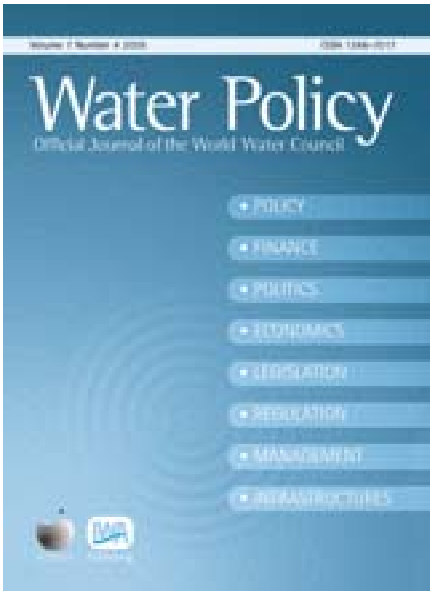

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Transboundary river floods: examining countries, international river basins and continents

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Abstract

The objectives of this study were (1) to quantify river floods shared by more than one country, that is, transboundary river floods and (2) to grasp more fully the degree of vulnerability of people to such events on a global, international river basin (IRB) and country level. To these ends, publicly available data were combined to identify such events and the resultant losses of life, flood-related affected individuals and financial damage statistics were related to national levels of development. It was determined that in the period 1985–2005, some 175 of the 1,760 river floods were transboundary, but globally accounted for 32% of all casualties and almost 60% of all affected individuals, illustrating the massive impact of shared floods. This database of transboundary floods was then merged with socio-economic and biophysical data, enabling analyses that revealed the degree of vulnerability of people to transboundary floods from a global to a country level. Selecting one country, continent or IRB most vulnerable to transboundary floods proofed to be unfeasible since the answer heavily depended upon the specific definition of vulnerability, illustrating the complexity of this phenomenon. However, together, the results significantly increased our current knowledge of shared floods which could aid policy-makers in identifying and evaluating potential vulnerability to transboundary river floods.

Keywords: International river basins; Transboundary floods; Vulnerability

1. Introduction

Floods are among the world's most frequent and damaging types of disaster and annually affect the lives of millions all over the globe. Over time and with population growth, climate related factors aggravated by urbanization and social, economic and political processes have massively increased and will continue to increase human exposure and vulnerability to floods. Nonetheless, vulnerability of societies to floods, whether transboundary or not, is still poorly understood.

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Previous studies have focused on all flood type data for specific countries or continents (Hoyois & Guha-Sapir, 2003), or looked at general statistics of various natural disasters on a worldwide scale (Haque, 2003; Guha-Sapir *et al.*, 2004; Mutter, 2005). Others have focused on a single (historical) flood event (Wind *et al.*, 1999; Christie & Hanlon, 2001), a single river (Hesselink, 2002; Mudelsee *et al.*, 2003), a single country (Tol *et al.*, 2003) or combinations of these topics. Only recently have researchers begun to analyze flood data on a global scale (Hossain & Katiyar, 2006), but few have touched upon the phenomena of shared or transboundary floods occurring in international river basins (IRBs) (Marsalek *et al.*, 2006). Nevertheless, rivers ignore political boundaries and have created 279 IRBs[1] (TFDD, 2006; unpublished data), all of which, without exception, create some degree of tension among the societies that they bind[2]. One source of tension is floods. The present study will fill this gap in knowledge by focusing on transboundary river flood events through the use of global data. In doing so, this paper will provide insight in the magnitude of loss of life and financial damage in relation to the level of development at a country, continent and IRB scale.

This paper will investigate the vulnerability of countries, continents and IRBs using the flood magnitude as the biophysical variable and the following socio-economic variables: (1) the level of development; (2) global national income (GNI; see also Section 2.1.6) and how these two variables relate to the total flood related financial damage, and (3) population density per country and per IRB and how these variables relate to the flood-related casualties and affected individuals.

The working hypotheses are that the biophysical and socio-economic variables are related to the vulnerability of a society as follows: lower developed countries will experience more floods and have more flood-related casualties because as a society they have fewer means to protect themselves. People and societies with resources and economic alternatives tend to be better protected from harm and are able to recover more quickly than individuals with fewer options and resources. The financial damage on the other hand will be higher in more developed countries because more costly properties are built in the floodplains of developed countries. Applying the before mentioned variables specifically to IRBs enables the identification of those IRBs most vulnerable to transboundary flood events.

The paper is structured as follows: the methodology is discussed in Section 2, which also includes definitions of the selected variables and points out how these variables are related to vulnerability and transboundary river floods. Section 3 presents the results. Section 4 discusses the results and draws conclusions.

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[1] From the time when Wolf *et al.* (1999) reported their classification of 263 international river basins and since the last update of the Transboundary Freshwater Dispute Database or TFDD (Wolf *et al.*, 2003), new basins have been "discovered" or were created but not yet published. A manual count of the IRBs resulted in an increase in basins from 263 to 279 basins at the time of this research. The "new" basins in Asia are: the Johore, Tebrau and Scudai (shared between Malaysia and Singapore), the Loes (between Indonesia and Timor L'Este) and the Shu and Talas (shared between Kazakhstan and Kyrgyzstan). In South America, six more basins were found: the Temash and Moho (shared between Guatemala and Belize), the Corredores/Colorado, the El Naranjo and Conventillos (shared between Costa Rica and Panama), the Chamelecon (shared between Guatemala and Honduras). In Africa, four more basins were added: the Thukela (shared between Lesotho and South Africa), the Sanaga (between the Central African Republic, Cameroon and Nigeria), the Pungwe (shared between Mozambique and Zimbabwe) and the Pangani (shared betweenTanzania and Kenya).

[2] The word "rival" has the same root as "river", derived from the riparian concept of dwellers on opposite riverbanks.

2. Methodology

2.1. Selected variables: measures of vulnerability

In order to test the hypotheses, biophysical and socio-economic variables considered to influence the impact of, or vulnerability to, transboundary river floods were selected to create a framework of vulnerability (see Table 1). Next to the total flood-related financial damage, total flood-related casualties and total flood-related affected individuals, the selected variables included: (1) the human development index or HDI as an indicator of the national level of development and as reported in the United Nations Development Programme Report of 2005 (UNDP, 2005); (2) the most current ranking at the time of research by the World Bank of the GNI (World Bank, 2004); (3) the country population in 2003 (UNDP, 2005); (4) the population density per country; (5) the population density per IRB (calculated with data from the TFDD, 2006), and (6) the flood magnitude.

Before this section continues with the methodology used, brief definitions of the selected variables will be given. Additionally, the relation of these variables to vulnerability and transboundary floods is clarified.

2.1.1. Floods. Flood events have been defined in many ways: "a relatively high flow which overtaxes the natural channel provided for the runoff" (Chow, 1956) and "a body of water which rises to overflow land which is normally not submerged" (Ward, 1978) are just two of many. A flood event in general is any type of situation where water temporarily covers land outside its normal confines. Therefore, a river flood is defined as the inundation of land along a riverbank owing to a river or stream overflowing natural or constructed confines. As a general rule, flooding is associated with harm and damage and considered an undesirable occurrence[3].

