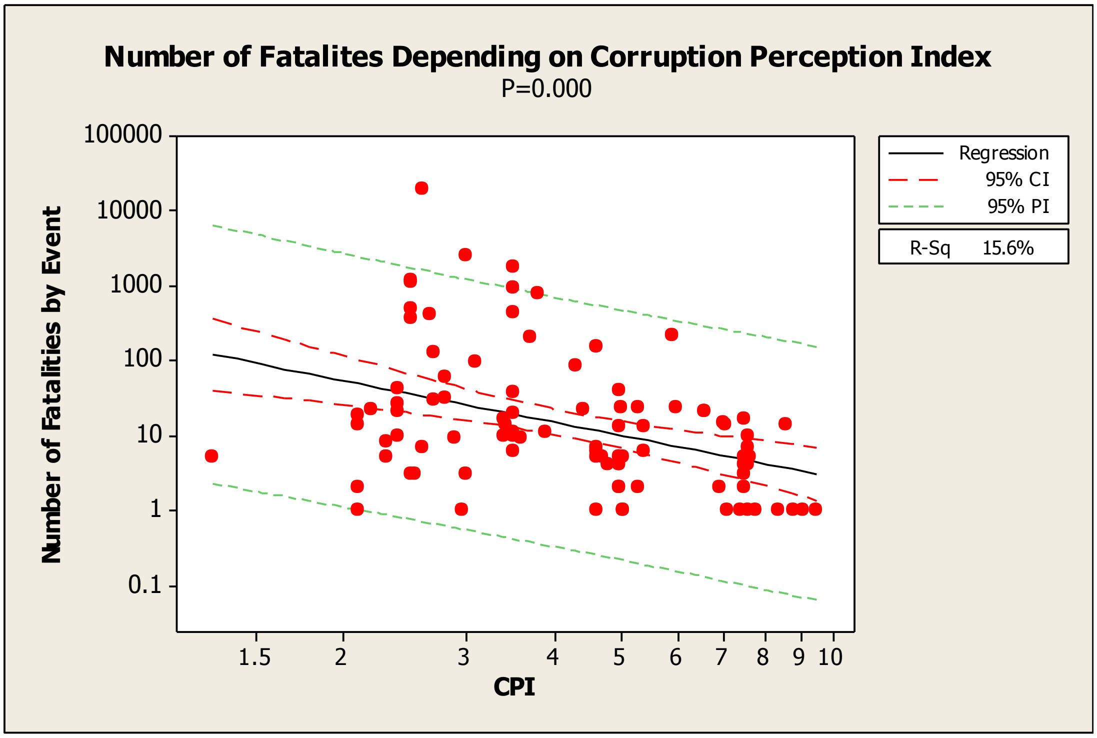

Figure 4.36: Graph of the relationship between fatalities per debris flow and CPI. The P value, trend line with confidence and prediction intervals, as well as the R^2 value are provided.

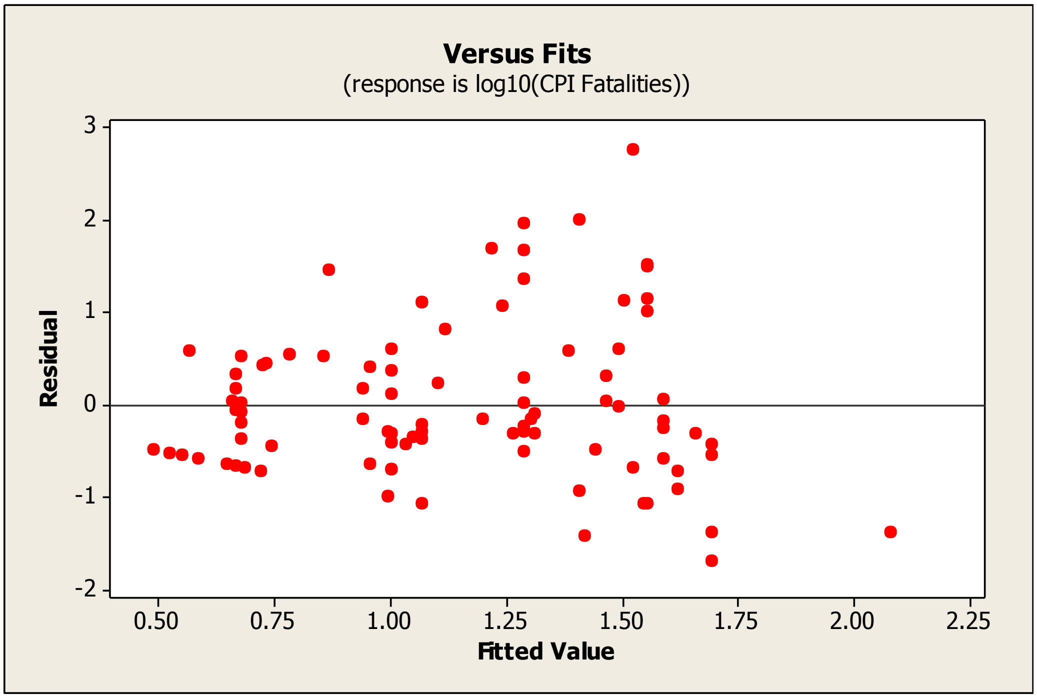

Figure 4.37: Residual versus fits plot for fatalities versus CPI regression.

4.5.6 Technical Journal Publications per Capita Regression

This subsection contains the results of the total technical journal publications per capita regression. These include all technical articles published in in various scientific fields. Table 4.8 provides the results for the F Test, Figure 4.38 provides a graph of the regression, and Figure 4.39 provides the residuals versus fit plot.

Table 4.8: Technical Journal Publication per Capita Regression F Test Results

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F Value	P Value
Regression	1	19.3932	19.3932	29.38	0.000
Error	95	62.7033	0.6600		
Total	96	82.0965			

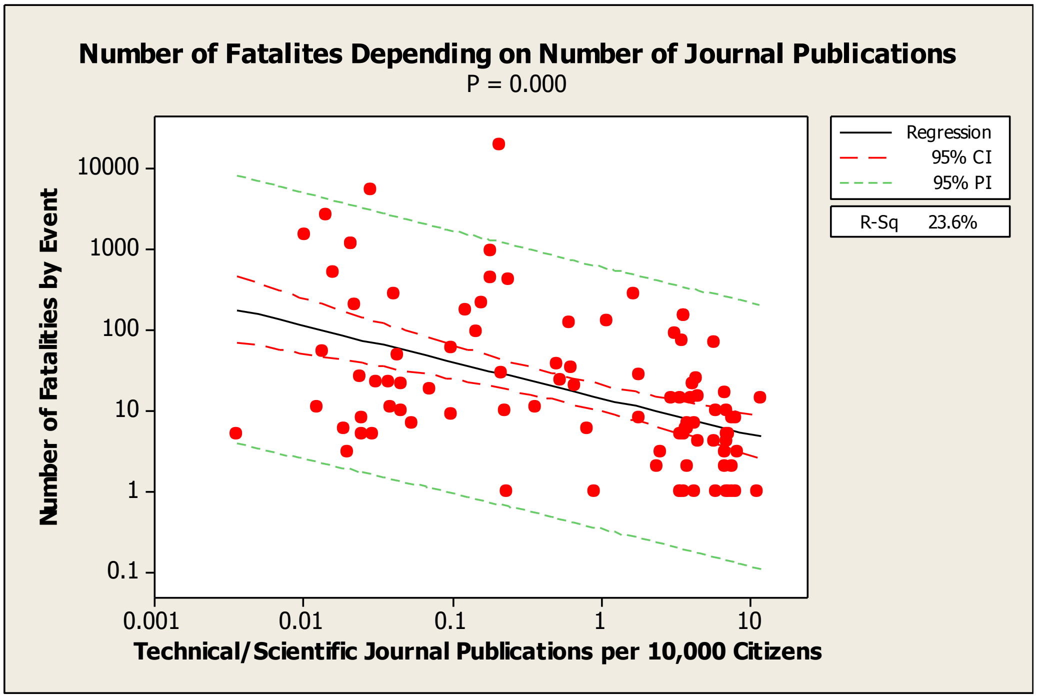

Figure 4.38: Graph of relationship between technical journal publications per capita and fatalities per event. The P value, trend line with confidence and prediction intervals, as well as the R^2 value are provided.

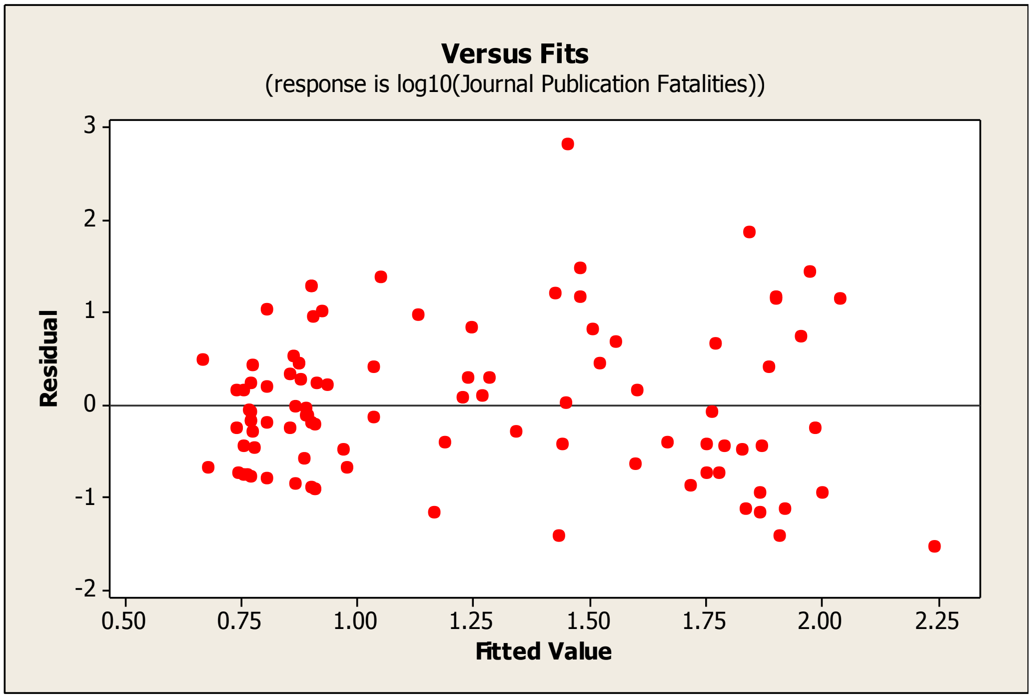

Figure 4.39: Residual versus fits plot for fatalities and technical journal publications per capita regression.

4.5.7 International Monetary Fund Classification

This subsection contains the results of the analysis of fatal debris flows and number of fatalities divided into the IMF classifications of "advanced" and "developing". Table 4.9 contains the descriptive statistics for advanced and developing nations. Figure 4.40 provides the histograms for these populations while Figure 4.41 and Figure 4.42 are charts showing the relative percentages of fatal debris flows and fatalities in each population, respectively.