Every flood is a unique phenomenon, but several types of floods can be distinguished. The most common type is where a river overflows its banks owing to a large input of rainfall or snowmelt. These are types of flood that can be predicted and explained in terms of catchment physical characteristics and climatic inputs (Arnell, 2002). When one looks at the size of the affected area and the duration of precipitation (or, in other words, the spatial[4] and temporal scale of flood events), two categories of floods can be distinguished (Waggoner, 1990; Bronstert, 2003). The first category includes extensive, long-lasting floods or plain floods, almost invariably caused by rainfall lasting several days or weeks in connection with high antecedent soil saturation. This can lead to flooding of wide areas, causing slow-moving, relatively shallow floods. The second category is local, sudden floods, or flash floods; floodings in small catchments mainly caused by short and highly intensive precipitation (e.g. a thunderstorm). Flash floods occur primarily in hilly or mountainous areas due to prevailing convective rainfall

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[3] The effects of floods are extraordinarily complex, but not exclusively negative. Potential beneficial effects of floods on society and the environment may be that they replenish the soils with alluvial silt which adds to soil fertility and subsequently, soil productivity. They may replenish soil moisture, which can result in increased crop yields. They can be beneficial to the aquatic ecosystem and to human livelihoods associated with them (e.g., fishing). On a medium to long term, industrial efficiency may be increased because plants and factories based on out-dated designs will be replaced or redesigned and updated. Lastly, family and community spirit and bonding may be increased.

[4] Note that catchment size is always an important parameter when discussing floods since unit area flow in floods of the same risk decreases with an increase in catchment area, influencing forecast, warning, response, defense and coping with floods.

Table 1. Variables of the vulnerability framework.

Vulnerability framework	
Physical variable	Flood magnitude
	Financial damage
Non-physical variables	Number of casualties
	Number of affected individuals

mechanisms, thin soils and high runoff velocities. The warning time for such events is short. In general, the duration of these flood events is also short, but this flood type is also frequently connected with severe damage, mainly because they are narrow, fast-flowing and deep.

Although heavy rain is the prime initiator of flooding worldwide, it does not follow that all floods are necessarily caused by an excess of rainfall or snowmelt. For instance, rivers can overflow because ice-dammed lakes are released or because of the periodic release of water stored behind or within glaciers. In addition, landslides can create temporary dams which produce floods when breached. Floods can also be the result of an unusually high rise in groundwater levels, such that the water table reaches the surface (Arnell, 2002). Similarly, a rise in lake levels can lead to inundation of the surrounding land. Both these types of flood are generated by prolonged heavy rainfall or snowfall. Lastly, floods can be generated by humans (Rossi *et al.*, 1994), for instance when structures built by society collapse (e.g. intentional or unintentional levee breaks, or a dam or dike breach), or by errors in operation (such as mismanagement of flood control gates or equipment).

2.1.2. Floods and societies. Socio-economic factors are related to the impact of disastrous events. Haque (2003), for instance, looked at disaster losses in south and south-east Asia and showed these losses cannot be separated from societal and developmental factors[5]. But what about losses specifically caused by transboundary river floods—are these also a function of human vulnerability to floods? Hypothetically, one could argue that more developed countries are technically more advanced and have more resources to predict or prevent floods and to notify neighboring countries, which might decrease the number of shared river floods and related losses. Lesser developed countries sharing river basins might not be able to predict floods, are less prepared for them and unable to contain or lessen floods starting in their own country. Therefore, this paper will attempt to answer the question whether relationships exist between the level of development of a country and the number of shared flood events it has experienced.

2.1.3. Floods and affected individuals. Human casualties related to flood events can be avoided by evacuation of specific areas prior to the actual flooding event. Evacuation presumably happens more often in countries that have the ability to predict flood events, have the financial and human resources to

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[5] Many socio-economic and demographic variables significantly influence disaster-related deaths and injuries in this part of the world. Haque's nine socio-economic and demographic variables correlated to natural disaster induced losses were: population size, population density, labor force, population ages, life expectancy, adult illiteracy rate, GNP (gross national product), GNPG (annual growth rate in GNP), urban population and energy consumption. His results show that demographic variables have become prominent predictors of disaster-loss in south, southeast and east Asian and the Pacific states, inferring that intervention into population growth and distribution could be used as disaster mitigation instruments (Haque, 2003).

warn people beforehand and help evacuate the area, hypothetically increasing the numbers of displaced/affected people, since governments will in all probability move more and not fewer people away from the hazard. Situations where a flood event happens unexpectedly are likely to occur more often in countries without adequate warning systems, but that does not necessarily mean that more or fewer people will be displaced/affected because again, when sufficient warning systems are in place, it is likely that more people will be vacated. Therefore, it is crucial to focus on figures for river flood-related displacements and investigate if there are any relations between the number of affected individuals and the level of development. As the previous section described, the level of national development theoretically influences the number of casualties; higher levels of protection can only be obtained by countries with the adequate financial means.

2.1.4. Floods and financial damage. Where economic growth takes place within flood-prone areas, it is reasonable to expect that whenever per capita incomes rise, so will property value at risk and average annual flood losses in real terms: more developed countries will have higher monetary damage related to floods. It is expected that the developed countries will have more financial damage per year and that there will be an increase in the losses compared to the impact of flood events in the past, because of the global trend towards increased investments and population in flood plains. Nevertheless, flood control investments are often seen as investments in the national economy; because of these investments, growth can occur, resulting in more property value damage. Thus although increased investment in flood plains has the potential to increase flood-related damage, it has also been shown to create platforms for economic growth. In absolute terms, richer nations may bear the greater proportion of losses, but poorer countries suffer more when economic loss is measured as a proportion of GNI or gross domestic product (GDP) (Schipper & Pelling, 2006). However, numbers alone fail adequately to capture the impact of the disaster on the poor who often bear the greatest cost in terms of lives and livelihoods and rebuilding their shattered communities and infrastructure. For instance, it may be reasonable to measure a Dutch householder’s relatively minor flood damage in thousands of dollars. But a flood in Bangladesh may entirely dispossess a farming household; they may even lose their farmland by the erosive effects of floods. Their loss may be measured in only hundreds of dollars, but they may not receive aid or insurance payments.

2.1.5. Vulnerability. In this paper, vulnerability is viewed as the condition of a person or a group or a society, in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard such as a flood. The vulnerability of any physical, structural or socio-economic system to a natural hazard is its probability of being damaged, destroyed or lost. Vulnerability is not a static but rather a dynamic process that depends upon social, economic and political contexts which change over time, so the probability of loss also varies. For instance, strengthening social resilience capacity would theoretically reduce vulnerability. This can happen to a community exposed to regular disturbances, like communities built in a floodplain; they may have developed organizational and infrastructural responses to absorb disturbances more easily than other societies.

2.1.6. Gross national income. The gross national income, or GNI and previously known as gross national product (GNP), comprises the total value of goods and services produced within a country (i.e. its GDP), together with its income received from other countries (notably interest and dividends) less similar payments made to other countries. For operational and analytical purposes, it is the World

Bank's main criterion for classifying economies. Based on its GNI per capita, every economy is classified as low, middle or high income.

2.1.7. Human development index. The United Nations' human development index, or HDI, is a comparative measure of poverty, literacy, education, life expectancy, childbirth and other factors for countries worldwide. It is a standard means of measuring well-being, especially child welfare. It is used to distinguish whether or not the country is a first, second or third world country (a high, medium, or low HDI score, respectively) (UNDP, 2005). An HDI below 0.5 is considered to represent low development and 30 of the 32 countries in that category were located in Africa, with the exceptions being Haiti and Yemen. The bottom ten countries were all in Africa. The highest-scoring sub-Saharan country, South Africa, is ranked 120th (with an HDI of 0.66), which is well above most other countries in the region. An HDI of 0.8 or more is considered to represent high development. This includes countries of northern and western Europe, Australia, New Zealand, Canada, United States, Japan, Israel and the so-called "East Asian Tigers" (Hong Kong, Singapore, South Korea and Taiwan). Other countries that exhibit high human development amidst countries with lower HDIs include (with their position) Costa Rica (47th), Cuba (52nd), Mexico (53rd) and Panama (56th) (UNDP, 2005). This categorization leads to 57 countries with high HDI scores, 88 countries with medium HDI scores and 32 countries with low HDI scores[6].