Table 4.9: Descriptive Statistics for Advanced and Developing countries based on IMF Classification

Statistic	**Advanced**	**Developing**
Total Fatalities	5327	72452
Total Debris Flows	101	113
Mean Fatalities per Event	52	620
Median Fatalities per Event	6	23
Mean Fatalities per Year	87	1188
Standard Deviation	158.4	2834.1
Skewness	5.5	6.9

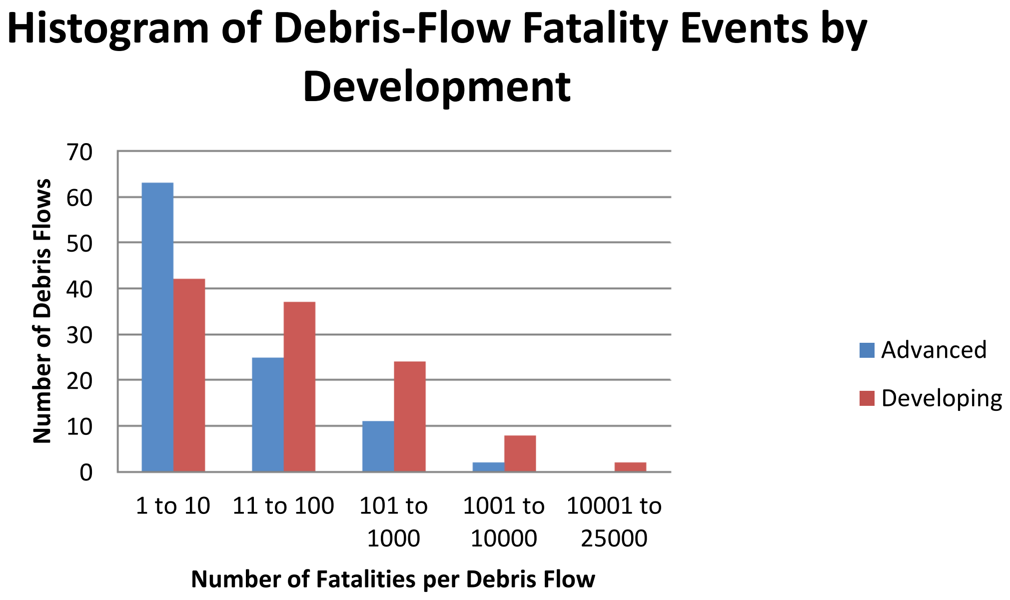

Figure 4.40: Histograms of fatalities per debris flows for developing and advance countries based on IMF classification.

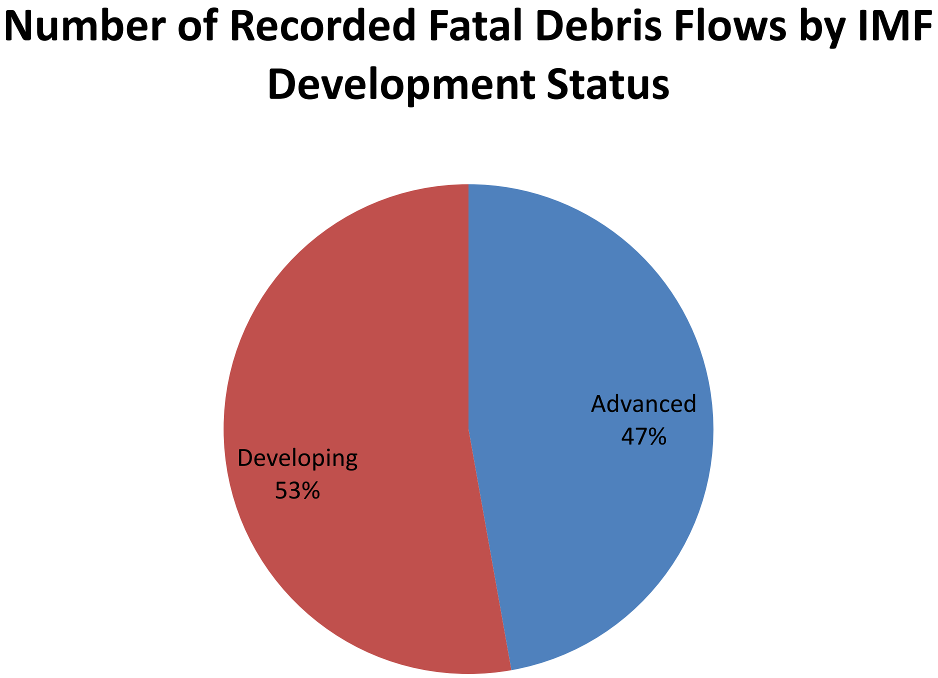

Figure 4.41: Chart of the percentage of fatal debris flows in the database based on IMF development status.

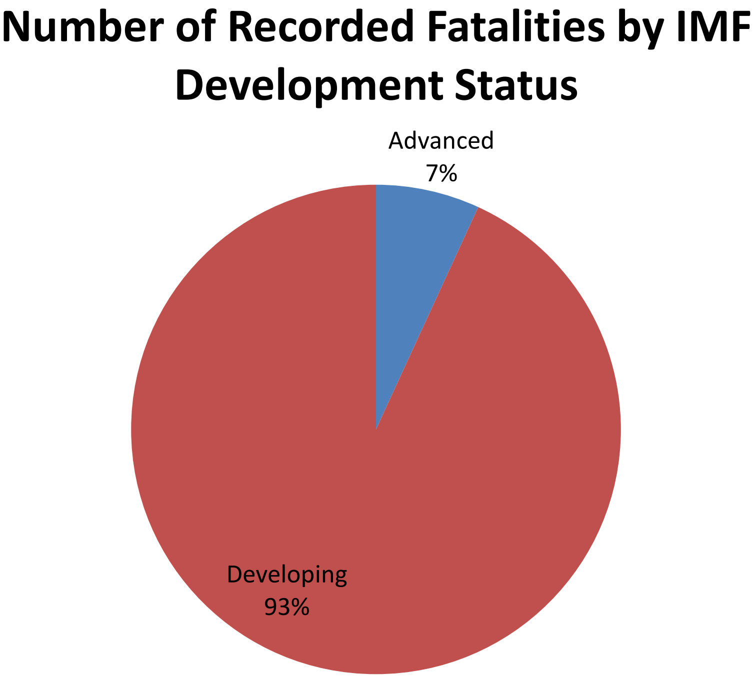

Figure 4.42: Chart of the percentage of fatalities in the database based on IMF development status.

CHAPTER 5

DISCUSSION

This chapter discusses the findings of the debris flow fatality database. Subsections are divided in the same way as the results chapter.

5.1 Descriptive Statistics

The debris flow fatality database provides necessary statistics that address the threat of debris flows throughout the world. Table 4.1 shows a total of 213 events were documented with a total fatality count of 77,779 over the 61 year timespan of the database. The data breaks down to an average of 3.5 fatal debris flows per year, with a median value of 165 fatalities per year. In Figure 4.1 the data is not normally distributed, and the great majority of fatal debris flows (166) having fatality counts less than 100. In fact, 185 out of 213 fatal debris flows have fatality counts lower than the outlier threshold value of 269 fatalities. While these smaller debris flows make up the majority of events, the majority of fatalities come from catastrophic debris flows. The most massive events killed 19,000 (Vargas, Venezuela) and 23,000 (Nevado Del Ruiz, Colombia) making up 53% of the fatalities in the database. The high fatality count in Vargas can be attributed to a large debris flow completely inundating the city of Vargas, which had been constructed on a debris flow fan. The Nevado del Ruiz debris flow event consisted of multiple eruption induced lahars that completely destroyed multiple towns. Of the 77,779 fatalities recorded in the database only 5,637 fatalities are from debris flows with fewer fatalities than the outlier threshold value. These massive debris flows have a profound impact on the descriptive statistics, causing the mean fatalities per event to be relatively high at 365. As described in section 3.2.1, this value is a biased indicator of the central tendency of fatal debris-flow causalities. Hence the median value of 11 fatalities per debris flow event is believed to be much more indicative of the number of people killed in a typical fatal debris flow.

These descriptive statistics provide useful quantitative data addressing the global hazard of debris flows, however it must be realized that the database is undoubtedly missing many fatal debris flows. Many smaller events are likely not included in the database, as technical literature has primarily focused on sizeable events and media sources have typically written articles on the largest, most newsworthy events. The lack of documentation is also correlated to the date of occurrence, as coverage is sparser from earlier years and limited to larger events (see section 5.3.1 for further discussion). Finally, the location of the incident also affects its documentation. Locations that are remote, within developing countries or sparsely populated areas, have less documentation (see section 5.3.1 for further discussion).

The missing data means these descriptive statistics represent minima and maxima statistics for various hazard parameters for debris flows. For example, the total fatality count represents a minimum number of fatalities from debris flows, as the count will increase as there are more historic events than those discovered for this research. For the same reason, the mean annual debris-flow fatality count is also a minimum. Conversely, the mean and median numbers of fatalities per event are expected to be maxima, as these statistics would be significantly lower if more low fatality events had been included in the database.

5.2 Spatial Distribution of Fatal Debris Flows

Fatal debris flows occur around the globe with recorded events in 38 countries (Figure 4.2). However, fatal debris flows and the number of fatalities are not distributed equally. Within the database, the top three nations with the highest number of fatal debris flows are the United States, Italy, and Japan (Figure 4.2). This is likely due to better reporting and intense debris flow research within these countries. However, these three countries do not have the highest average debris-flow fatality rates. In fact, Figure 4.3 shows that countries in North America have the lowest median debris-flow fatality rates. The countries with the highest median debris-flow fatality counts in the database are in South America and Asia with the top countries being Colombia, Venezuela, Peru, and Nepal. These high median are mostly due to particularly catastrophic events. These countries contain many of the elements necessary for disastrous debris flows: they are tectonically active, receive large precipitation events, and contain dense population centers in mountainous regions. These countries, as seen in Figure 4.2, do not necessarily have many recorded debris flows within the database. It is likely that within these countries, many smaller fatal debris flows have not been reported. The median value of fatalities per flow in these countries is probably significantly lower.

5.3 Temporal Analysis of Fatal Debris Flows

The temporal analysis has been subdivided into two sections, based on annual and monthly trends.

5.3.1 Database Overview

The graphs of yearly debris-flow fatalities indicate an increase in the number of reported debris flows over time, with a decrease in the median number of debris-flow fatalities per event. Figure 4.4 clearly shows an increasing trend in the number of fatal debris flows per decade with the exception of the decade from 2000 to 2010. The decade between 1950 and 1960 only has 10 fatal debris flows recorded while the decade between 1990 and 2000 has a high value of 55 fatal debris flows. As the number of debris flows has increased, Figure 4.5 shows the median number of fatalities per debris flow has varied over the timeframe of the database. A steep decrease from 327 in 1950’s to 9 in the 1960’s is the most notable trend, followed by a slight increase in the 1970’s to 21 fatalities per event. This slight increase was followed by a decrease to 7 fatalities per event in the 1980’s. This median value has remained fairly constant to the present day, with a slight increase to 10 fatalities per event in the early 2000’s. The initial large drop in the median value for the 1950’s to 1960’s indicates that the number of fatal debris flows did not increase between these decades, but the documentation of debris flows did. If fatal debris flows had indeed been increasing, one would expect the median number of fatalities per debris flow to remain constant, not decrease. However, no real discernible trend is strong in the median values for the decades following 1960.

While these observations may indicate an increase in the number of fatal debris flows, analysis of the data broken into the two IMF classifications reveals this is not completely the case. Figure 4.6 clearly indicates the number of recorded fatal debris flows has steadily increased every decade in developing countries. At the same time, Figure indicates the median number of fatalities per debris flow has dropped steadily in developing countries every decade. This decrease is significantly more apparent than in the undivided data of Figure 4.5. As stated, an increase in the number of events but a decrease in the median size of events indicates greater documentation of fatal debris flows, not an increase in the number of fatal debris flows. This decrease not only indicates debris flow documentation is improving, but that smaller, less severe flows are being documented in developing nations as time progresses. This is likely due to increased research and technological advances that allow for easy publication of these events to a global audience.