Mutter (2005) showed that when HDI is plotted against latitude, there is a clear separation between high and low HDI countries. Lower HDI countries were mostly located near the equator and appeared much more vulnerable to flooding than the other, higher scoring HDI countries. However, that study included all types of floods.

2.1.8. Flood magnitude. The Dartmouth Flood Observatory flood magnitude of a flood is the result of the following calculation: Flood magnitude $= \ln(\text{duration}) \times \text{severity class} \times [\sqrt{}(\text{affected region})/100]$ in which the severity class is a magnitude assessment and floods were ranked on a I–III scale, where a class I flood stands for a large flood event with significant damage to structures or agriculture, fatalities and/or a 1–2 decades-long reported interval since the last similar event. A class II flood is a very large event with a greater than two decades but less than 100 year estimated recurrence interval and/or a local recurrence interval of at 1–2 decades. In addition, a class II flood has affected a large geographic region ($>5{,}000\,\text{km}^2$). A class III flood is an extreme event with an estimated recurrence interval greater than 100 years. The resulting flood magnitude scale was seen as a more appropriate variable to compare floods than only the severity class, since the outcome accounts for the most important flood characteristics: duration, severity and size of the affected region[0].

2.2. Analyzing flood data

2.2.1. OFDA/CRED International Disaster Database: EM-DAT. The Centre for Research on the Epidemiology of Disasters (CRED) in Brussels in cooperation with the United States Office for Foreign Disaster Assistance (OFDA), maintains the OFDA/CRED International Disaster Database (EM-DAT)

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[6] The list has 194 countries, but not all UN member states choose to or were able to provide the necessary statistics. Notable absences from the list (excluding micro-states) were Afghanistan, Iraq, Liberia, North Korea, Serbia, Montenegro and Somalia. These countries were generally considered to have medium to low human development. Although they have also experienced floods, they have been omitted from the calculations and, consequently, the graphs included herein.

used in this study. EM-DAT is publicly accessible at http://www.em-dat.net/. The main objective of the database, as specified on the CRED website, is to serve the purposes of humanitarian action at national and international levels. It contains essential core data on the occurrence and effects of international disasters, including floods. Each disaster is recorded by type, date, country of the disaster and numbers of people dying, injured and affected/injured/homeless. Data are collected for events with ten or more casualties, or when international assistance was requested. The data are obtained from insurance companies (Munich Re, Suisse Re and Lloyds of England), Federation of Red Cross, the United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA), the World Health Organization (WHO, 2002), Reuters and governments.

2.2.2. Dartmouth flood observatory database: DFO. The second database used in this study in combination with the EM-DAT database, is compiled and maintained by the Dartmouth Flood Observatory (DFO) in New Hampshire. The DFO database is a global listing of extreme flood events compiled from diverse sources for the period 1985–present. Unlike the EM-DAT database which lists events per country, the DFO database lists individual floods. The DFO database is publicly accessible at http://www.dartmouth.edu/~ floods/. The DFO detects, maps and measures major flood events worldwide using satellite remote sensing. Each flood is recorded by country, location, date, casualties, displaced people, damage and more details about the type of flood. The data used and processed in the DFO database are derived from a wide variety of news sources, governmental, instrumental and remote sensing sources.

The data from the DFO and EM-DAT databases were joined in order to look at transboundary river floods that occurred worldwide in the period 1985–2005, as explained in the following sections.

2.2.3. Selection of floods. The DFO database started compiling data in 1985, which limited the period this study could focus on to 1985–2005. Both databases had gaps in their description of flood events; main causes were not mentioned and/or it was not clear whether the flood was exclusively a river flood. When in doubt about the exact nature of the flood and when additional sources (articles, newspapers, World Wide Web) could not provide clarity about the event, the event was excluded. Furthermore, only fresh water flooding of rivers was analyzed. In addition, the following flood events were defined as separate hazards and thus excluded from this study: tsunamis, tidal waves, typhoons and hurricanes that led to river flooding.

Classification of shared river floods. Unlike the EM-DAT database which lists events per country, the DFO database lists individual floods. Consequently, the combination of the two databases enabled the detection of events shared by one or more countries or, in other words, transboundary river flood events. However, the DFO only reports one number per event for the number of casualties and financial damage, making it unclear how much damage each individual country has experienced. Therefore, every shared flood reported by the DFO was compared to data from EM-DAT. If the floods were similar in date and location, DFO's information on casualties, displaced individuals and financial damage were cut and replaced by EM-DAT's country-specific data. This resulted in a single database with numbers for every country that experienced a shared flood. Combined with the geographic dataset of the world's IRBs (Wolf *et al.*, 1999) and complemented by the selected variables, a useful basis for truly global studies of transboundary flood events was created.

Note that whenever the date and location reported in the DFO database did not match any of the EM-DAT events, the DFO statistics were assigned to only one country. Whenever the EM-DAT data only had values for the number of casualties, but no data on financial damage or displacements for shared floods, DFO's data for the casualty-count were replaced by the EM-DAT counts because the EM-DAT database is more accurate on a country-by-country basis.

3. Results

3.1. Comparison between transboundary and all river floods events

At the time of research, 279 rivers around the world crossed the boundaries of two or more nations (TFDD, 2006, unpublished data). The catchment areas that contribute to these rivers comprise approximately 42% of the land surface of the Earth[7], include 40% of the world's population and contribute almost 80% of freshwater flow (TFDD, 2006; UNEP, 2006). Much like rivers, floods respect no political boundaries. Therefore, transboundary floods are not uncommon. From the 194 countries[8] on the UN HDI list, 42 (a bit more than 21%) of those did not experience any river floods during the period 1985–2005. Of the remaining 152 countries, including countries that are not part of IRBs, like Australia and small island states, 40 did not experience any transboundary floods, but the remaining 112 did. In other words, 75% of countries that experience river floods share this event with other countries.

Information from the two databases was combined as described in the previous section. The result was a new database consisting of 1,760 river floods, taking the lives of 112,000 people, affecting around 354,370,000 people and resulting in US$6.87 × 10^{11} financial damage. During the period considered, 175 of the total 1,760 river flood events were transboundary and caused almost 37,000 people to lose their lives, affected about 210 × 10^6 people and resulted in more than US$97 × 10^9 financial damage. Although only about one-tenth of all the river floods in the last 21 years were categorized as transboundary, they represent a considerable number—always more than 10%—of the total number of casualties, affected people and financial damage caused by all river floods[9]. These findings could be explained by the difference in the severity of the different river flood events. Therefore, the DFO-variable of the flood magnitude per flood was considered next.