Trends in advanced countries differ significantly from those in developing countries. Figure 4.6 shows fatal debris flows increase from 1950 to 2000 but have a sharp decrease in number in the decade from 2000 to 2010. It is hypothesized that this decrease may be explained by increased debris flow mitigation and regulation in advance countries. As for the median number of fatalities per debris flow, advanced countries have not seen a significant change in the median value of fatalities per event since the 1960's. The median value for the 1950's was 234.5 but has ranged from 5 to 8 fatalities per debris flow since 1960 (Figure 4.7). The decrease in reported debris flows in the earlier part of the database likely indicates better reporting of debris flows in advanced countries. However, the lack of change in the median number of fatalities indicates that documentation of debris flows has not changed much since 1960. The trend in debris flows within advanced countries is likely indicative of the actual quantity of fatal debris flows.

5.3.2 Monthly Analysis

The monthly analysis of the data exposes seasonal variation for debris-flow fatalities. Looking at the monthly data of the entire database (Figure 4.9), it becomes apparent that fatal debris flows increase in number during the northern hemisphere summer, peaking in July, and decrease in late winter and early spring with a minimum number in April. An interesting trend is apparent in the mean number of debris-flow fatalities per event (Figure 4.9). The highest mean occurs in April, while the lowest average occurs in July. Therefore, even though July has the highest number of fatal debris flows, they tend to be less severe.

Trends in the regional graphs provide a different perspective. In North America, the highest number of fatal debris flows occurs in January, but the threat remains constant for most of the year (Figure 4.10). There is a decrease in the early spring months with March containing only 2 recorded events and April containing none. The high number of fatal debris flows in January is likely caused by winter storms on the west coast of North America, specifically in California and British Columbia. Fatal debris-flow occurrence remains fairly constant throughout the summer and fall due to the summer monsoon season in the west and the fall hurricane season in the east. Looking at the average number of fatalities per debris flow (Figure 4.10), August appears to be the most hazardous month with a mean value of 77 deaths per debris flow. This high number can be attributed to one hurricane event that occurred in Virginia in 1969 in which 150 people were killed by debris flow. Another peak in danger occurs in November where the mean is 18 fatalities per debris flow. Once again, this higher number can be attributed to hurricane induced debris flows, caused by late season storms.

In Central America, the majority of debris flows occur in the fall months from September through December, peaking in the month of October (Figure 4.11), it is evident that October is the most deadly month for debris flows in Central America. This high mean value is a result of hurricane-triggered debris flows, whose severity is discussed in detail in Section 5.4.3.

Recorded fatal debris flows peak in November in South America (Figure 4.12). The number of debris flows is also elevated through the months of January to April. This corresponds to the South American Monsoon Season. This system occurs in the Southern Hemisphere summer months from December through May (Liebmann and Mechoso, 2011). The deadliest month for debris flows is September (Figure 4.12). The high mean value is attributed to only one event, the Rio Limon debris flows caused by heavy, prolonged rainfalls (Schuster et al., 2002). It should be noted that data from South American countries has been fairly sparse until recently and relies mostly on large events. As severe debris flows dominate this analysis, the monthly analysis for South America is likely not a complete representation of trends in this region.

Fatal debris flows in Europe peak in the months of October and November with notable increases in May and August (Figure 4.13). The large values in October and November correspond to the wet season of the Mediterranean, starting in October, peaking in November, and lasting until March (Mehta and Yang, 2008). The increased activity in the summer (notably May) corresponds to summer rainstorms in northern Europe brought on by the European monsoon flow. April also has an elevated mean fatality count as the only debris flow recorded for the month struck a hospital and led to 72 fatalities.

Data for Africa is sparse, particularly in the earlier years of the database. From the recorded data, August appears to have both the highest number of fatal debris flows and the highest mean debris-flow fatality count (Figure 4.14). This does not appear to correspond with monsoonal rainfall, which typically occurs in two phases from April to May and October to November (Nieuwolt, S., 1979). The lack of correlation to known seasonal precipitation patterns is likely due to the minimal amount of debris-flow information from the African continent. There is simply not enough data from Africa to make any real interpretations on seasonal trends and debris-flow fatalities.

Asia has distinct seasonal trends in the number of fatal debris flows. The number increases throughout the spring, peaking in July, and decreasing into the fall (Figure 4.15). This corresponds to the Asian monsoon which begins in late spring and continues through summer (Li and Yanai, 1995). The mean fatalities per debris flow follow an opposite trend, with the largest value in April and the second largest in September, and a relative minimum between these two peaks occurring in July. The decreasing trend in fatalities over the summer may be explained by human behavior. That is, as the monsoon season sets in, it is hypothesized that populations adapt to deal with the increased rainfall, leading to an overall decrease in the size of fatal debris flows. The secondary peak in the fall may be attributed to intense regional storms brought on by the typhoon season (Li and Yanai, 1995).

Southeast Asia appears to follow a similar trend to Asia with a rise in debris flows in the spring. However, the peak in debris-flow activity is slightly later, in August rather than July (Figure 4.16). There also appears to be a secondary increase in activity in the late fall, particularly in November. These increases in fatal debris flows correspond with the Asian monsoon and typhoon seasons (Li and Yanai, 1995). The month with the highest mean fatality count per event is July (Figure 4.16). This is due to a typhoon that hit Taiwan in 2001. December has the second highest mean fatality count per event with an average of 200. This, too, was caused by a typhoon that hit the Philippines in 1993.