The outcome of an analysis of flood magnitudes for all floods and all shared floods showed that the average flood magnitude for shared floods is higher 90% of the time. When comparing the median values, it is clear that shared floods, with a median of 18.5 ± 1.7 standard error (SE) were almost twice as severe as non-transboundary floods with a median of 10.0 ± 0.12 (Figure 1). Thus on a global scale, shared river floods were more severe than all river floods combined. The analysis was continued by looking at the flood magnitude for shared floods and all floods per country. Again, it is unmistakable that the shared floods were much more severe than all the river floods combined. Plotting the median values of the high, medium and low HDI countries shows a threshold around a flood magnitude of 13; below it includes all the river floods, above it were all the shared river floods. The high HDI countries experienced only slightly less severe shared and non-shared floods than the medium developed countries

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[7] Numbers used for calculation: land area of the Earth: 147,142,344 km^2 and the land area of all the 279 international river basins combined is 61,852,502 km^2.

[8] As noted earlier, some countries were not ranked on the HDI list but have experienced floods and were therefore included in this calculation.

[9] For a complete list of the transboundary river flood events, see Bakker (2006).

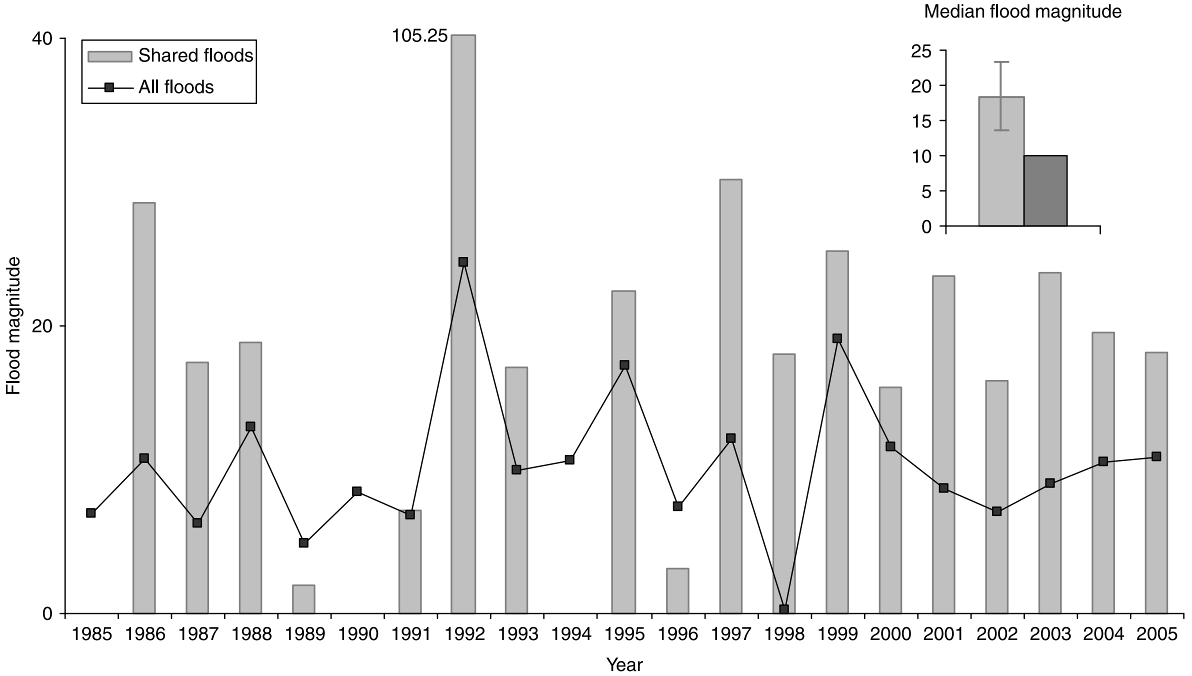

Fig. 1. The DFO flood magnitude scale shows that transboundary river floods were more severe than non-transboundary events.

did, while the low developed countries on average experienced the most severe transboundary and non-shared floods.

When the average affected area (defined as not only the flooded areas but also the extent of geographic regions affected by flooding) is looked at, shared floods affect larger areas on average than all river floods combined did: shared floods influence on average 222,000 km^2 while all river floods affect an average area of about half that size (128,000 km^2).

When the link between the death toll divided by the number of all river floods versus the death toll divided by the number of shared river floods was compared, the high developed countries experienced higher death tolls relative to their population during all river floods, while the low developed countries experienced higher death tolls relative to their population during shared floods. The medium developed countries also on average experienced higher death tolls during shared floods. When a similar analysis was applied to the displacement toll, again, the majority of all the river floods together had higher displacement tolls than the shared floods did. The high developed countries on average, though, had higher displacement tolls for shared floods.

Last, a comparison of the financial damage relative to the GNI of a country was made, which unmistakably showed that the majority of the financial damage of the shared floods was higher than the financial damage caused by all floods.

In sum, transboundary floods differed significantly from non-shared river flood events: transboundary river floods were more severe in their magnitude, affected larger areas, resulted in higher death tolls (except in the high developed countries) as well as higher displacement tolls in high developed countries and caused more financial damage than non-shared river floods did. On a global and country scale, shared floods were more severe than all river floods combined. Lastly, the majority of the financial damage from the shared floods was higher than the financial damage caused by all floods.

3.2. Vulnerability to transboundary floods—country level

Starting at the lowest level, the focus is first on countries; what can be said about the number of shared river floods a country experienced and the selected biophysical and socio-economic variables? Data in relation to the number of shared floods and the national level of development showed a great deal of spread and no apparent pattern. This indicates that a variety of influences were important when looking at complex relationships like this. There were a few outliers. India and Bangladesh, for instance, were the two countries that experienced the highest number of shared river floods (27 and 20, respectively). In addition, Bangladesh is part of four IRBs and more than 80% of its land surface lies within these basins. India is part of six IRBs, with about 45% of its land surface within these basins. This explained why both countries experienced a higher than average number of shared floods. The United States was the only high developed country with a relatively high number of shared river floods, compared to the other high developed countries. This could be attributed to the large surface area of the country inside IRBs (more than 62%) and the number of IRBs (19 total), but the degree of human modification of rivers, that is the degree of straightening out rivers, the number and height of dikes along a river, could also play an important role.

The highest displacement toll was experienced by Nigeria, Nepal and Bangladesh, but there was no apparent pattern between the displacement toll per country caused by transboundary floods and the level of development. The highest number of total financial damage was experienced by Romania, Germany and Pakistan. Additionally, the annual economic losses associated with shared river flood events were always lower for the low HDI scoring countries, with the exception of the year 2000, in which a catastrophic flood hit Mozambique and surrounding countries. Timor L'Este, the Dominican Republic and Haiti experienced the highest average death tolls. When looking for a relationship between transboundary river floods, the resulting casualties and the level of development, it was apparent that, with the exception of one year[10], the developed countries experienced fewer casualties than the developing countries.

Lastly, the medians of financial damage and casualties per HDI class (Figure 2) confirmed the hypothesis that high developed countries, compared to the less developed countries, experienced the highest number of financial damage per shared river flood and the fewest number of casualties.

3.3. Vulnerability to transboundary floods—continent level

The level of continents was next; which continents are vulnerable to transboundary flooding? Transboundary floods did not take place every year on every continent, but it did appear that they became more frequent over the past ten years, especially in Asia, South America and Europe (Figure 3).

The median flood magnitude (see Section 2.1.7) for shared floods per continent showed that, even including the SE, African and South American countries experience the most severe floods, while the other three continents were in roughly the same category: between 7 and 9.5.

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[10] In 1996, Greece experienced one flood that caused four casualties, while the medium and lower developed countries reported zero flood-related casualties that year.

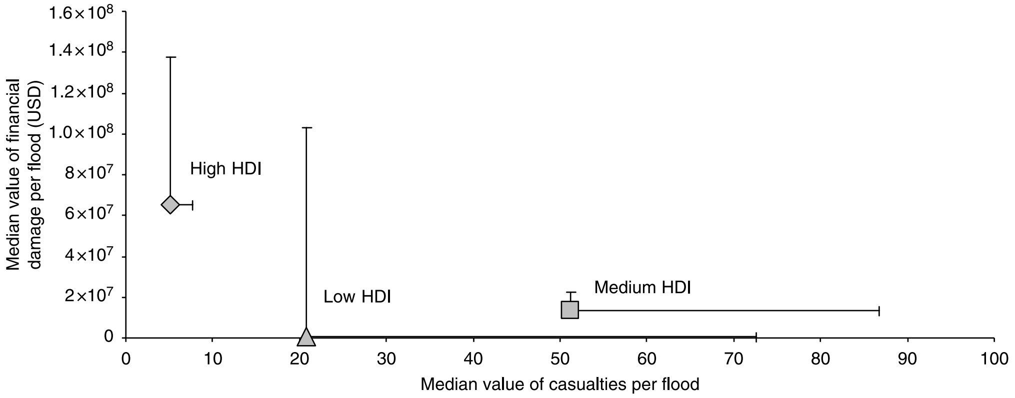

Fig. 2. Median values of financial damages per flood accumulated for all high, medium and low scoring HDI countries, plotted against the median values of casualties per flood. High developed countries have the fewest casualties, but the highest number of financial damage. The error bars indicate the standard error.

The statistics categorized per continent, only taking into account those IRBs that have experienced transboundary floods over the past two decades (Figures 4 and 5), showed that Asia and Africa have seen the most transboundary floods, which resulted in the largest number of affected people. North America experienced the fewest number of transboundary floods and had the lowest scores for all three variables. Europe had the second highest quantity of transboundary floods, but the second lowest number of casualties.

Globally, the average death toll for IRBs was just below ten people per million population. However, only Europe comes close to the average (Figure 6) because all 13 IRBs experienced transboundary floods

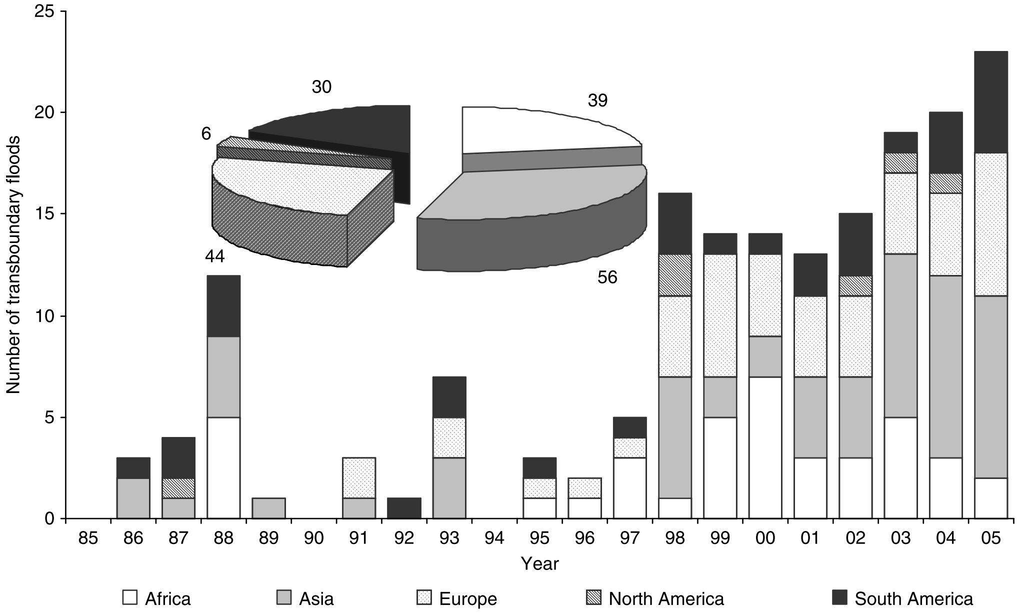

Fig. 3. Shared river floods per year per continent show a steady increase of transboundary floods over the years globally, but especially on the Asian and European continents. Both continents also dominate the total number of shared river floods.

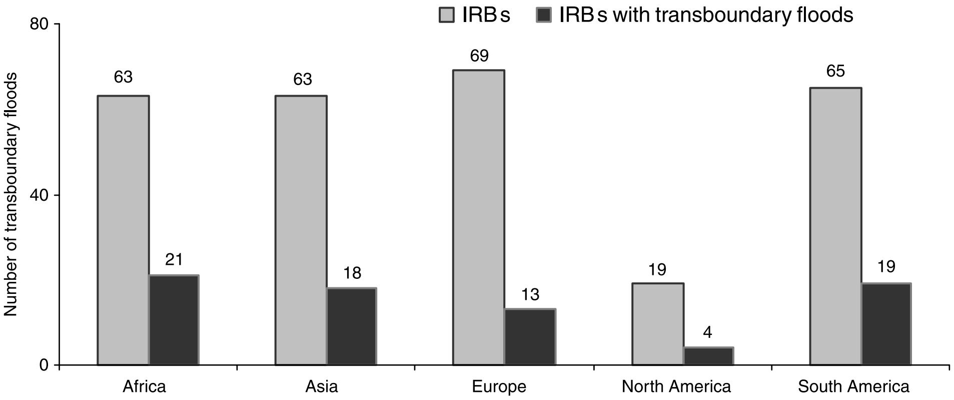

Fig. 4. The largest share of IRBs that experience transboundary flooding can be found on the African continent (33%), followed by South American IRBs (29%), Asian IRBs (29%), North American IRBs (21%) and European IRBs (19%). Please note that in this paper, the South American continent includes the countries of Central America with 27 IRBs.

with below ten casualties per million basin population, Nestos being the exception with a value of 15. The average death toll for South America was the highest of all the continents although only North America experienced fewer floods. However, outliers strongly influenced the average death toll (not only for South America).

When comparing the different amounts of financial damage caused by shared floods, Europe by far had the highest accumulated damage. Their total of almost UD\$90 × 10^9 was 90 times larger than the damage in North America, 40 times larger than the damage in Africa, nine times higher than the financial damage in South America and still four times higher than the financial damage in Asia (Figure 5). Even when dividing the total amount of damage by the total number of transboundary river floods,

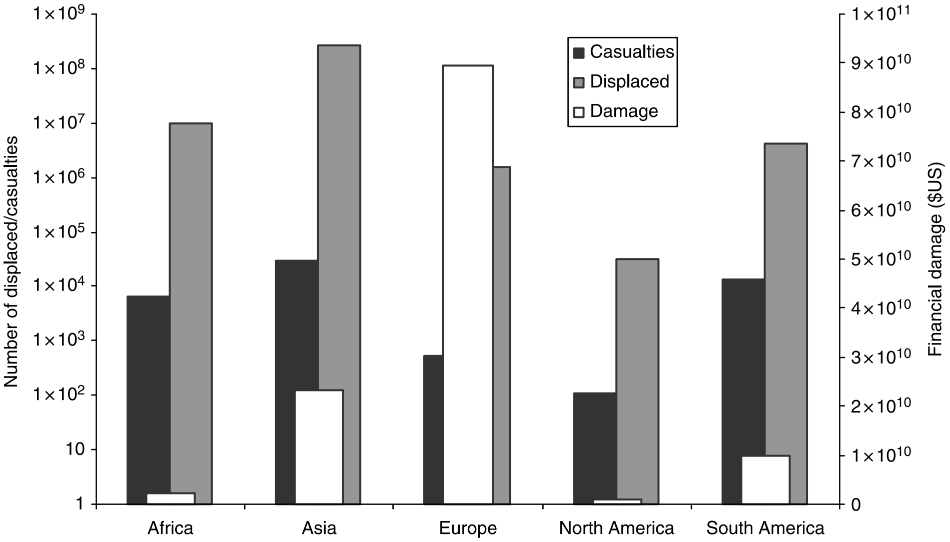

Fig. 5. Transboundary flood statistics for all three variables, per continent. Europe by far has had the most financial damage, while Asia has experienced the highest number of casualties and displaced/affected individuals. Note that the financial damage experienced by North America was lower than in Africa.