The data from Oceania are lacking with only a few recorded events from New Zealand and the Federated States of Micronesia. There are no observable trends due to this lack of data, except for a large number of debris flows in July (Figure 4.17). These however were all caused by one typhoon that hit the Federated States of Micronesia in 2002. The high mean debris-flow fatality toll in December was due to a lahar that hit a train in New Zealand in 1953. This event, though not caused by seasonal circumstances, was less than the outlier value and thus included in the analysis. More data are needed before any seasonal trends can be established for the Oceania region.

Overall, there appears to be strong correlations between fatal debris flows and seasonal weather trends. Around the world, regional weather patterns, particularly monsoonal flow and tropical cyclone seasons appear to affect both the number and severity of fatal debris flows. This indicates that fatal debris flows are typically not random events caused by freak rainstorms, but can instead be forecasted to some degree based on the timing of known weather cycles.

5.4 Physical Characteristics of Fatal Debris Flows

Analysis of the physical characteristics of the data has been subdivided by characteristic, in the same manner as subdivided in Section 4.4.

5.4.1 Warning Signs

Various long and short term warning signs appear to be more common than others amongst fatal debris flows. The most common long term warning sign for fatal debris flows appears to be a recent history of debris flows in the region closely followed by the presence of debris-flow landforms (Figure 4.18). These common long term warning signs are expected, as fatal debris flows likely will occur in areas where evidence of debris-flow processes is notable. The least common long term warning signs are the presence of massive boulders and the presence of debris-flow mitigation nearby. Underreporting is believed to be a severe problem for long term warning signs. Documentation, particularly in media articles, likely does not mention anything about landforms or physical evidence of debris-flow processes, and these warning signs are likely much more common than this analysis concludes.

Unusually high rainfall is the most common short term debris-flow warning sign (Figure 4.19). This is not surprising, as rainfall events are the most common triggers or cause of fatal debris flows (see Section 5.4.3). Distantly following, shaking of the ground and roaring/loud noises are the next most common short term warning signs. Like long term signs, underreporting is believed to be an issue with short term warnings. Logically,, shaking of the ground and loud, roaring sounds would be expected to precede most debris flows, and these early warning signs were likely present in most fatal debris flows but were not documented. Like long term warning signs, the underreporting of short term warning signs limits the usefulness of this analysis.

5.4.2 Mitigation

For debris flows in the database, the majority had no reporting on the presence or lack of debris-flow mitigation. Out of 57 events in which the status of debris-flow mitigation was reported, only 14 had debris-flow mitigation (Figure 4.20). Of these 14 events, the debris-flow mitigation failed in eight cases. This may suggest that the failure of the mitigation may have contributed to the fatalities. Unfortunately, severe underreporting makes it difficult to draw any real conclusions about the impact of mitigation on fatal debris flows.

5.4.3 Triggers and Causes

Rainfall is the dominant trigger or cause of fatal debris flows (Figure 4.21). One hundred forty four events within the database list rainfall as one of the key factors leading to the debris flow. The second most dominant cause, landslides mobilizing into debris flows, often occurs due to high rainfall events. Figure 4.21 illustrates that non-rainfall induced debris flows are somewhat uncommon. However, it is these less common triggers and causes that appear to have the greatest consequences. As seen in Figure 4.22, earthquakes and landslide dam burst have the highest median fatality counts of 699 and 500, respectively. These are followed in severity by lahars triggered by eruptions, volcanic flank collapses and mine dump failures. Rainfall induced landslides have a fairly low median fatality count of 9, while debris flows caused by rapid snowmelt have the lowest median fatality count of 4. Analysis of rainfall-specific causes and triggers reveal that these debris flows also have a wide range of occurrence and severity. Figure 4.23 shows the number of debris flows caused or triggered by various rainfall events. Monsoon rainfall causes the majority of fatal debris flows, followed by winter and tropical cyclone storms. These are all seasonal events, as discussed in section 5.3.2. In terms of severity, lahars caused by precipitation on fresh ash cause the most severe rainfall-induced debris flows with a median fatality count of 43 per debris flow. This is followed by debris flows triggered by tropical cyclones and rain after fire, which are tied with median values of 16 fatalities per debris flow. The least deadly rainfall triggers or causes are summer thunderstorms and rain following logging or clearing.

The most severe debris flows are caused by abnormal, regional events, such as earthquakes, lahars (both eruption and rainfall induced), and tropical cyclones, which are capable of killing anywhere from hundreds to thousands of people in a single occurrence. However, these events are not very common. The risk of being caught by a smaller debris flow triggered by a monsoonal or winter rainstorm is much greater. While it may be difficult to mitigate the impacts of large scale abnormal disasters, these findings indicate a country may be able to greatly reduce its risk from debris flows by focusing efforts on mitigating small debris flows caused by seasonal rainfall events.

5.4.4 Debris-Flow Volume

The number of fatalities caused by debris flows is influenced by debris-flow volume. The Minitab analysis of 66 events that contained volume data (Figure 4.25) produced a positive, linear log-log regression. The regression is provided by Equation 5.1.

$$\mathrm{Log(Fatalities)} = -0.8433 + 0.4215 * \mathrm{Log(Volume)} \tag{5.1}$$

The p value found by the F test was 0.000 (indicating a p value of less than 0.001), much less than the level of significance value of 0.05. The R^2 value is 0.352, indicating that only a small amount of variation is accounted for in the regression. The residual versus fits plot indicates that the regression is suitable for the relationship with data evenly distributed on either side of the zero residual axis, and no pattern present (Figure 4.26).