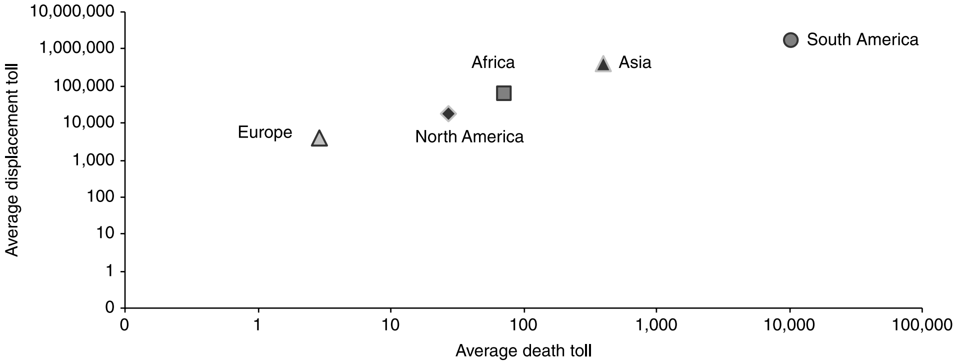

Fig. 6. Average death toll plotted against the average displacement toll per million population, split up by continent; Europe has the lowest score for both, while South America has the highest for both. Note that outliers strongly influenced the average death toll, especially for South America.

Europe was still leading with US$1.8 × 10^9 damage per flood. The runner up was Asia, with almost US$0.4 × 10^9 per transboundary flood. Shared floods in South America resulted in almost US$0.3 × 10^9 damage and in North America the damage was around US$0.14 × 10^9. Africa came in last with US$5.4 million per shared flood.

Hypothetically, the chances for shared flood events increase when there are more countries in an IRB. Therefore, an analysis was executed to see whether the number of countries that share an IRB indeed influenced the number of shared flood events that took place. The data showed that this relationship is not as apparent as expected; IRBs which experienced one flood have the required minimum of two countries, but there were also cases which had a maximum of eight countries (the Lake Chad river basin). This was the case for all transboundary floods, indicating that the number of countries that share a river basin did not guarantee more or less transboundary flood events to occur within that basin.

3.4. Vulnerability to transboundary floods—IRB level

In order to identify IRBs that proved to be vulnerable to transboundary floods, the focus is shifted from the continental level to the individual IRB level. Some 27% (76 of the 279) of all IRBs experienced transboundary flooding during the past 21 years. The number of transboundary floods occurring over the past 21 years in an IRB ranged from a high of 24 in the Danube river basin and the Ganges-Brahmaputra-Meghna river basin, to lows of only one shared flood in the last two decades in the 45 other basins. The graphs (Figure 7a and b) show the top 12 IRBs ranked according to the number of transboundary river floods that took place in the basin, which resulted in a list with only IRBs that experienced four or more transboundary floods. Even though the Danube and Ganges-Brahmaputra-Meghna have seen the most shared floods in the past 21 years, they do not automatically rank first and second when it comes to the number of casualties, or affected people.

If other variables were taken into consideration, the ranking changed. There were IRBs with a higher number of casualties but not in the top 12 IRBs of flood events; the most casualties and affected number of people were in the Ganges-Brahmaputra-Meghna, Irrawaddy and Indus basins, but the Irrawaddy, the Pedernales, the Lempa, the Coatan Achute, the Dasht, the Limpopo and the Incomati river basins all had less than four transboundary flood events, yet were also in the top 12 of casualties. This was also the case

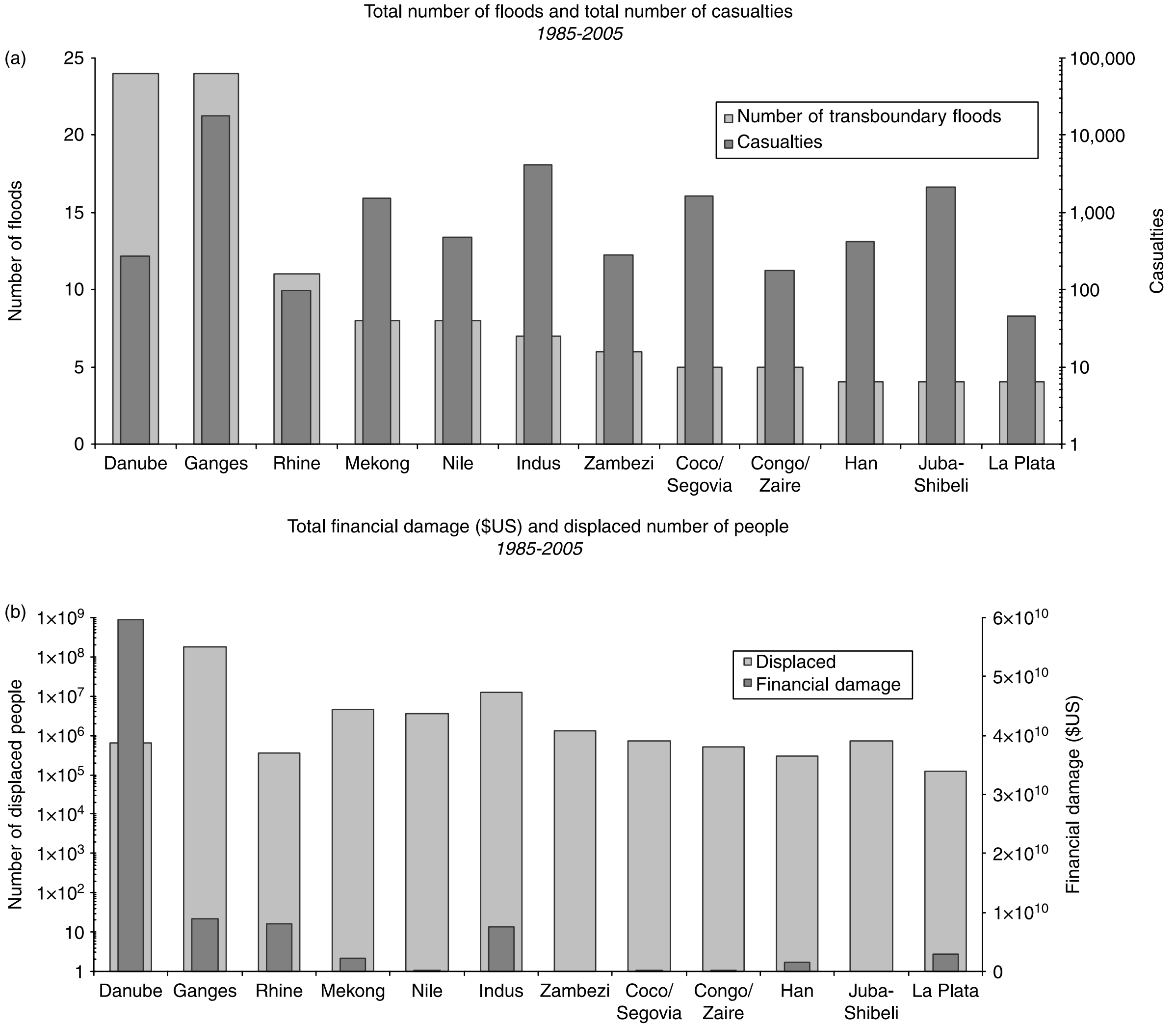

Fig. 7. IRBs ranked according to the number of transboundary river floods they have experienced over the period 1985–2005. It is evident is that the high numbers of transboundary floods do not necessarily result in high amounts of financial damage, and number casualties or displaced/affected individuals.

when examining the number of affected people; the Ganges-Brahmaputra-Meghna, Indus, Mekong, Nile and Zambezi river basin were included in the top 12, but the Irrawaddy, the Coatan Achute, the Karnaphuli, the Limpopo, the Lempa, the Incomati and the Umbelezi river basins experienced fewer than four floods, yet were in the top 12 for affected people. The top 12 for the total amount of financial damage per IRB included the Danube, the Ganges-Brahmaputra-Meghna, the Rhine, the Indus, La Plata, Mekong and Han river basins, but the Elbe, Coatan Achute, Irrawaddy, Amazon and Tijana river basins all had less than four transboundary flood events, yet were included in the top 12 for financial damage resulting from shared flood events. In addition, the average death toll (relative to the population in the basin) of the Pedernales, Coatan Achute and Sembakung river basins were the most vulnerable, although the number of transboundary river floods in these basins was one, two and one respectively.

Even though it can be misrepresentative[11] to average the HDI scores of all the countries within a basin, it did provide a bit more insight. For instance, in the top 12 for affected persons and casualties, only medium and low developed basins were represented. However, the top 12 for highest death tolls and financial damage did not include low developed basins. The medium developed basins were represented the most in all ranked data.

When the average flood magnitude per IRB was ranked, six of the top 12 were African basins and four were South American. The IRB with the highest flood magnitude was the Irrawaddy in Asia. This basin experienced one class II shared flood in 2004 which lasted 110 days and affected over 1,163,000 km^2, which explained the extreme large flood magnitude.

Some IRBs are more densely populated than others[12], resulting in more people being vulnerable to flooding, thus it was more precise to relate the number of casualties to the number of people living in the IRBs. The number of floods experienced by an IRB was plotted against the average death toll per million basin population. As a result, highly impacted IRBs will have many deaths and casualties compared to the basin population. It might be expected that IRBs with a high number of transboundary floods were also the most impacted. However, the results show a considerable number of IRBs with less than five shared floods especially compared to the IRBs with the highest number of floods (the Danube basin and the Ganges-Brahmaputra-Meghna basin). The Pedernales river basin experienced the highest death toll per million basin population. This basin only experienced one flood, which caused about 3,300 casualties, but with a basin population of only 17,920 people, the relative impact was immense: per million basin population, 187,000 people lost their lives.

Basins that experienced considerably more floods, like the Danube and the Ganges-Brahmaputra-Meghna, showed a much lower impact. Although the Ganges-Brahmaputra-Meghna basin has over 580 million people living in it and experienced 24 shared floods, almost 18,000 people lost their lives owing to floods, about 30 people per million. The Danube also experienced 24 floods, but with a basin population of 78 million, it lost 274 people over the last two decades, which is merely about 3.5 people per million population. Although there was substantial scatter in the data, the individual numbers per IRB suggested that if a country experienced more than the average number of 2.6 (i.e., three) floods, the spread of the average death toll per million basin population seemed to stabilize per continent; Asian IRBs did not fall below 19, while European IRBs did not exceed four. Most IRBs had death tolls below ten people per million basin population, underlining just how extreme the Pedernales death toll was.

As stated previously, the average death toll for South America was the highest of all continents, arguably because of the extreme outliers. But even if extreme outliers like the event in the Pedernales basin, or the event in the Tumbes basin, resulting in 364 casualties (which is high relative to a basin population of 154,070) were taken out of the analysis, the average death toll plunged down to 707, which was still the highest. This might be because half of the basins experienced more than one flood, which meant that half of the IRBs have populations living in them with no or limited flood-related experience, resulting in more casualties. However, there were three IRBs with one flood event and no reported

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[11] For instance, the La Plata basin has a HDI range from 34 (Argentina), which would represent a high developed country, to 113 (Bolivia) representing a medium developed country; the average for the entire basin is 69 (medium developed). The Danube has Switzerland it in, ranked 7, but also Moldova, rank 115, while the average is 46 for the entire basin.

[12] With a few exceptions, countries with a higher population tend to have more people occupying shared river basins. This can be attributed to the fact that people have always been attracted to water and river locations, although in the less developed countries it more an issue of survival, while in the developed countries it can also be an aesthetical consideration.

casualties (Hondo, Rio Grande and Lake Titicaca), although this in turn also could have been the result of a low population density in the flood-affected area.

The average death toll of the African IRBs combined was not the highest; there were 14 basins (out of the 20) that only experienced one flood event, but none of these resulted in an excessive number of casualties[13]. Although all three basins with five or more floods had death tolls below ten, the theory that experienced communities have fewer flood-related casualties does not seem to hold up with respect to the African IRBs, or it must be attributed to the fact that either the floods in these basins were not severe or sudden enough to cause large numbers of casualties relative to the basin population, or took place in sparsely populated areas. Lastly, in Asia, seven (of a total of 19) IRBs had one transboundary flood event. The outliers were once more the basins with the fewest number of transboundary floods and thus the smallest number of experience. The Dasht and Sembakung basin both experienced one flood, with death tolls of 2,300 and 4,300 respectively, resulting in an average death toll for the Asian IRBs of almost 400 individuals per million basin population.

The number of affected/displaced individuals per IRB showed that, on average, the South American IRBs had the highest displacement tolls relative to the basin population, followed by Asian IRBs, African IRBs, North American IRBs and European IRBs with the lowest average displacement tolls. The displacement toll for European IRBs did not have nearly as much spread as the other four continents. When the displacement tolls were plotted against the death tolls per IRB and categorized per continent, the relationship between the two was not immediately apparent, although the European IRBs had less scatter than the other IRBs. On a linear scale, however, the displacement toll rose quickly, while the death toll did not follow this increase up until a threshold around 10,000. After that, the death toll increased along with the displacement toll. This implies that the location and/or severity of the flood event resulted in more victims if the number of displaced/affected people exceeds 10,000.

4. Discussion and conclusions

In order to grasp vulnerability to transboundary floods, available information from the OFDA/CRED International Disaster Database (EM-DAT) and the Dartmouth Flood Observatory (DFO) were combined to identify transboundary flood events. The resulting database was merged with socio-economic and biophysical data, enabling analyses that revealed the degree of vulnerability to transboundary floods from a global, an international river basin (IRB), and a country level.

While a thorough attempt has been made to obtain all publicly available data on global flood events, it must be kept in mind that measuring the global flood problem is fraught with problems because of (1) gaps and numerous deficiencies in data, (2) the highly variably quality of available data and (3) the problems of comparing flood impacts along the socio-economic development spectrum (Parker, 2000). As media penetration and information communications have improved, events that might not have been reported in previous years are now routinely reported. Still, in many parts of the world there are no reliable data on the extent of exposure of people and property to flood hazards and reports of the effects of flood disasters are always likely to be less complete in regions with limited resources.