Some of the variability that is not explained by the overall volume regression can be explained by the size of the population in the area in which the debris flow occurred. If a small debris flow occurs in a city with a high or dense population it could potentially kill hundreds or thousands of people, whereas if a massive debris flow occurs in a rural setting, the number of victims may be much lower. The relationships between volume and fatalities given differing population sizes are shown in Figure 4.27. As can be seen in this plot, city and town sized populations have similar relationships between debris-flow volume and fatalities. The city regression has a R^2 value of 0.325, similar to the overall volume regression. The town regression has a much higher R^2 value of 0.718, indicating a strong correlation. The regression for village sized populations has a similar slope to the city regression, but a lower intercept and hence lower number of fatalities for a given sized debris flow. The R^2 value for the village population was also higher than the overall volume analysis, with a value of 0.483. The regression for rural populations has a much lower slope than the other regressions and hence has a much lower number of debris-flow fatalities as volume increases. However, the correlation in this regression is not very strong, with a value of only 0.051. These findings indicate that population size does affect the relationship between debris-flow volume and fatalities.

5.5 Socioeconomic Indicators

The discussion of socioeconomic indicators is subdivided by indicator, in the same manner as subdivided in Section 4.5.

5.5.1 GDP per Capita Regression

Gross domestic product (GDP) per capita is the total value of all goods and services produced by a country divided by the population of that country. It can serve as an indicator of the economic wealth of a country (Gleditsh, 2002). The relationship between GDP per capita and the number of fatalities per debris flow is negative, with a strong decrease in debris-flow fatalities as GDP increases (Figure 4.28). The P value from the F test was found to be 0.000 (Table 4.3), indicating a strong relationship, but the coefficient of determination, R^2, is fairly weak with a value of only 0.116. While it is likely that the number of fatalities per flow is related to GDP per capita, there is still a large amount of variability that is not accounted for in the regression. The residual versus fits plot (Figure 4.29) indicates equal distribution on either side of the zero line, but does show a strong pattern of spreading as the fitted value increases. This indicates a violation of homoscedacity within the data (Kachigan, 1991). Data that obeys homoscedacity does have a change in variance of the dependent variable over the range of the dependent variable (Kachigan, 1991). The violation of homoscedacity for this regression means that as GDP decreases, the spread in the range of fatalities per debris flow increases. This is discussed in further detail in Section 5.5.7.

5.5.2 Hospital Beds per Capita Regression

The number of hospital beds per capita serves as a surrogate measurement for the ability of a country to handle emergencies. It is expected that countries with more hospital beds per citizen will have better emergency service infrastructure. This expectation is confirmed by the data: there is a negative relationship between hospital beds per capita and the number of fatalities caused in a debris flow (Figure 4.30). Table 4.4 shows the P value from the F test was 0.000, indicating a strong relationship, but the R^2 value is 0.118, a relatively low value. The residual versus fits plot (Figure 4.31) shows data equally distributed about the regression with a slight widening in the spread as the fitted value increases, indicating a violation of homoscedacity.

5.5.3 Maternal Mortality Rate Regression

Maternal mortality rate (MMR) serves as a surrogate for the development of a nation's healthcare system. The relationship between MMR and debris-flow fatalities is positive (Figure 4.32), showing the expected trend that higher fatality counts are observed in countries with higher MMR. The P value from the F test was calculated to be 0.001 (Table 4.5), indicating a strong relationship, and the R^2 value is 0.095, indicating a very weak correlation. The residual versus fits plots show a widening pattern, indicating a violation of homoscedacity (Figure 4.33).

5.5.4 Life Expectancy Regression

Another indicator for the development of a country's healthcare system is the statistic of life expectancy at birth. Figure 4.34 illustrates the relationship between life expectancy at birth and the potential number of fatalities in a debris flow. It shows an anticipated negative trend: countries with higher life expectancy experience lower rates of debris-flow mortality. The P value was found to be 0.002 (Table 4.6), indicating a strong relationship, but not to the same degree as indictors with p values of 0.000. The R^2 value is quite low for this indicator, with a value of 0.067. This indicates a very weak correlation between life expectancy and debris fatalities. The residual versus fits plot illustrates a strong widening pattern (Figure 4.35). As with other indicators, it indicates a violation of homoscedacity.

5.5.5 Government Corruption Regression

The government corruption regression was created using Transparency International's Corruption Perceptions Index (CPI), a measurement of the perceived level of corruption in the public sector on a scale from 0 to 10. The level of corruption could impact the effectiveness of a government to respond to natural disasters. As expected, a negative relationship exists between the CPI and the number of fatalities in debris flows (Figure 4.36) indicating that higher fatality count debris flows occur in countries with lower CPI ratings. The P value from the F test was 0.000, indicating a strong relationship (Table 4.7). The R^2 value is 0.156, indicating a fairly weak correlation of the data to the regression. The residual versus fits plot shows an equal distribution of the data but a widening pattern (Figure 4.37).

5.5.6 Technical Publications per Capita Regression

The number of technical journal articles per capita indicates the level of investment a nation has in science and technology research. The relationship between technical journal articles per capita and debris-flow fatalities is negative, with the highest fatality counts corresponding to countries with lower rates of publication (Figure 4.38). The P value from the F test is 0.000 indicating a strong relationship (Table 4.8). The R^2 value is 0.236, the highest value of all the socioeconomic indicators. The residual versus fits plot in Figure 4.39 indicate a somewhat robust regression. There is no apparent pattern in the plot and an equal distribution of the residuals about the regression.

5.5.7 Socioeconomic Indicator Ranking

Within all indicators, the R^2 value was not exceptionally high, with the highest being 0.236. This indicates these regressions do not account for a large amount of variability within the data. Variability exists because countries with weak socioeconomic indicators have both severe and less severe debris flows, whereas countries with strong economies tend to have only less severe events. This leads to a widening in the range of fatalities as the socioeconomic indicators weaken, explaining why most of the regressions violate homoscedacity.

Additional variation exists because the largest events may not occur in countries with the weakest indicator value. This is because the conditions in these locales may not be as conducive to disastrous debris flows as they are in countries with slightly better socioeconomic conditions. For example, South American countries have had the most severe debris flows in the database. While these countries tend to have weaker socioeconomic indicators, they are not the worst within the database, as many countries in Africa, and Asia have far weaker indicators. However, the conditions under which these debris flows occurred increased their severity, either through the triggering mechanism (volcanic/rainfall induced lahars and large landslides) or the impacted population size (cities and towns). As a result, there is a group of relatively lower fatality events in countries with the weakest indicators. This creates a greater amount of variation, and a reduction in the R^2 value for the regression.