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[13] A possible explanation, not further explored in this article, might be an oral tradition of the early recognition of the severity of floods or the social-cognitive factors that affect human behavioral response to them.

From 1985–2005, 175 of the 1,760 river floods were shared by two or more countries, but globally accounted for 32% of all casualties, nearly 60% of all affected individuals and 14% of all financial damage. On a global as well as a country scale, it is evident that shared floods were more severe than all river floods combined. The data furthermore showed that transboundary floods were more severe in their magnitude, affected larger areas, resulted in higher death tolls (except in the high developed countries) plus higher displacement tolls in high developed countries and caused more financial damage than non-shared river floods do.

Lesser developed countries did not necessarily experience more transboundary floods than more developed countries. This might indicate that technical advancements or abilities to predict or prevent floods, all supposedly better developed mechanisms in more highly developed countries, did not influence the number of transboundary floods, while at the same time, communities in developing countries might be more resilient to floods than industrialized countries due to experience with past floods and a stronger social, structural and environmental coping capacity.

Transboundary events have become more frequent on every continent, but especially in Asia. African and South American countries experienced the most severe floods. Although Asia does not have the highest number of IRBs, it experienced the highest number of transboundary floods (56), followed by Europe (44), Africa (39), South America (30) and North America (six), in that order. The number of countries sharing an IRB had no link to the number of transboundary flood events in that basin. Asian IRBs had the highest number of casualties and affected individuals. European IRBs had the lowest death tolls; South American IRBs the highest. Average death tolls per continent were lowest for European and highest for South American IRBs. However, outliers on all continents (except Europe) heavily influenced the average death tolls. The outliers were often basins with the fewest number of flood events, confirming the hypothesis that experience with flood events lowers the death toll in IRBs. When the average death toll per IRB was plotted against the average displacement toll per IRB, categorized per continent, the average death toll did not climb nearly as fast as the average displacement toll did. Threshold-like behavior was detected around 10,000 displaced people per million basin population, which indicated that when the average displacement toll rose above 10,000, the flood was apparently so severe that it caused comparatively more victims than floods that did not displace as many people.

Lastly, transboundary floods in the European IRBs have caused the most financial damage. Together with the findings related to the HDI, this suggests that the low development countries experienced less material loss than the more developed countries. Communities in developing countries might have fewer capital resources to spend on sustainable protection strategies and might not be able to buy flood insurance. More developed communities might be more vulnerable to tangible flood losses, but they presumably have the ability to obtain better protection systems and have the possibility to obtain flood insurance (Dixit, 2003). And, as noted, richer nations may bear the greater proportion of losses in absolute terms, but poorer countries suffer more when economic loss is measured as a proportion of GNI. Additionally, the more a country chooses to invest in flood protection, the higher the costs of implementing these measures will be. However, as a country chooses to invest in flood protection, it takes into account the benefits of that kind of protection as well, such as lessening the effects of floods and increasing economic growth[14].

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[14] Cost benefit analysis (CBA) is a practical way of assessing the desirability of projects, i.e. it implies the enumeration and evaluation of all the relevant costs and benefits. As such, CBA is a way of setting out the factors which need to be taken into account in making certain choices and is embedded in economic welfare theory as the most appropriate framework to assess the impact of large infrastructure projects in an integrated way (Eijgenraam *et al.*, 2000), such as the consequences of flood protection measures.

Some 76 of the presently known 279 IRBs experienced shared floods in the period 1985–2005. The top 12 IRBs with the most transboundary floods have seen four or more floods—the remaining IRBs (64) have seen three or less shared flood events. For the period considered, the Ganges-Brahmaputra-Meghna and the Danube river basin experienced the most transboundary flood events: 24. The Rhine river basin had the second highest number of floods (11 events), followed by the Mekong (eight events). Based on this single variable, the Ganges-Brahmaputra-Meghna, Danube and Rhine river basins were identified as the most vulnerable IRBs.

Within the 12 river basins with the highest severity score on average, six of the top 12 were African basins and four of them were South American. The IRB with the highest flood magnitude was the Irrawaddy river basin in Asia. Taking the scatter of the data points into account, the individual death tolls per IRB suggest that if an IRB experienced more than the average number of 2.6 floods (i.e. three), the spread of the average death toll per million basin population seems to stabilize per continent; Asian IRBs do not fall below 19, while European IRBs do not exceed four. Not only was this an effect of fewer data points (fewer IRBs experiencing more than the average number of floods), it also indicated that societies, whether developed or less developed, that have experienced floods on a regular basis (like civilizations in the Danube or the Ganges-Brahmaputra-Meghna) might be more adapted to these events and thus more resilient and less vulnerable to floods. Obviously, the number of casualties was influenced by the type and severity of the flood event which is not, in the last place, heavily influenced by differences in geography. Other major factors determining the consequences of a flood are whether the event was predicted or a complete surprise and whether or not the flood took place in a densely populated area (a city, for instance) or not. The latter may explain the lower impacted IRBs in less developed countries.

Thus, depending on the definition of "vulnerability", there were several answers to the question of which country, continent or IRB is the most vulnerable to transboundary flooding. India, Bangladesh and Romania saw the highest number of transboundary river floods, but Timor L'Este, the Dominican Republic and Haiti experienced the highest death tolls, while Nigeria, Nepal and Bangladesh had the highest displacement tolls. However, when only financial damage was looked at, Romania, Germany and Pakistan were the most vulnerable countries.

When the most vulnerable IRBs and the average death toll were taken into consideration, the Pedernales, Coatan Achute and Sembakung river basins were the most vulnerable. When IRBs were ranked according to the most casualties or number of affected people, the Ganges-Brahmaputra-Meghna, Irrawaddy and Indus basins were the top three. Ranking the total amount of financial damages per IRB, the top three consisted of the Danube, Elbe and Ganges-Brahmaputra-Meghna. The Danube, Ganges-Brahmaputra-Meghna and Rhine were the basins where the most shared floods took place. Lastly, the basins that experienced the floods with the highest average flood magnitude were the Irrawaddy, Okavango and Chamelecon. Vulnerable IRBs were found mostly in South America and Asia; the minority of vulnerable IRBs was located in North America and Europe.

Future research could discover more statistically relevant linkages if more databases are developed containing additional detailed information on each and every unique shared river flood event. The type, severity, geographical location, size and population density of the location are important variables influencing the impact of, or vulnerability to, transboundary river floods. In addition, area characteristics such as population magnitude, land-use, and warning- and emergency-systems differ on a regional scale and influence the impact caused by a flood. Other important socio-economic factors that influence this impact are the level of flood protection and the organization of flood defense and disaster management[15]. More comprehensive data might even lead to the development of a transboundary flood vulnerability index.

Together, the results point to the fact that vulnerability to shared river floods is a complex phenomenon that cannot be fully explained using only the variables of the vulnerability framework (Table 1). Nevertheless, taken together, this research significantly increased the current knowledge of shared river flood events and allowed the discovery of new insights in the relationships between flood losses (human and financial) and vulnerability factors, including developmental characteristics. The results of this research could help policy makers identify and evaluate potential vulnerability to transboundary river floods, which in turn can aid international water management and international cooperation over shared river floods. In addition, the results indicate that the greatest impact of floods is still on the poorer countries in the world exerting an enormous toll on future development. Therefore, it is highly recommended to decrease the vulnerability of those who are most exposed, first.

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[15] See Bakker (2009) for a study on the identification of IRBs with adequate institutional capacity for the management of transboundary floods.

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