Even with these issues, it is possible to rank the socioeconomic indicators using regression analysis. The strongest regression is technical journal publications per capita. It has the lowest possible P value, the highest R^2 value and has the strongest residual versus fits plot. The government corruption regression is the second strongest. It has the lowest possible P value and the next highest R^2 value. The residual versus fits plot shows a violation of homoscedacity, but all other regressions have the same issue. The next strongest regression is actually a statistical tie between GDP per capita and hospital beds per capita. Both have the lowest possible P value, and very similar R^2 values. MMR is the second weakest regression, with a P value of 0.001 and a very low R^2 value. The weakest regression is life expectancy at birth, with the highest P value of 0.002, and the lowest R^2 value.

While some socioeconomic plots have stronger regressions than others, all indicate that the magnitude of debris-flow fatalities is dependent on the socioeconomic strength of a country. As the strength of socioeconomic indicators increases, the maximum number of fatalities caused by debris flows decreases. The trends provided by the regressions of socioeconomic indicators show that populations vulnerable in either economic, social, or political means are more at risk for debris-flow fatalities. This supports a hypothesis of this study that debris flows are disasters of social vulnerability.

5.5.8 International Monetary Fund Classification

Subdividing the dataset by the IMF Classification illustrates the difference between the debris-flow fatality distribution between advanced and developing nations. Table 4.9 provides the descriptive statistics between the two populations and shows how much they differ. In all statistics, developing nations have values indicating more severe debris flows. Advanced nations only have 5,335 fatalities in the database while developing nations have 72,453 (Table 4.9, Figure 4.42). However, both groups have nearly the same number of fatal debris flows recorded in the database, with developing nations only having 12 more recorded events (Figure 4.41). The median value of fatalities per event in advanced nations is only 6, while in developing nations it is 23. This is nearly a fourfold increase. The average fatalities per year shows an even greater disparity, with a mean of 87 debris-flow fatalities per year in advanced countries and 1,188 fatalities per year in developing countries (Table 4.9).

The distribution of the data also indicates that developing nations have more severe debris-flow disasters. Figure 4.40 shows that the distribution of debris-flow fatalities in advanced nations is skewed towards smaller events, with the majority of debris flows killing fewer than 10 people. In developing nations, the decrease in the number of events as the fatality count increases is much more gradual. Developing nations also have significantly more events in the higher fatality range than advanced countries. The most severe debris flows in the database all occur in developing countries.

All of these statistics indicate that debris flows pose a much greater threat in developing countries than they do in advanced countries. Developing countries likely cannot devote the resources necessary to protect their citizens from debris flows and other natural hazards to the same extent as advanced countries. These data are in agreement with the socioeconomic regressions found in the section 5.5.7 above. Most of the lower socioeconomic indicators are found in countries listed as “developing” by the IMF. The countries with weaker socioeconomic indicators consistently had more severe fatal debris flows. Between the socioeconomic regressions and the analysis of the debris-flows fatalities divided by the IMF classification scheme, it appears that debris flows are indeed disasters of social vulnerability.

CHAPTER 6

CONCLUSIONS

The following are conclusions that can be drawn from the debris flow fatality database.

- Debris Flows kill a median of 165 people worldwide annually.
- The maximum median number of people killed in fatal debris flows is 11 per event.
- Fatal debris flows were recorded in 38 countries.
- North American countries have the lowest median debris-flow fatality rates while South American and Asian countries have the highest median debris-flow fatality rates.
- Increases over time in the number of recorded debris flows in developing countries is predominantly due to improved documentation techniques.
- Changes in the number of recorded debris flows in advanced countries reflect actual trends in the number of fatal debris flows (documentation levels have remained fairly constant).
- Fatal debris flows show seasonal variability and appear to be controlled by seasonal processes in most locations. More data are needed to evaluate seasonal trends in Africa and Oceania.
- More data are necessary on debris-flow warning signs in order to assess the most common long and short term warning signs.
- More data are necessary on debris-flow mitigation in order to assess the impact of mitigation on debris-flow fatalities.

- The most common debris-flow trigger/cause was rainfall, and the most common rainfall triggers/causes are monsoonal storms.
- The most severe debris-flow triggers/causes are earthquakes, while the most severe rainfall triggers/causes are lahars caused by rainfall on ash.
- The number of fatalities in a debris flow is dependent on the volume of the debris flow. This relationship is affected by the size of the population in the vicinity of the debris flow.
- There are relationships between the number of fatalities in a debris flow and certain socioeconomic indicators. The ranking of the strengths of regressions of these indicators is as follows:
    1. Technical Journal Publications per Capita
    2. Government Corruption Ranking
    3. GDP per Capita and Hospital Beds per Capita
    4. Maternal Mortality Rate
    5. Life Expectancy at Birth
- Weaker socioeconomic ratings have increased maximum fatality rates for all indicators.
- Debris flows are more severe in developing countries than in advanced countries.
- Debris flows appear to be “disasters of social vulnerability.”

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APPENDIX A

SUPPLEMENTAL ELECTRONIC FILE

This appendix contains the debris flow fatality database as a Microsoft Excel workbook. The database contains all debris flow events analyzed in this thesis. Any data used in the various analyses within the thesis is included in the database. This includes information on the number of fatalities, location, timing, physical characteristics, and socioeconomic indicators.

File	Description
Debris_Flow_Fatality_Database.xlsx	Excel workbook containing the debris flow fatality database. Sheet 1, Main Database, is the debris flow fatality database. See sheet 2, Indicator Codes, for definitions of the codes used for certain attributes in the database.